HOW NUMERICAL COGNITION EXPLAINS AMBIGUITY AVERSION

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How Numerical Cognition Explains Ambiguity Aversion

ABSTRACT

Consumers generally prefer precise probabilities or outcomes over imprecise ranges with the same expected value, a bias known as 'ambiguity aversion.' We argue that two elementary principles of numerical cognition explain great heterogeneity in this bias, affecting consumer choices in many domains where options are characterized by varying levels of uncertainty (e.g., lotteries, discounts, investment products, vaccines, etc.). The first principle, the 'compression effect,' stipulates that consumers' mental number lines are increasingly compressed at greater number magnitudes. This alone suffices to predict ambiguity aversion as it causes a midpoint (e.g., $40) to be perceived as closer to the upper bound of a range (e.g., $60) compared to its lower bound (e.g., $20). Furthermore, as the compression effect distorts the mental number line especially at lower numbers, it follows that ambiguity aversion should decrease around greater numbers. The second principle, the 'left-digit effect' causes a range's relative attractiveness to decrease (increase) disproportionately with every left-digit transition in its lower (upper) bound, thus increasing (decreasing) ambiguity aversion. Due to the overall compression effect, the impact of the left-digit effect increases at greater numbers. We present 34 experiments (N = 10634) to support the theory's predictions and wide applicability.

KEYWORDS: ambiguity aversion, risk, uncertainty, decision-making, numerical cognition

How Numerical Cognition Explains Ambiguity Aversion

Consumers often encounter numeric information (e.g., in prices, product features, probabilities, discount levels etc.) which can vary in its degree of specificity or ambiguity. In department stores, for example, discounts may be specified precisely, as in ‘60% off,’ or with more uncertainty, such as ‘50–70% off’ (Dhar, González-Vallejo, and Soman 1999; Fan, Li, and Jiang 2019). Similarly, the pricing of secondhand goods may be listed as a precise amount—‘$15k for a used car’—or as a range—‘$10k-$20k for a used car’ (Ames and Mason 2015), while a product’s expected lifespan might be advertised as ‘4 years’ or ‘3-5 years,’ vaccine effectiveness could be communicated as ‘94% effective’ or ‘90-98% effective,’ and potential investment returns might be stated as ‘an average 7.5% annual return’ or ‘returns between 5-10% annually’ (Du and Budescu 2005). Although the use of ranges is a popular marketing tactic (Fan et al. 2019), studies from various fields suggest that consumers exhibit ‘ambiguity aversion,’ preferring precise probabilities (e.g., a 60% probability) and outcomes (e.g., a $50 gain) over their imprecise equivalents (Curley and Yates 1985; Du and Budescu 2005; Ellsberg 1961). This raises the question whether and when marketers’ range-based communications might be misaligned with consumer preferences.

Although ambiguity aversion is a well-established phenomenon, it is also characterized by ‘massive heterogeneity’ (in the words of l’Haridon et al. 2018; see also Trautmann and Van De Kuilen 2015). For instance, sometimes the typical response of ambiguity aversion disappears (Abdellaoui et al. 2011; Curley and Yates 1985; Du and Budescu 2005; Sarin and Weber 1993) and other times, it even reverses into ‘ambiguity seeking’ behavior (Abdellaoui, Vossmann, and Weber 2005; Khan and Sarin 1988). It’s important to note that the specific conditions under which ambiguity attitudes change remain unclear because, more than six decades after its introduction, ambiguity aversion is still in search of a psychological theory able to explain both the basic emergence of the phenomenon and, more challenging, a great amount of its heterogeneity (Trautmann and Van De Kuilen 2015).

In the current paper, we draw on two well-established principles from the numerical cognition literature to provide an account of why and when ambiguity aversion can emerge in the first place, while, crucially, predicting the types of ranges and numerical magnitudes for which ambiguity aversion will be most pronounced, will be attenuated, or can even switch into ambiguity seeking behavior. The first principle is the ‘compression effect,’ stipulating that consumers’ mental number lines (i.e., their psychological representations of numbers) are increasingly compressed with greater number magnitudes (Dehaene 2011). As we outline below, this alone suffices to predict the basic emergence of ambiguity aversion as well as an attenuation of the effect when ranges are centered around greater numbers. The second principle is the ‘left-digit effect,’ which elongates the mental number line at left-digit changes (Thomas and Morwitz 2005). This causes the relative attractiveness of a range of outcomes or probabilities to decrease (increase) disproportionally with every left-digit transition in the range’s lower (upper) bound. Thus, when upper bound transitions outnumber lower bound transitions, ambiguity aversion is attenuated or turns into ambiguity seeking. In this paper and its accompanying web appendix, we report seven studies, comprising 34 experiments ($N = 10634$), that support our theory’s predictions and illustrate its wide applicability.

By outlining the circumstances under which consumers prefer offers featuring certain outcomes (or probabilities) over uncertain ones (and vice versa), we offer an important contribution to the uncertainty and range marketing literatures (Alavi, Bornemann, and Wieseke

2015; Ames and Mason 2015; André, Reinholtz, and De Langhe 2022; Buechel and Li 2023; Fan et al. 2019; Janiszewski and Lichtenstein 1999; Kovacheva and Nikolova 2024), as well as medical (Berger, Bleichrodt, and Eeckhoudt 2013), and financial (Epstein and Schneider 2010) decision-making literatures. In addition, the theory proposed in this paper offers an important contribution to the literature on judgment and decision making, where ambiguity aversion has been a central concept since its original demonstration caused a paradigm shift (see Theoretical Background). As we will argue and show, the theory explains an unprecedented amount of heterogeneity in ambiguity aversion, testifying to its explanatory breadth, while being solidly grounded in well-established principles from cognitive psychology.

THEORETICAL BACKGROUND

Precise versus Imprecise Marketing Offers

An early study by Mobley, Bearden, and Teel (1988) found that imprecise offers tend to be heavily discounted by consumers, due to their aversion to ambiguity. Thus, they urged marketers to use precise messages in advertising when possible. However, later work found that attitudes toward imprecise marketing offers are more nuanced and there can be many circumstances where consumers appreciate some uncertainty. For example, range offers—those with a span of possible discounts — can be more enticing than precise offers under certain conditions. Specifically, they are more effective when the stock on sale is limited, creating a perception of scarcity and exclusivity (Dhar et al. 1999). Furthermore, research by Fan and colleagues (2019) found that in situations of resource scarcity, people preferred range to precise offers. Range offers have also been studied in the context of trust. For instance, Ames and Mason (2015) found that range offers signal politeness and foster trust in social exchanges, with the potential to improve deals. Furthermore, consumers in communal relationships with brands exhibit a lower degree of ambiguity aversion as they trust the brand more (Liu and Chang 2017). Most recently, Buechel and Li (2023) showed that when options are horizontally differentiated, consumers can appreciate uncertainty more as it adds a level of 'mystique' with the potential to surprise consumers.

These findings from the range marketing literature indicate that the perceived advantages of range offers are subject to a variety of influences, such as the consumer's relationship with the brand, their level of trust, and the context in which the offer is made. Range marketing offers in pricing may have an additional advantage over fixed price discounts since those may lead to negative repercussions—where customers come to expect a fixed discount level in the future and adopt it as their benchmark reference price (Alavi et al. 2015). These examples illustrate the need for marketers to understand when imprecise offers can be effectively employed while mitigating the effects of ambiguity aversion. Therefore, it is important to understand the main causes of ambiguity aversion and the circumstances under which it will be most pronounced.

Ambiguity Aversion

Ambiguity aversion has been a cornerstone concept in decision-making under uncertainty since Ellsberg's (1961) seminal paper challenged the then-prevalent Subjective Expected Utility (SEU) theory (Savage 1954). In one prototypical variation of Ellsberg's experiments, participants would repeatedly bet on drawing a red or a black ball and could choose between two urns to draw from. The first urn had a precisely defined distribution of 50 red and 50 black balls, while the second urn had an unknown distribution of 100 red or black balls (in total). Regardless of whether participants were betting on drawing a red or a black ball, they consistently favored the urn with the known distribution. This would imply, according to Subjective Expected Utility (SEU), that participants estimate the probability of drawing a specific color from the unknown urn to be less than 50% for *either* color, violating a core principle of SEU where event probabilities need to be additive. Becker and Brownson (1964) later broadened the domain of ambiguity aversion by introducing the concept of ranges to operationalize ambiguity, proposing that consumers prefer precise probabilities and that an increase in range width heightens ambiguity aversion. Du and Budescu (2005) demonstrated that ambiguity aversion also applies to outcomes. When given a choice between a range of outcomes versus a certain equivalent (CE), individuals display aversion to range outcomes even when the probabilities are precise.

While ambiguity aversion is robustly documented, it exhibits significant heterogeneity (l'Haridon et al. 2018; Trautmann and Van De Kuilen 2015). Some researchers found that consumers are ambiguity averse for events with moderate- to high-likelihood yet remain ambiguity neutral for those with low likelihood (Abdellaoui et al. 2011; Curley and Yates 1985; Sarin and Weber 1993). Conversely, other studies suggest that individuals seek ambiguity in the context of low likelihood events (Curley and Yates 1989; Khan and Sarin 1988). Losses are similarly heterogeneous, with some research indicating ambiguity seeking (Abdellaoui et al. 2005), while others reveal a tendency towards ambiguity neutrality (Du and Budescu 2005). No theory to date offers a comprehensive account for the heterogeneity in ambiguity attitudes across likelihood ranges or domains. Furthermore, it is worth noting that most of the psychological explanations proposed to account for ambiguity aversion to date predict ambiguity aversion in both the gains and loss domains. Examples include theories based on the assumption that people would feel a need to justify their decisions to others (Curley, Yates, and Abrams 1986; Keren and Gerritsen 1999; Muthukrishnan, Wathieu, and Xu 2009), that people expect that experimenters, deal brokers or market actors want to 'cheat' them into a bad outcome (Curley et al. 1986) or that people expect worse outcomes because they feel comparatively ignorant in a domain (Fox and Tversky 1995). Yet, in the loss domain, it is predominantly observed that consumers are ambiguity seeking (Trautmann and Van De Kuilen 2015).

Numerical Cognition: The Compressive Mental Number Line and the Left-Digit Effect

Numerical cognition, a subfield of cognitive psychology, focuses on the mental processes behind the representation and manipulation of numbers and numerical information (Dehaene 2011). Numerical cognition has been applied to the study of consumer behavior and decision-making in various contexts, such as sales promotions and pricing (Laurent and Vanhuele 2023; Lembregts and Pandelaere 2013; Monnier and Thomas 2022; Thomas and Morwitz 2005). Additionally, numerical cognition has been shown to play a crucial role in shaping our perception of probabilities and prospects (Schley and Peters 2014). Surprisingly, the relevance of numerical cognition for decision making under ambiguity, where ranges of possible outcomes or probabilities are present, has not been investigated.

Our theory is grounded in two of numerical cognition's most well-established principles. The first principle is the continuous compression of the mental number line, which suggests that as numbers increase, their mental representations become progressively more compressed. This compression implies that as numbers get larger, our ability to differentiate between them decreases. For instance, the difference between 1 and 2 seems larger than the difference between 8 and 9, which still seems larger than the difference between 22 and 23, despite all pairs having the same objective difference (Dehaene 2003; Holloway and Ansari 2009). As we will argue below, this continuous compression principle will greatly affect ambiguity aversion, predicting its occurrence in regions lower on the mental number line as well as its gradual disappearance higher up. The second principle is the effect of left-digit transitions, which lead to discontinuities or elongations of the mental number line. For example, the distance between 89 and 90 is perceived as larger than the distance between 90 and 91 (Dehaene 2003; Sokolova, Seenivasan, and Thomas 2020; Thomas and Morwitz 2005). As we will argue and show below, these left-digit transitions also impact ambiguity aversion, being able to accentuate, cancel or even inverse the phenomenon (i.e., reversing into ambiguity seeking behavior under the right conditions).

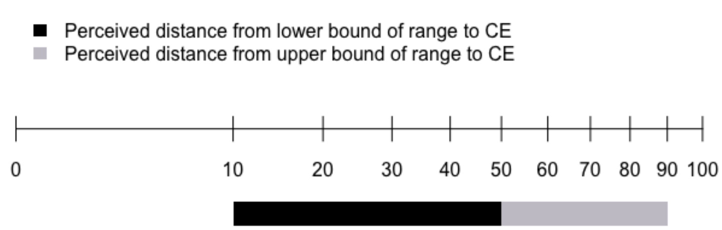
Effects of Mental Number Line Compression on Ambiguity Aversion

A first and fundamental insight from the numerical cognition literature is the compression effect, according to which the psychological representations of numbers on our internal ‘mental number line’ are increasingly compressed as number size increases (Dehaene 2011; Thomas and Kyung 2019; Vanhuele, Laurent, and Dreze 2006). Recent integrations of empirical evidence in this domain have proposed that the mental number line’s shape is in line with a power function (Izard and Dehaene 2008), as illustrated in figure 1. There, we also illustrate the most basic insight provided in the current paper: the compressive nature of the mental number line is, by itself, sufficient to explain the emergence of ambiguity aversion.

Consider what happens when a consumer compares an uncertain range of outcomes (or probabilities) of, say US $10–90 (or %) with a Certain Equivalent (CE) of US $50 (or %). While 50 is, not accidentally, the objective midpoint of the 10-90 range, this might not be immediately or explicitly obvious to the consumer. In fact, we propose that consumers will compare the CE and range on an implicit scale, rather than an objective one (De Langhe et al. 2011; Donnelly, Compiani, and Evers 2022; Sokolova 2023). Crucially, we expect that *the shape of the scale* on which consumers implicitly compare the CE with the range *must abide to the principles of their mental number line.* On that scale, 50 does not lie in the center, but is perceptually closer to the upper bound (90) than the lower bound (10) of the range. For the development of our hypotheses, we assume simply that *the closer the certain comparison point (CE) is perceived to the upper bound relative to the lower bound of the uncertain range, the greater its desirability relative to the range will be.* After all, the closer a CE appears to the upper bound of the range, the less upward potential the range appears to have over the CE; concurrently, the further a CE appears from the lower bound of the range, the greater the range's downward potential appears to be. Hence, it follows that a consumer who compares these options on a mental number line, should prefer the certain option.

FIGURE 1

COMPARING A POINT WITH A RANGE ON A COMPRESSIVE MENTAL NUMBER LINE



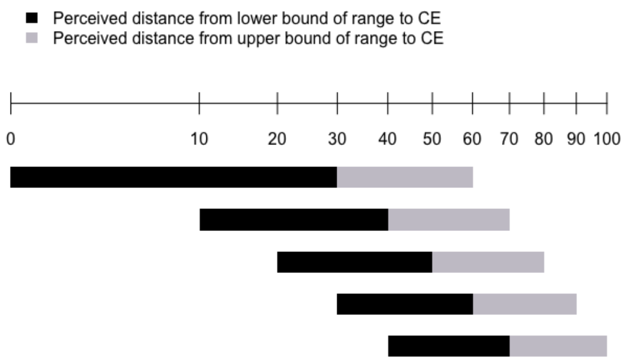
NOTE- The figure represents a comparison of an imprecise range of 10 – 90 with its certain equivalent (CE) of 50. Due to continuous compression of the mental number line, 50 appears closer to the upper bound of the range (90) than the lower bound (10).

Importantly, we note that this basic insight does not just suffice to explain the emergence of ambiguity aversion in the first place, it is also consistent with one of its earliest known moderators: ambiguity aversion increases as the width of the range increases (Becker and Brownson 1964). Indeed, if the consumer had compared the CE of 50 with a (smaller) range of, say 40 – 60, the disparity in distance perceptions to the range's upper and lower bounds wouldn't have been nearly as pronounced. This is because as ranges extend in width, their downward elongation will (implicitly and perceptually) increasingly outpace their upward elongation on the mental number line, due to its increasing compression (see figure 1). Hence, the wider the range extends, the more ambiguity aversion should be increased.

Yet, how else could we test whether ambiguity aversion can (at least partially) be explained by the progressively compressed shape of the mental number line? Interestingly, the compression effect is not expected to operate equally strongly across the mental number line. In particular, and as illustrated in figure 2, its effect on ambiguity aversion would be expected to *decrease* when ranges get centered around higher CEs. This is because, as numbers get increasingly compressed further up the mental number line, for any range with a fixed width (60 in the figure's example), the *disparity* in distance perceptions between the CE and the range's upper- versus lower bounds *decreases* as the magnitude of the CE *increases*.

FIGURE 2

RANGE COMPARISONS AS COMPARISON POINTS GET LARGER



NOTE- The figure represents a comparison of imprecise ranges with a fixed width of 60, centered around progressively increasing midpoints or CEs (30, 40, 50, 60, 70). Due to increasing compression of the number line, the CE always appears closer to the upper bound of the range than its lower bound, but the size of this discrepancy reduces as CE magnitude increases.

Hence, numerical cognition's compression principle does not just suffice to explain the basic emergence of ambiguity aversion (and at least one known moderator), it also leads to a unique prediction. If consumers compare uncertain ranges with CEs along a mental number line, it follows that (for ranges with a fixed width and in the gains domain):

H1: Ambiguity aversion decreases as the magnitude of the CE increases.

Left-Digit Effects of Mental Number Line Elongations on Ambiguity Aversion

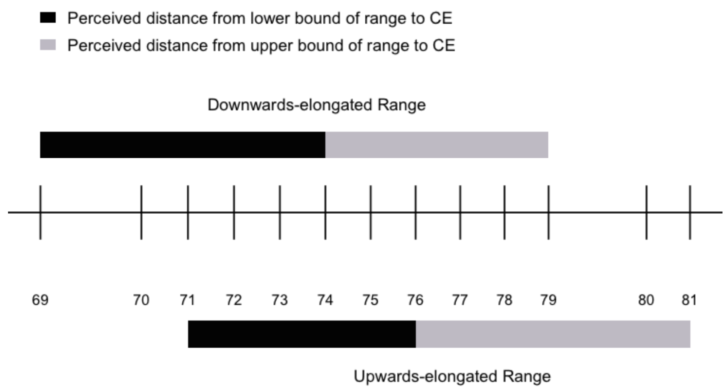
In the previous section, we argued that due to the compression effect, a CE will generally be perceived as closer to the upper bound than the lower bound of a range. In the current section, we argue that a second principle from numerical cognition – the left-digit effect – has the potential to significantly moderate this basic tendency. Previous research has shown that consumers elongate the psychological distance between numbers whose left-most digit changes. For example, the difference between $2.99 and $3.00 feels larger than between $2.98 and $2.99 (Manning and Sprott 2009; Thomas and Morwitz 2005). Similarly, in the domain of probabilities, a difference between 58% and 62% feels larger than between 54% and 58% (Schley et al. 2021). While the left-digit effect for point versus point comparisons has been extensively documented in both outcomes and probabilities, we propose that this effect is also crucial in point versus range comparisons.

Consider the range 71-81 and its CE of 76. The left-digit difference between the lower bound and the CE is zero, while the difference between the upper bound and the CE is one. We refer to such ranges as *upwards-elongated* because the left-digit difference between the CE and the range's upper bound is larger than that between the CE and the lower bound. Contrast this with a situation where the CE is just two units lower, for example, a CE of 74, and the range maintains an equal width, that is 69-79. Here, the left-digit difference between the lower bound and the CE is one, and between the upper bound and the CE is zero. We call this type of range *downwards-elongated*. As illustrated in figure 3, the CE appears closer to the upper bound in downwards-elongated ranges. Conversely, in upwards-elongated ranges, it appears closer to the lower bound. Based on this, if consumers compare imprecise ranges with CEs along a mental number line, we predict the following for ranges of fixed width and in the gains domain:

> **H2:** Ambiguity aversion is amplified (versus attenuated) when a range is downwards-elongated relative to the CE (versus upwards-elongated).

FIGURE 3

DOWNWARDS-VERSUS UPWARDS-ELONGATED RANGES



NOTE- A downwards-elongated range has more left-digit changes compared with the CE on its lower-bound (e.g., 69 vs 74) than on its upper-bound (e.g., 79 vs. 74). An upwards-elongated range has more left-digit changes in its upper-bound compared with the CE (e.g., 81 vs. 76) than on its lower-bound (e.g., 71 vs. 76). With downward-elongated ranges (vs. upward-elongated ranges), the CE appears closer to the upper (vs. lower) bound of the range, so people will be more (vs. less) inclined to prefer the CE and display ambiguity aversion.

It is important to note that upwards-elongated ranges are not limited to those where the difference between the CE and the lower bound is zero and the difference between the upper bound and the CE is one. They include any range where the left-digit difference between the CE and the upper bound is greater than that between the CE and the lower bound (e.g., 40-70 vs. a CE of 55). Similarly, downwards-elongated ranges are not confined to those where the left-digit difference between the lower bound and the CE is one and between the upper bound and the CE is zero. They encompass any range where the left-digit difference between the CE and the lower bound is greater than that between the CE and the upper bound (e.g., 39-69 vs. a CE of 54).

We proposed that ambiguity aversion should decrease as numerical magnitude increases because the perceived difference between the range's upside and downside region becomes progressively smaller, due to the increasing compression of the mental number line (H1). What about the effect of range elongation, caused by left-digit differences (H2)? How would this effect be modified across the mental number line? We argue that this effect intensifies at higher magnitudes due to the difficulty of distinguishing larger numbers where compression is at its peak (Thomas and Morwitz 2005). In high magnitude comparisons (e.g., when comparing the range 81-91 versus a CE of 86), numbers without left-digit changes become increasingly undifferentiated due to the high level of compression (e.g., all numbers between 81-89 feel subjectively very close or similar), lending a disproportionate influence to the effect of a left-digit change (e.g., the shift to 90 has a strong impact). In contrast, for smaller magnitudes (e.g., when comparing the range of 11-21 versus a CE of 16), all numbers are still individually discriminable, whether or not there is a left-digit change. A left-digit change will, of course, still be a source of additional differentiation (and subjective elongation of the mental number line), but it is no longer the *only* source of differentiation. Therefore, we suggest that consumers may be more influenced by the left-digit change in the range of 81-91 than they would be in the range of 11-21, in comparison with the point estimate. Formally, we hypothesize that, for ranges of fixed width and in the gains domain:

> **H3**: The effect of upwards- versus downwards-elongated ranges (stipulated in H2) increases at higher CE magnitudes.

It is worth noting that we do not argue that people would perceive a left-digit change between higher numbers (e.g., from 8 to 9) as larger than a left-digit change between lower numbers (e.g., from 1 to 2). Due to the mental number line's increasing compression, likely the opposite is true. Instead, our argument pertains to the *effect* left-digit changes in range boundaries have *on the comparison process* between a CE and a range. There we argue that this effect of left-digit changes will become more impactful when other sources of discriminability between the numbers are low (i.e., when numbers become increasingly compressed), in line with established knowledge about the operation of left-digit effects (cf. H3 in Thomas and Morwitz

2005).

Process Evidence and Boundary Conditions

The majority of research documenting ambiguity aversion did so in the domain of gains, while in the domain of losses, findings are decidedly more mixed (Trautmann and Van De Kuilen 2015). This is also the reason why in the current paper, we are predominantly focused on gains. As we noted above, most of the psychological theories that have been proposed to explain ambiguity aversion, would predict ambiguity aversion also in the loss domain (Curley et al. 1986; Trautmann and Van De Kuilen 2015). Interestingly, our explanation based on the principles of numerical cognition predicts an opposite pattern. After all, our core assumption that the closer the CE is perceived to the upper bound of the range, the greater its attractiveness relative to the range, would only be true when consumers aim to maximize the outcome (or probability) they will obtain. When their goal is to minimize this outcome (or probability), as in the case of losses, this choice pattern should reverse. We test one straightforward prediction explicitly in the domain of losses, namely a reversal of the effect stipulated in H2.

> **H4**: In the domain of losses, ambiguity aversion is amplified (versus attenuated) when a range is upwards-elongated relative to the CE (versus downwards-elongated).

Finally, we include one study where we attempt to manipulate the psychological process directly. Central in our theorizing is that ambiguity aversion is strongly impacted by systematic misperceptions of CE's position on the mental representation of the range, due to numeric compression and left-digit effects. It follows that a simple explanation of where the CE *really* (objectively) falls on the range (i.e., directly in the middle), should significantly reduce these biases. We will test this idea directly in the context of the effects of left-digit elongations on ambiguity aversion:

> **H5**: Highlighting that the CE is the objective midpoint of the range, should reduce the difference in ambiguity aversion between downwards- and upwards-elongated ranges.

OVERVIEW OF STUDIES

In the main manuscript, we present six studies testing our theory (more are presented in the Web Appendix, see below). In study 1, participants are presented with a choice between a precise (CE) and an imprecise (range) outcome lottery, featuring increasing CE magnitudes but a fixed range width, to test H1. Next, we demonstrate the impact of left-digit effects and range elongations on ambiguity aversion (H2). Study 2 tests H2 in six consumer domains (choosing between vaccines, store discounts, investment returns, sales agents, product lifespans and product ratings) while study 3 applies this test in the classic ambiguity paradigm conceived by Ellsberg (1961). In study 4, across 16 experiments, we examine whether the effect of range elongations (caused by left-digit asymmetries) varies across the mental number line as stipulated in H3 (the study also finds additional support for H1). Finally, studies 5 and 6 provide process evidence and boundary conditions. In study 5, we test whether the effects of range elongations indeed reverse in the loss domain (H4). Study 6 tests whether highlighting the CE as the midpoint of the range attenuates the impact of range elongations on ambiguity aversion (H5).

Supplemental experiments C1-3 (Web Appendix C) test H2 and H3 in a consumer context. Supplemental experiments E1-3 (Web Appendix E) were conducted independently by a reviewer to test H1, H2 and H3 in consumer contexts. Finally, we conducted preliminary experiments F1-2 (Web Appendix F) to test extensions of our theory to larger numbers (i.e., > 100, experiment F1) and to middle digits (experiment F2). Studies 1, 2, 3, 4 (the outcome experiments), 5, 6 and C2-3 were pre-registered. In line with the pre-registration, we did not exclude any participants from these or other studies. The data sets, study materials, and analysis codes of all our experiments can be accessed in the following OSF repository: https://tinyurl.com/ambiguity-aversion

STUDY 1: THE INFLUENCE OF CE MAGNITUDE ON AMBIGUITY AVERSION

In study 1, we explore our first proposition: as the magnitude of the CE increases, ambiguity aversion diminishes (H1). We test this by making participants choose between a CE and a range in a lottery setup. We vary CE magnitude but hold range width constant.

Method

Participants and design. 1003 participants[1] were recruited via Prolific from the US and UK (540 females, M_{age}= 38). Participants were randomly assigned to one of five CE magnitude conditions: 30, 40, 50, 60, 70. Consistent with our pre-registration, we did not exclude any of the participants in this study (or any of the subsequent ones).

Procedure. We informed all participants that they would be choosing between two hypothetical lottery options. Participants were then presented with a choice between a precise (CE) and an imprecise (range) lottery outcome, featuring between-subjects variation in CE magnitude. In all five CE conditions, the options constituted a lottery win of either the [CE] or a range of [CE - 30, CE + 30]. For example, in the CE 40 condition participants had to choose between the following two options: 50% probability of winning $40 versus 50% probability of winning $10-$70.

In study 1, we did not provide participants with any information on interpreting the imprecise (range) option or its distribution, thus preserving the ambiguity of the option. The order in which the precise (CE) and imprecise (range) options appeared – as the first versus second option – was counterbalanced.

In this study, and in all other studies presented in this paper, we gathered demographic data, including gender and age, prior to starting the experiment. Then, following the experiment, all participants were asked in which country they reside and were invited to provide feedback on

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[1] As detailed in the preregistration, we initially targeted a sample size of 500 participants (100 per cell of the experimental design). However, after collecting the initial data, the results were directionally but not statistically significant (the key test for H1 came out as $\beta = 0.01$, SE = 0.006, $z = 1.56$, $p = 0.11$). We decided to collect additional data, doubling the sample size. While our test of H1 on this enlarged sample came out as highly significant (see below), it has to be recognized that the overall (experiment-wise) type I error rate has been inflated from alpha = .05 to .0831 due to our initial 'peek' at the results (André and Reinholtz 2023; Simmons, Nelson, and Simonsohn 2011).

the survey or to explain the reasoning behind their choice. As we restricted participants from revisiting the lottery question during the feedback phase, their reflections could not affect their original decisions.

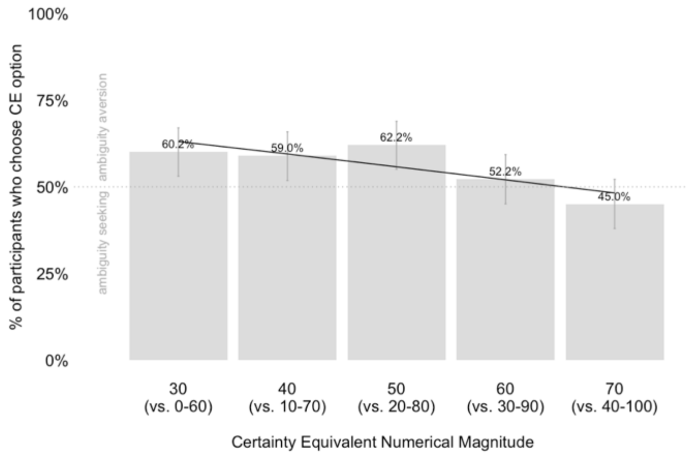
Results

To explore the impact of CE magnitude on participants' choice between the precise (CE) and ambiguous (range) lottery outcomes, we ran a logistic regression analysis. In support of H1, we found that ambiguity aversion, defined as the preference for the precise (CE) lottery outcome, diminished as CE magnitude increased ($\beta = -0.015$, SE = 0.004, $z = -3.336$, $p < .001$). For details on the proportion of participants choosing the precise outcome by CE magnitude level (and the corresponding logistic regression predictions), refer to figure 4.

Additionally, we conducted a chi-square test for each CE magnitude condition to test for ambiguity aversion in that condition (i.e., a significant departure from a 50/50 selection of the precise (CE) versus the imprecise (range) lottery option). The chi-square tests revealed ambiguity aversion in the 30 ($\chi^2(1) = 8.3$, $p = .003$), 40 ($\chi^2(1) = 6.4$, $p = .01$), and 50 ($\chi^2(1) = 11.9$, $p < .001$) CE conditions, but ambiguity neutrality (i.e., a *lack* of significant departure from a 50/50 selection) in the 60 ($\chi^2(1) = 0.4$, $p = .52$) and 70 ($\chi^2(1) = 2$, $p = .15$) CE conditions.

FIGURE 4

CHOICE OF PRECISE LOTTERY OUTCOME BY CE MAGNITUDE



NOTE- The gray bars show the proportion of participants who preferred the precise (CE) over the ambiguous (range) outcome in each condition. The black line represents the logistic regression predictions at each CE magnitude. The dotted line at 50% represents ambiguity neutrality (indifference between the precise (CE) and imprecise (range) options). When the proportion of participants choosing the precise option is above 50%, this reflects an overall propensity for ambiguity aversion. In contrast, when the proportion of participants choosing the precise option is below 50%, this reflects an overall propensity for ambiguity seeking. The grey error bars represent the 95% confidence interval for each condition.

Discussion

In H1, we proposed that ambiguity aversion should decrease as the magnitude of the CE increases. Study 1 found clear support for this prediction. A logistic regression demonstrates that ambiguity aversion decreases when CE magnitude increases and chi square tests confirm that ambiguity aversion is present at lower CE levels, namely 30, 40, and 50, but ambiguity neutrality emerges at the higher CE levels of 60 and 70. This transition, from ambiguity aversion to neutrality, points to CE magnitude as a previously unexplored moderator of ambiguity aversion and is consistent with the presumed role of the mental number line's progressive compression in generating ambiguity aversion.

Despite the broadly consistent pattern of our results, a small deviation appeared to emerge at the CE value of 50, where the preference for the precise (CE) option is most pronounced, defying the overall declining trend. One apparently plausible explanation could lie in the distinct appeal of gaining US $ 50,-. Unique in being the only CE with its own banknote representation among the CEs that were tested (the 30-70 range), the prospect of gaining $ 50,- might hold a specific allure to participants due to the denomination effect (Raghubir and Srivastava 2009). However, this interpretation is post hoc and does not detract from the overall significance of the pattern as hypothesized in H1 in our final sample, though it may have contributed to the lack of significance of this test when we conducted it on the first 500 data points collected (footnote 1). Finally, we note that further support for H1 is presented in study 4 and in data collected independently from the authors, by a reviewer who tested the effect in more consumer-centric domains (Web Appendix E).

STUDY 2: IMPACT OF RANGE ELONGATION ON AMBIGUITY AVERSION IN CONSUMER CHOICE

While study 1 tests our first proposition on the impact of the compression effect on ambiguity aversion, study 2 focuses on our second proposition — the effect of range elongations caused by left-digit asymmetries on ambiguity aversion. We test the effect of these range elongations on consumers' preferences for precise versus uncertain options in six consumer context experiments: vaccine effectiveness, discount offers, used car sales, investment returns, product lifespan, and product ratings.

Method

Participants and design. We tested the effect of left-digit range elongations in six experiments with varying CE magnitudes. A total of 1,208 participants were recruited via Prolific

(681 females, M_{age}= 39). Each participant took part in one of the 6 experiments, five of which were conducted in one session, and one was conducted independently on a different day. In each experiment, participants were randomly assigned to one of two range conditions: upwards-elongated or downwards-elongated.

Procedure. In each of the six experiments, participants were asked to imagine choosing between two options, one communicated precisely and the other imprecisely. In each experiment, we had two conditions: downwards-elongated and upwards-elongated range. For example, in the discount offer experiment, participants in the downwards-elongated range condition had to choose between a store with a 74% fixed discount and another store with uncertain (range) discounts of 69% - 79%, while participants in the upwards-elongated condition chose between a store with a 76% fixed discount and one with uncertain (range) discounts between 71% - 81%. Two of the experiments were designed to test whether the range elongation effect also occurs in decimal numbers smaller than 10, where every integer transition entails a left-digit change. We did not provide participants with more information on interpreting the imprecise (range) option or its distribution, thus preserving the ambiguity of the option. The order in which the precise (CE) and imprecise (range) options appeared—as first versus second item—was counterbalanced. Details of the six experiments, including the choices participants had to make in each condition, can be found in table 1.

TABLE 1

CONSUMER CONTEXT EXPERIMENTS (STUDY 2)

Context	Condition*	Description	Choice to make

Vaccine Effectiveness	DE: X = 74, Y = 69, Z = 79 UE: X = 76, Y = 71, Z = 81	Please choose which of these two vaccines you would prefer. Imagine everything is equivalent except the effectiveness information.	Vaccine A: X% effective Vaccine B: Y-Z% effective
Discount Offers	DE: X = 74, Y = 69, Z = 79 UE: X = 76, Y = 71, Z = 81	Imagine it is Black Friday and you are shopping. Please indicate your preference of store based on the information below, assuming all other factors are equal.	Store A: Discount of X% Store B: Discount of Y-Z%
Used Car Sales	DE: X = 74k, Y = 69k, Z = 79k UE: X = 76k, Y = 71k, Z = 81k	Imagine you are selling your expensive car. Please indicate your preference of salesperson, assuming all other factors are equal.	Person A: Offers to sell your car for $X Person B: Offers to sell your car for $Y-$Z
Investment Returns	DE: X = 74, Y = 69, Z = 79 UE: X = 76, Y = 71, Z = 81	Imagine you have a chance to invest $1,000. You are now deciding between two investment options. Please indicate your preference based on the information below, assuming all other factors are equal.	Investment A: After one year your expected return would be $X Investment B: After one year, your expected return would be $Y-$Z
Product Lifespans	DE: X = 7.4, Y = 6.9, Z = 7.9 UE: X = 7.6, Y = 7.1, Z = 8.1	Imagine you are deciding between two products. Which do you prefer, assuming all other factors are equal.	Product A: Has a lifespan of X years Product B: Has a lifespan of Y-Z years

Product Ratings	DE: X = 7.4, Y = 6.9, Z = 7.9 UE: X = 7.6, Y = 7.1, Z = 8.1	Imagine you are deciding between two products. Which do you prefer, assuming all other factors are equal.	Product A: Has a rating of X out of 10 Product B: Has a rating of Y-Z out of 10

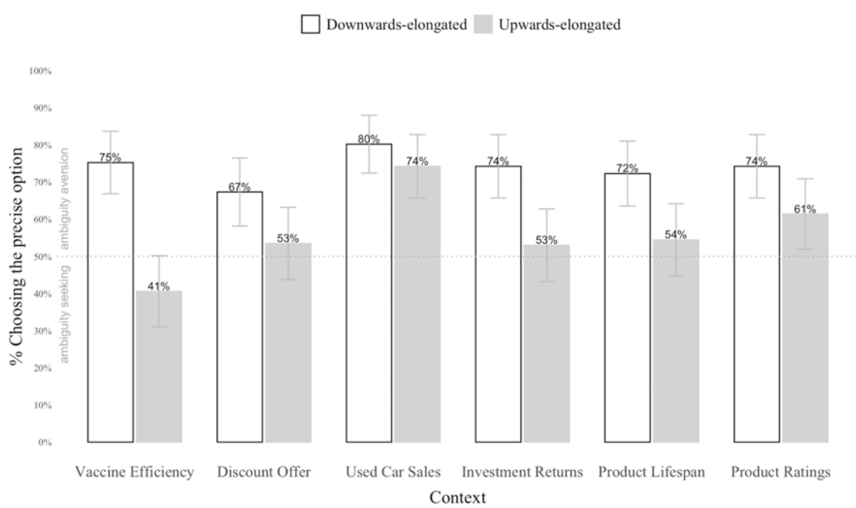
Note - *DE = downwards-elongated range condition, UE = upwards-elongated range condition

Results

The results of the downwards- and upwards-elongated conditions of the individual experiments are visualized in figure 5 (the exact choice proportions and corresponding chi-square tests can be found in table A1 in Web Appendix A).

FIGURE 5

CHOICE OF PRECISE OPTION (CE) BY RANGE ELONGATION CONDITION (STUDY 2)



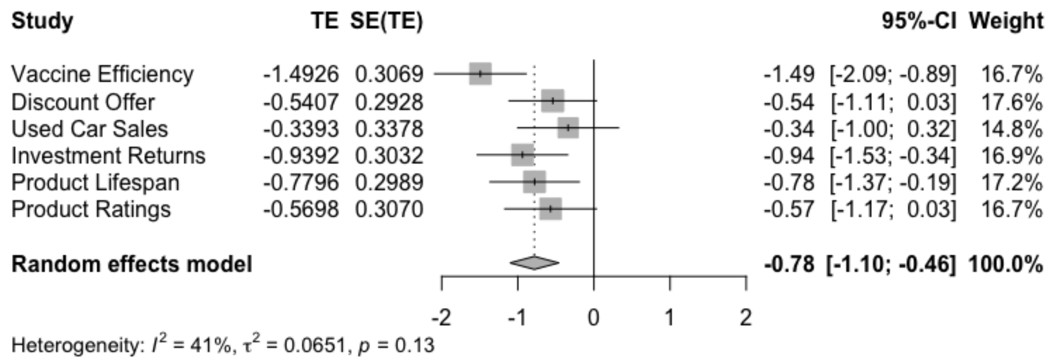
NOTE- The dotted line at 50% represents ambiguity neutrality (indifference between the CE and range options). The error bars show the 95% confidence intervals for each condition.

Here, we report an aggregated analysis on the impact of range elongation in the various consumer contexts. We use the ‘meta’ package (Balduzzi, Rücker, and Schwarzer 2019) in R to conduct a single-study meta-analysis of the six experiments (McShane and Böckenholt 2017). We compute the effect size and its 95% confidence interval for the effect of range elongation (number of studies k = 6) in the individual experiments by a generalized linear model (GLM) expressed in log odds ratio (logOR) units. The upwards-elongated condition was coded as the ‘experimental’ group and the downwards-elongated one as the ‘control.’ Hence, a negative effect size confirms the direction of our predicted effect, whereby we expect that participants would be less likely to choose the certain option (i.e., be less ambiguity averse) in the upwards-elongated range condition.

First, we checked the effect of counterbalancing the choice order and found that counterbalancing had no significant main effect ($p = .54$) or interaction effects with the range elongation condition ($p = .25$). Therefore, this factor was dropped. We employed a random effects model, as the studies displayed variations in context and numerical format (Borenstein et al. 2009), but the results of a fixed-effects model were analogous. We find a statistically significant overall effect size for the effect of range elongations across six studies (overall log odds ratio: -0.78, 95% CI: -1.10 to -0.46, $z = -4.80$, $p < .001$). The negative effect size confirms that individuals are less likely to choose the precise option in the upwards-elongated compared to the downwards-elongated condition. See figure 6 for a Forest Plot of the effect sizes and confidence intervals across studies. We report further information on the heterogeneity of effect sizes across contexts in Web Appendix A.

FIGURE 6

FOREST PLOT OF THE RANGE ELONGATION EFFECT (STUDY 2)



NOTE- Forest plot and summary statistics for the range elongation effect. Effect sizes (in log odds ratio) and 95% confidence intervals for the individual studies (gray boxes and black lines) and overall estimate (gray diamond). Negative effect sizes indicate that the odds of choosing the precise option are lower in the upwards-elongated condition than the downwards-elongated condition.

Discussion

In H2, we propose that ambiguity aversion is accentuated (versus attenuated) when numerical ranges are downwards- (versus upwards-) elongated. Study 2 provides evidence supporting this effect across six consumer context studies. In all contexts, the highest (vs. lowest) level of ambiguity aversion is observed when the range is downwards- (vs. upwards) elongated. Upwards-elongated ranges are characterized by significantly lower levels of ambiguity aversion. As can be seen in figure 5, in three of the choice contexts (discount offers, investment returns and product lifespans), ambiguity aversion disappeared altogether for upwards-elongated ranges as there was no significant preference anymore for the certain option (p = .58; p = .54 and p = .37 respectively). In the vaccine efficiency scenario, people even seemed to prefer the upward-elongated range (59%) over the CE (41%), thus demonstrating ambiguity-seeking behavior. However, the p value of this test is only marginally significant (p = .058) and the results stand out as unusually strong compared with the other conditions, so interpretations should be made with caution (this was also the sole experiment that was run on another day). It's also worth noting that the range elongation effect generalizes to contexts where people compare decimal numbers smaller than 10 (in the product lifespan and ratings studies). Hence, range elongations caused by left-digit asymmetries can significantly mitigate and potentially even reverse ambiguity aversion.

STUDY 3: IMPACT OF RANGE ELONGATION ON AMBIGUITY AVERSION IN ELLSBERG'S PARADIGM

In study 3 we test the proposed impact of upwards- vs. downwards range elongations caused by left-digit asymmetries in the Ellsberg's (1961) ambiguity paradigm. While Ellsberg's original experiment gave participants the choice between a precise urn (CE) with 50 winning balls and an ambiguous (range) urn with any number between 0 and 100 winning balls, we manipulate the CE and range in our experiment to test for the impact of range elongation on ambiguity aversion. Participants are asked to choose between urns containing a precise (CE) versus an imprecise (range) number of winning balls. We manipulate the range elongation condition between subjects, while maintaining a constant range width. While in study 2 we used downwards- and upwards- elongated conditions, in study 3 we expand the design and also use a non-elongated baseline condition (where the number of left-digit changes between the CE and the range's lower bound is the same as between the CE and upper bound). We expect to see the greatest (vs. lowest) proportion of participants choose the precise urn in the downwards-elongated condition (vs. upwards-elongated), with the baseline condition in between.

Method

Participants and design. A total of 1,357 participants from the US and UK (666 females, M_{age} = 39) were recruited via Prolific. Participants were randomly assigned to one of three between subjects conditions: downwards-elongated, non-elongated, or upwards-elongated. The sample size was determined by a power analysis following an initial exploratory experiment with 300 participants, during which we assessed the presence and magnitude of the effect. Based on the effect size from this exploratory study, we determined the necessary sample size to achieve 80% power. Apart from the sample size, this (unreported) exploratory study did not differ from the main experiment in any way.

Procedure. Participants were asked to imagine participating in a lottery where they had to choose between two urns, each filled with red and black balls. Each urn had 100 total balls. If a red ball was selected, they would win $ 20,-. In each condition—downwards-elongated, non-elongated, and upwards-elongated—participants were asked to choose between an urn with a precise (CE) number of red balls (63, 65, and 67, respectively) and an urn with an imprecise (range) number of red balls (47 - 79, 49 - 81, and 51 - 83, respectively). The range width was uniformly set at [CE - 16, CE + 16] across all conditions. For example, in the downwards-elongated condition participants had to choose between the following two options:

Urn A: Has 63 red balls. The rest of the balls are black. If a red ball is drawn from this urn, you will win $20.

Urn B: Has 47-79 red balls. The rest of the balls are black. If a red ball is drawn from this urn, you will win $20.

In study 3, like in studies 1 and 2, we did not provide participants with any information on interpreting the imprecise (range) option or its distribution, thus preserving the ambiguity of the option. The order in which the precise (CE) and imprecise (range) urns appeared – as first versus second item – was counterbalanced.

Results

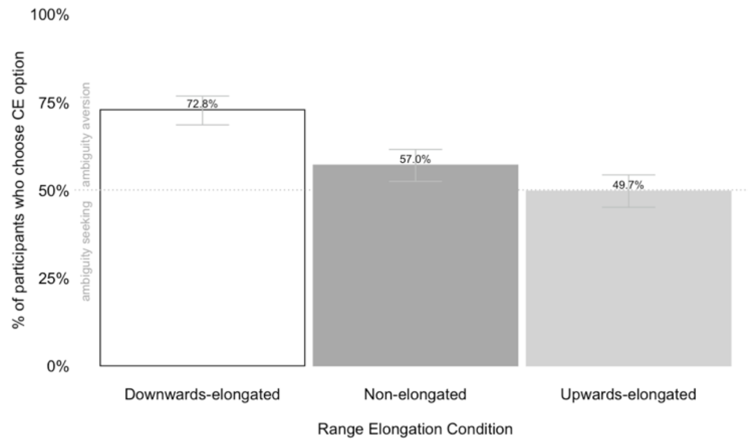
First, we checked the effect of counterbalancing the choice order and found that counterbalancing had no significant main effect (p = .35) or interaction effects with any of the range elongation conditions (all p > .19). Therefore, this factor was dropped.

We performed a chi-square analysis to explore whether there is a significant difference in the choice of the precise urn in the three conditions. In support of H2, the difference between conditions is statistically significant ($\chi^2(2) = 69.12$, $p < .001$) — 73% of participants chose the precise urn in the downwards-elongated condition, 57% in the non-elongated condition, and 50% in the upwards-elongated condition (see figure 7). Next, we performed chi-square tests to compare conditions. The chi-square tests revealed a significant difference between the downwards-elongated and non-elongated condition ($\chi^2(1) = 23.94$, $p < .001$), and between the non-elongated and upwards-elongated condition ($\chi^2(1) = 4.66$, $p = .03$).

Finally, we conducted chi-square tests to check for ambiguity aversion or ambiguity seeking in each of the three conditions (i.e., a significant departure from a 50/50 selection of the precise (CE) versus the imprecise (range) urn option). The chi-square tests revealed ambiguity aversion in the downwards-elongated ($\chi^2(1) = 93.88$, $p < .001$), and non-elongated ($\chi^2(1) = 9.02$, $p = .002$) conditions, but ambiguity neutrality (i.e., a *lack* of significant departure from a 50/50 selection of the precise (CE) versus the imprecise (range) lottery option) in the upwards-elongated condition ($\chi^2(1) = 0.01$, $p = .88$).

FIGURE 7

CHOICE OF PRECISE URN BY RANGE-ELONGATION CONDITION (STUDY 3)



NOTE- The dotted line at 50% represents ambiguity neutrality (indifference between the precise (CE) and imprecise (range) options). The grey error bars represent the 95% confidence interval for each condition.

Discussion

In H2, we propose that ambiguity aversion is amplified (vs. attenuated) when ranges are downwards- (vs. upwards-) elongated. In study 3, we find evidence supporting this effect in the Ellsberg urn paradigm. The highest level of ambiguity aversion is observed in the downwards-elongated condition, where the range’s lower bound has a greater left-digit difference with the CE than its upper bound. In contrast, we do not detect any ambiguity aversion in the upwards-elongated condition, where the range’s upper bound has a greater left-digit difference with the CE than its lower bound. In this study, we use a non-elongated control condition as a baseline to identify the basic level of ambiguity aversion in the Ellsberg paradigm at this zone of the mental number line, thus any deviations in ambiguity aversion from the levels observed in this condition could reasonably be attributed to the upwards- and downwards-elongation effects.

STUDY 4: INTERACTION OF RANGE ELONGATION AND NUMERICAL MAGNITUDE

Study 4 comprises 16 experiments. The initial experiments were conducted to test the range elongation effect (H2) at different magnitudes of the CE. Upon formulating H3—which posits that the strength of H2 amplifies as the magnitude of the CE increases—we carried out additional experiments. Combined, the 16 experiments cover most of the mental number line from 0-100, in both outcomes and probabilities. In each experiment, participants are asked to choose between precise (CE) and imprecise (range) outcomes or probabilities of winning a lottery. In the probability experiments (7 in total), varying CE magnitudes in the 0-100% probability space are utilized. For instance, in one experiment participants are asked to choose between a 74% and a 69%-79% chance of winning a lottery (downwards-elongated condition). In the outcome experiments (9 in total), varying CE magnitudes in the €0-€100 outcome space were used. For example, in one experiment participants are asked to choose between a €74 and a €69-€79 lottery outcome (downwards-elongated condition).

Method

Participants and design. We tested the effect of left-digit elongations in 16 experiments with varying CE magnitudes. A total of 3,027 participants were recruited via Prolific and the student panel of our university (2048 females, M_{age} = 34). Each participant took part in one of the

16 experiments, which were conducted independently on different days. In each experiment, participants were randomly assigned to one of two range conditions: upwards-elongated or downwards-elongated. Details of the 16 experiments, including the choices participants had to make in each condition, can be found in table B1 of Web Appendix B.

Procedure. In each experiment, we informed participants that they would be choosing between two hypothetical lottery options. Participants were then presented with a choice between a precise (CE) and an imprecise (range) lottery probability or outcome, with between subjects variation in CE magnitude and downwards-versus upwards-elongation of the range option. We informed participants that, for the range (imprecise) option, the exact amount they would win would be randomly selected from the range provided.[2] In the probability experiments (7 total), participants made a choice between a precise (CE) and imprecise (range) probability of winning a lottery. For example, in experiment 14 (see table B1 of the web appendix), participants in the downwards-elongated condition would choose between a 74% probability of winning €20 versus a 69-79% probability of winning €20, while participants in the upwards-elongated condition would choose between a 76% probability of winning €20 versus a 71-81% probability of winning €20 (in counterbalanced order).

Analysis Overview and Meta-Analytic Approach

For study 4, we conduct a single-study meta-analysis (McShane and Böckenholt 2017) since the 16 experiments were executed on separate occasions but share high similarity—only

[2] In contrast to prior studies where the distribution of the range was not specified, in this experiment, participants were explicitly informed of a uniform distribution (i.e., every range value having the same probability to be chosen).

differing in CE magnitude and numerical format (outcomes, probabilities). First, an unmoderated meta-analysis of all experiments is presented, showcasing the impact of range elongation over different magnitudes on the mental number line. Next, we include the CE value magnitude as a moderator, testing whether the effect of H2 intensifies with higher magnitudes (H3).

We used the 'meta' package (Balduzzi, Rücker, and Schwarzer 2019) in R for our single-study meta-analysis of the 16 experiments. We computed the effect size and its 95% confidence interval for the effect of range elongations (number of studies k = 16) in the individual experiments by a generalized linear model (GLM) expressed in log odds ratio (logOR) units. The upwards-elongated condition was coded as the 'experimental' group and the downwards-elongated as the 'control.' Hence, a negative effect size confirms the direction of our predicted effect, whereby we expect that participants would be more likely to choose the precise option in the downwards-elongated compared to the upwards-elongated condition.

In addition to providing insights on the size of the range elongation effect, we explored whether the effects are moderated by CE magnitude (H3). To this end we coded the CE's left digit in each experiment from 0-9 and conducted a meta-regression to test the moderating role of left-digit magnitude. Additionally, we separated the dataset into two: outcome experiments and probability experiments and ran a logistic regression on each dataset using left digit magnitude as the moderator, to probe the moderation direction for outcomes and probabilities separately.

Results

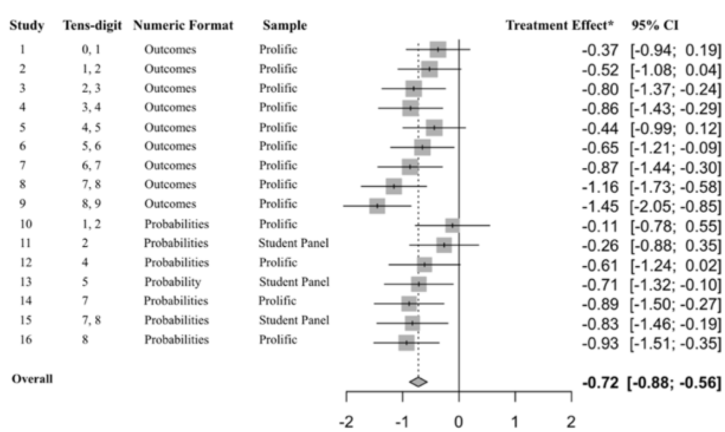
First, we checked the effect of counterbalancing the choice order and found it had no significant main (lowest $p = .32$) or interaction effects with the range elongation condition (lowest $p = .14$). Therefore, this factor was dropped.

We divide the analysis into two sections. The first set of tests was conducted to examine the basic range elongation effect (H2). Here, we expect consumers to exhibit more ambiguity aversion in the downwards-elongation condition than in the upwards-elongation condition. Secondly, we test whether the range-elongation effect becomes stronger with increasing magnitude of the CE (H3).

Range elongation effect (H2). In our meta-analysis, we employed a random effects model, which revealed a statistically significant overall effect size for the effect of range elongations across 16 studies (overall log odds ratio: -0.72, 95% CI: -0.88 to -0.56, $z = -8.91$, $p < .001$). We report the results of a random effects model, as the studies displayed variations in tens-digit magnitude, numerical format, and population types (Borenstein et al. 2021), but the results of a fixed-effects model were analogous. See figure 8 for a Forest Plot of the effect sizes (log ORs) and confidence intervals of the studies. We report further information on the heterogeneity of effect sizes in Web Appendix B.

FIGURE 8

FOREST PLOT OF RANGE ELONGATION EFFECT IN 16 EXPERIMENTS (STUDY 4)



NOTE- Forest plot and summary statistics for the range elongation effect. Effect sizes (in log odds ratio) and 95% confidence intervals for the individual studies (gray boxes and black lines) and overall estimate (gray diamond). Negative effect sizes indicate that the odds of choosing the precise option are lower in the upwards-elongated condition than the downwards-elongated condition.

Strength of range elongation effect with increasing CE magnitudes (H3). We proceeded to examine the moderating effect of CE magnitude, operationalized by coding its tens-digit and treating it as a continuous variable. The moderation test is conducted using a mixed-effects meta-regression. Of primary interest, the test of the tens-digit as a moderator is significant ($QM(1) = 19.61$, $p < .001$). This reveals that the influence of range elongation on choice varies depending on the CE's tens-digit magnitude.

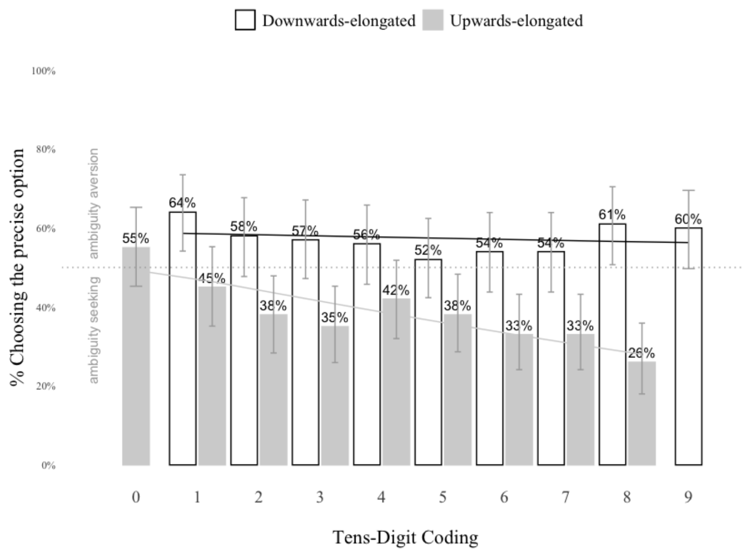
To further understand the moderating direction of the CE magnitude on the range elongation effect, we split all the outcome experiments (1-9) and all the probability experiments (10-16) into two datasets. We then performed hierarchical logistic regression for outcomes and probabilities separately using the 'glmer' function from the 'lme4' package in R (Bates et al. 2009). As the experiments were run on separate occasions, we opted for a random intercept and random slope model to account for baseline choice differences and differences between elongation conditions across studies. For robustness, we also tested a fixed intercept model; however, the choice of model neither altered the significance nor the direction of the results.

For the nine outcome experiments, consistent with the results of the combined meta-regression, the interaction between the CE magnitude (tens-digit value) and the range elongation condition is significant ($\beta = -0.10$, SE = 0.03756, $z = -2.72$, $p = .006$). To understand the direction of the interaction, we examined the impact of CE magnitude on each range elongation condition separately. The choice of precise option decreases with increasing CE magnitude in the upwards-elongated condition ($\beta = -0.11$, SE = 0.02704, $z = -4.23$, $p < .001$), but there is no effect of increasing CE magnitude in the downwards-elongated condition ($\beta = -0.01$, SE = 0.02, $z =$

0.45, *p* = .64). In other words, preferences remain stable in the downwards-elongated condition as CE magnitude increases. However, in the upwards-elongated condition, there is a trend toward greater ambiguity-seeking as CE magnitude increases, see figure 9.

FIGURE 9

CHOICE OF PRECISE OUTCOME BY RANGE ELONGATION CONDITION (STUDY 4)



NOTE- The solid black and gray lines in the figure represent the logistic regression predictions of choosing the precise outcome by range elongation condition and number magnitude. The white and gray bars show the proportion of participants who choose the precise outcome. The dotted line at 50% represents ambiguity neutrality.

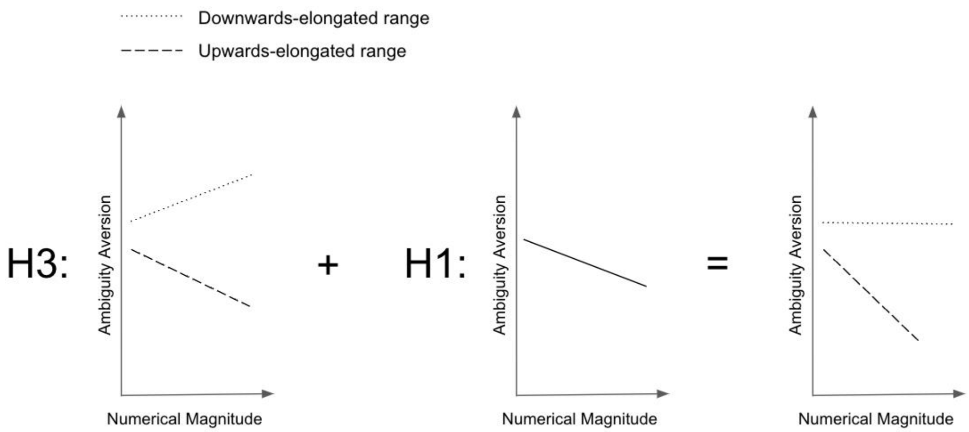
Similarly, for the seven probability experiments, the interaction between the CE magnitude (coded tens-digit value) and the range elongation condition is significant (β = -0.11, SE = 0.04, *z* = -2.32, *p* = .02). The choice of the precise probability option decreases with increasing CE magnitude in the upwards-elongated range condition (β = -0.09, SE = 0.03, *z* = -2.986, *p* = .002), but there is no effect of increasing CE magnitude in the downwards-elongated range condition (β = 0.014, SE = 0.03, *z* = -0.41, *p* = .67). As the pattern of results in the probability experiments is analogous to that in the outcome experiments, we report its visualization in Web Appendix B (figure B1).

Discussion

In study 4, we found additional evidence in support of H2, indicating that ambiguity aversion is heightened when ranges are downwards-elongated versus upwards-elongated. Additionally, the study provides evidence that the effect of downwards- versus upwards-range elongation becomes larger as the CE's numerical magnitude increases (H3). Interestingly, while H3 was confirmed, at first sight the results appear entirely driven by the increasingly *reduced* ambiguity aversion in upwards-elongated ranges around higher CE's (see figures 9 and B1). Why might this be the case? In other words, why did we not also observe *increased* ambiguity aversion in downwards-elongated ranges as the numerical values increased? We believe the answer lies in the interplay between H3 and another hypothesis, H1. H1's effect offsets the anticipated outcome from H3 in the context of downwards-elongated ranges. In contrast, it amplifies the effect seen in upwards-elongated ranges. Although it was not the primary focus of study 4, we tested H1 on the overall data set (outcomes and probabilities) using a hierarchical logistic regression and there was indeed an overall decline of ambiguity aversion with increasing tens-digit magnitude (β = -0.05, SE = 0.018, z = -2.788, p = .005). Figure 10 depicts this interdependency, highlighting how the combined effects of H1 and H3 produce the observed pattern in study 4.

FIGURE 10

COMBINED EFFECT OF H3 + H1



NOTE- H3 predicts that the difference in ambiguity aversion between downwards-versus upwards-elongated ranges should increase as CE numeric magnitude increases, which in its basic form would result in a pattern as displayed in the left panel. However, H1 predicts that overall ambiguity aversion should decrease with increasing numeric magnitude, as displayed in the middle panel. The sum of these effects is displayed in the right panel.

Finally, it is worth noting that while study 4 obtains strong evidence for H3, it does so in the relatively decontextualized and abstract setting of hypothetical lotteries. In supplemental experiments C1-3, we find that the effect of H3 might be weaker in more contextualized consumer choice settings such as when consumers choose between discounts on vouchers or store offers (Web Appendix C).

STUDY 5: RANGE ELONGATIONS IN THE LOSS DOMAIN

Extant explanations of ambiguity aversion incorporate various psychological processes, such as consumers' belief that choosing a precise option over an imprecise one will lead others to judge them more favorably (Curley et al. 1986; Keren and Gerritsen 1999; Muthukrishnan et al. 2009), expectations that the experimenter might deceive them into a poor outcome if they choose the imprecise option (Curley et al. 1986), or the belief that they will get poor outcomes from ambiguous options as people feel comparatively ignorant in the decision domain (Fox and

Tversky 1995). Such theories typically converge in predicting ambiguity aversion for both gains and losses, because they identify reasons why people believe that choosing the CE would lead to a *better outcome* in general. However, in the loss domain, the predominant finding is ambiguity seeking behavior, rather than ambiguity aversion (Trautmann and Van De Kuilen 2015).

Our theory deviates from extant approaches in a subtle way. Rather than identifying reasons why people think choosing the CE would be *better*, we identify reasons why they think the CE would often be *higher* than the outcome they expect from the ambiguous (range) option. This naturally leads to a divergent prediction in gains versus losses, as in the loss domain, people would prefer the *lowest* expected outcome. Thus, it follows that if consumers perceive the CE as closer to the upper bound than the lower bound of a range, they should prefer the CE in the gain domain where the goal is to maximize gains. In contrast, they should prefer the range in the loss domain, where the goal is to minimize losses.

In study 5, we test this prediction by giving participants a choice between a CE and a range centered around the CE in a loss context. We employ a between subjects design, manipulating the downwards-versus upwards-elongated nature of the range, while maintaining a constant range width. Contrary to H2 and the findings in Studies 2, 3, and 4, we expect that, in this loss context, ambiguity aversion will be accentuated (vs. attenuated) when ranges are upwards- (vs. downwards-) elongated.

Method

Participants and design. A total of 199 participants were recruited via Prolific. Participants were based in the US and UK (142 females, M_{age}= 38) and randomly assigned to one of two range conditions: upwards-elongated or downwards-elongated.

Procedure. We informed all participants that they would be choosing between two hypothetical loss scenarios. Participants were then presented with a choice between a precise (CE) and an imprecise (range) probability of losing €20. The choice was as follows:

> **Downwards-elongated condition:** 81% probability of losing €20 or 76-86% probability of losing €20.
>
> **Upwards-elongated condition:** 79% probability of losing €20 or 74-84% probability of losing €20.

Like in studies 1, 2, and 3, we did not provide participants with any information on interpreting the imprecise (range) option or its distribution, thus preserving the ambiguity of the option. The order in which the precise and imprecise options appeared was counterbalanced.

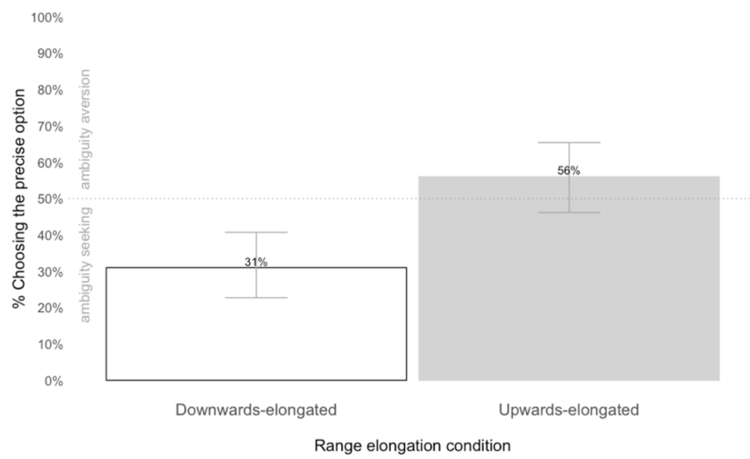
Results

First, we checked the effect of counterbalancing the choice order (i.e., whether the precise option (CE) or the imprecise option (range) appeared first on the list) both as a main effect and as an interaction with the range elongation condition. We found that counterbalancing had no significant main effect (p = .11) or interaction effects with the range elongation condition (p = .57). Therefore, this factor was dropped.

In the downwards-elongated range condition, 31% of participants chose the precise option, while in the upwards-elongated range condition, 56% of participants chose the precise option (figure 11). A chi-square analysis indicated that this difference was statistically significant ($\chi^2(1) = 11.71$, $p < .001$). Additionally, we conducted a chi-square test for each individual condition to determine whether there is a significant departure from a 50/50 selection of the precise (CE) versus the imprecise (range) loss option. These tests revealed ambiguity seeking in the downwards-elongated condition ($\chi^2(1) = 14.44$, $p < .001$), but ambiguity neutrality in the upwards-elongated condition (χ^2 $(1) = 1.44$, $p = .23$).

FIGURE 11

CHOICE OF PRECISE OPTION BY RANGE ELONGATION CONDITION IN THE CONTEXT OF LOSSES (STUDY 5)



Note- The dotted line at 50% represents ambiguity neutrality (indifference between the precise (CE) and imprecise (range) options).

Discussion

Study 5 extends our theory into the loss domain, demonstrating a pattern that is opposite to that observed in the gain domain in previous studies. In the downwards-elongated range condition, most participants chose the imprecise (range) option, while in the upwards-elongated range condition, the majority preferred the precise (CE) option. This study therefore provides additional process evidence that consumers compare the location of the CE relative to the ambiguous range option on their mental number line to determine which option would likely result in a higher outcome. Previously proposed explanations for ambiguity aversion typically provide reasons why people prefer certainty over uncertainty in general (Curley et al. 1986; Fox and Tversky 1995; Keren and Gerritsen 1999; Muthukrishnan et al. 2009).

Thus, study 5 not only extends the relevance of our theory across both gain and loss domains, but it also addresses a discrepancy between prior theories and empirical evidence on ambiguity aversion in the loss domain. Specifically, no prior theory would predict the divergent pattern in the gain and loss domains that is commonly observed in empirical work. Hence, our findings provide an important explanation for the heterogeneity observed across these domains. While study 5 provides indirect process evidence supporting our theory, study 6 more directly manipulates the perception of the CE relative to the range option.

STUDY 6: MIDPOINT DISCLOSURES MODERATE THE RANGE ELONGATION EFFECT

Our theoretical framework outlines how basic principles of numeric cognition lead to systematic biases in the perceived position of a CE relative to a range of possible outcomes centered around it. We have argued and shown how these misperceptions lead to predictable variation in consumers' aversion to uncertain ranges of outcomes (i.e., ambiguity aversion). If a misperception of the CE's position relative to the range lies at the root of this variation in ambiguity aversion, it follows that a simple, yet effective counter biasing technique could consist of a straightforward explanation of the CE's objective position relative to the range. In study 6, we therefore test whether clarifying that the CE is the midpoint of the uncertain range, will be enough to significantly reduce the range elongation effect stipulated in H2.

Method

Participants and design. A total of 400 participants were recruited via Prolific. Participants were based in the US and UK (273 females, M_{age} = 38). Participants were randomly assigned to one of two range elongation conditions (downwards-elongated or upwards-elongated) and one of two midpoint disclosure conditions (explicit disclosure or no disclosure).

Procedure. We informed all participants that they would be choosing between two hypothetical lottery scenarios. Participants were then presented with a choice between a precise (CE) and an imprecise (range) probability of winning €20, with between subjects range elongation conditions (upwards-elongated or downwards-elongated) and midpoint disclosure conditions (explicit disclosure or no disclosure). The explicit disclosure conditions were identical to the no disclosure conditions, except that they additionally mentioned that [CE] is the midpoint of [range]. The specific choices made available to participants can be found in table 2. Like in study 4, we informed participants that for the imprecise option, the exact amount they would win would be randomly selected from the range provided. The order in which the precise (CE) and imprecise (range) options appeared was counterbalanced.

TABLE 2

CONDITIONS IN STUDY 6 (MIDPOINT DISCLOSURE x RANGE ELONGATION)

	Downwards-elongated	Upwards-elongated
No disclosure	50% probability of winning €74 or 50% probability of winning €69 - €79.	50% probability of winning €76 or 50% probability of winning €71 - €81.

Explicit disclosure	50% probability of winning €74 or 50% probability of winning €69 - €79 (€74 is the midpoint of €69 - €79).	50% probability of winning €76 or 50% probability of winning €71 - €81 (€76 is the midpoint of €71 - €81).

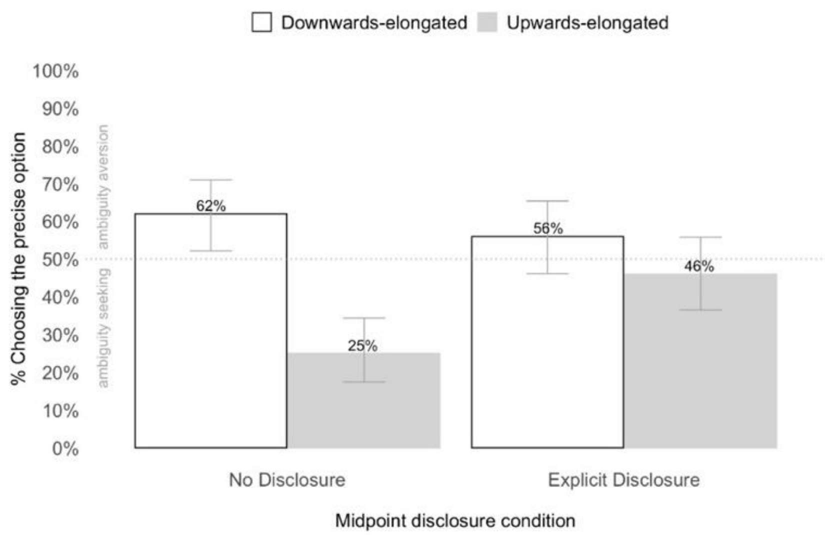
Results

First, we checked the effect of counterbalancing the choice order. We found that counterbalancing had no significant main (p = .49) or interaction effects with any of the conditions (lowest p value = .14). Therefore, this factor was dropped.

A logistic regression analysis revealed a significant interaction between range elongation and the midpoint disclosure condition on participants' choice between the precise and imprecise lottery options (β = -1.18, SE = 0.42, z = -2.82, p = .004). In line with our expectations, in the 'no disclosure' condition, there was a significant difference in preference for the precise option between the downwards-and upwards-elongated range conditions (β = 1.58, SE = 0.30, z = 5.13, p < .001). However, this preference did not differ significantly in the 'explicit disclosure' condition (β = 0.40, SE = 0.28, z = 1.41, p = .15, see figure 12). Additionally, a chi-square test showed that the majority of participants in the 'no disclosure, downwards-elongated' condition displayed ambiguity aversion ($\chi^2(1) = 5.7$, p = .01). Conversely, those in the 'no disclosure, upwards-elongated' condition exhibited ambiguity seeking ($\chi^2(1) = 25$, p < .001). In the 'explicit disclosure' condition, participants in both the downwards-elongated ($\chi^2(1) = 1.44$, p = .23) and upwards-elongated ($\chi^2(1) = 0.64$, p = .42) conditions demonstrated ambiguity neutrality.

FIGURE 12

CHOICE OF PRECISE OPTION BY RANGE ELONGATION AND MIDPOINT DISCLOSURE CONDITION (STUDY 6)



NOTE- The dotted line at 50% represents ambiguity neutrality (indifference between the precise (CE) and imprecise (range) options).

Discussion

As predicted, participants' choices in the 'no disclosure' condition were more impacted by range elongation than those in the 'explicit disclosure' condition. Specifically, in the 'no disclosure' condition, when the range was downwards-elongated, participants showed a strong propensity towards ambiguity aversion. In contrast, when the range was upwards-elongated, participants showed a propensity for ambiguity seeking. This aligns with our findings in studies 2-4 and reaffirms the robustness of the range elongation effect. However, when participants were informed that the CE is the midpoint of the range, the effects of range elongation were attenuated. Therefore, the findings are in line with the idea that range elongation effects on ambiguity aversion stem from biased perceptions of the location of the CE relative to the range on the mental number line.

GENERAL DISCUSSION

Extant research on ‘ambiguity aversion’ has often shown that consumers are averse to the uncertainty inherent in ranges, particularly when more unambiguous and precise options are available (Fox and Tversky 1995). Yet, no existing theory, to date, has been able to explain both the basic emergence of ambiguity aversion and its extensive heterogeneity across contexts and domains (Trautmann and Van De Kuilen 2015). Our research sought to address this gap by identifying basic numeric cognition principles that might underlie this core phenomenon in human judgment and decision making: the ‘compression effect’ and the ‘left-digit effect.’ We report 26 experiments (N = 7194; grouped into 6 studies) in the main body of this paper and 8 more (N = 3440) in the Web Appendix to test our theoretical framework. The results provide strong evidence of the influence of numerical cognition principles on consumer preferences between precise (CE) and imprecise (range) outcomes and probabilities.

The first numeric cognition principle we invoke – the ‘compression effect’ – provides a new and straightforward explanation for the fact that people generally prefer certain options over their uncertain counterparts, that is, the basic phenomenon of ambiguity aversion. Due to the increasing compression of numbers as represented on an internal mental number line, consumers generally perceive a certain equivalent (e.g., $40) as closer to a symmetric range’s upper bound (e.g., $60) than its lower bound (e.g., $20). Consequently, people generally perceive a greater potential downside than upside in a range when compared to a CE. Moreover, due to the rapidly increasing rate of compression of the mental number line at higher numbers, we argued that this discrepancy between range upside and downside perceptions will diminish around larger numbers. Hence, the theory allowed for a first new prediction: ambiguity aversion should decrease when ranges are centered around higher numbers or CEs.

The second numeric cognition principle we invoke is the left-digit effect, a cognitive bias where the left-most digits in a number have a disproportionate influence on numerical valuation (Thomas and Morwitz 2005). This bias distorts and extends the mental number line at points where there are left-digit transitions, thus altering the perceived appeal of a range. We proposed and found that ambiguity aversion intensifies when the lower bound of a range is further removed in left digits from the CE than the upper bound. Conversely, when the range's upper bound is further removed in left digits from the CE than its lower bound, ambiguity aversion decreases, or even reverses (as seen in studies 2, 4 and 6). We predicted and found a greater influence of these range elongations when ranges are centered around larger CEs (study 4 and Web Appendix C) because as magnitudes increase, the mental number line is more compressed, making the leftmost digit the primary distinguishing factor.

Importantly, and uniquely consistent with our theory, we also predicted and found a reversal of the effect of left digit range asymmetries in the domain of losses (study 5). This diverges from current theories on ambiguity aversion, which generally predict ambiguity aversion across both the gain and loss domains. Our findings align with and explain previously puzzling empirical evidence showing attenuated or reversed ambiguity aversion in the loss domain (see also the implications for theory below). Finally, in study 6 we offered a simple and straightforward process test. If systematic misperceptions of the CE's position relative to the range on an implicitly constructed scale indeed underlie ambiguity aversion, making explicit that the CE is the midpoint of the given range should reduce these biases.

Implications for Theory

Incorporating these two basic principles of numerical cognition into our understanding of ambiguity aversion leads to novel predictions and addresses several inconsistencies in the existing literature. For instance, most psychological theories proposed to explain ambiguity aversion would predict ambiguity aversion also in the loss domain (Curley et al. 1986; Trautmann and Van De Kuilen 2015). Yet, a common empirical observation is a reversal of preferences in the loss domain (Trautmann and Van De Kuilen 2015). Our theory predicts this divergent pattern. Our core assumption that the closer the CE is perceived to the upper bound of the range, the greater its relative desirability to the range, would only be true when consumers aim to maximize the outcome or probability they will obtain. When their goal is to minimize this outcome or probability, as in the case of losses, this choice pattern should reverse.

Moreover, the results contribute to the longstanding debate regarding the interplay between range width and ambiguity aversion. Currently, some studies identify an amplification of ambiguity aversion with increasing range width (Becker and Brownson 1964; Viscusi and Magat 1992) while others do not find such a trend (Curley and Yates 1985; Yates and Zukowski 1976). Our findings suggest a potential interaction between range width and numerical magnitude, which could explain these mixed results. The compression effect indicates that the importance of range width increases with higher CE magnitude. Smaller range widths at lower CEs are sufficient to induce ambiguity aversion, but at higher CEs, larger ranges are necessary to produce a similar effect. Consistent with this observation, studies that found ambiguity aversion with increasing range width reported higher CE numbers, such as 50% (Becker and Brownson 1964) and 150 (value of environmental risk; Viscusi and Magat 1992) compared to the studies that did not observe such effects, which had CEs starting as low as 10% (Curley and Yates 1985) and 5 (out of 10 chips; Yates and Zukowski 1976). Additionally, we showed that under the right circumstances, expanding the range might, paradoxically, diminish ambiguity aversion if it changes the range from non-elongated (or downwards-elongated) to an upwards-elongated range.

An established moderator that is seemingly inconsistent with our theory is that individuals are ambiguity seeking for very low likelihood events (Trautmann and Van De Kuilen 2015). At first glance, this seems to contradict H1, which suggests that ambiguity aversion is most pronounced when the certainty equivalent (CE) magnitudes are low. However, the "low likelihood" events referenced in existing literature typically involve decimal probabilities below 1% (for example, 0.01). Studies on how decimals are represented indicate that they are processed differently from whole numbers, being represented by individual integer components rather than holistically (Bonato et al. 2007; Cohen 2010; Cohen, Ferrell, and Johnson 2002). Therefore, if the mental number line representation is primarily used for numbers greater than 1, it would be expected that very low-likelihood events, being processed differently, yield distinct outcomes.

There are other findings in the ambiguity aversion literature that can be explained with the numerical cognition account proposed here. For example, Budescu, Weinberg and Wallsten (1988) predicted that people should be more averse to bets when their probability of winning is expressed in non-numeric formats (e.g., graphically or verbally) as the information conveyed in these formats should be more ambiguous than in a straight numeric presentation (e.g., a verbal description of a probability as 'very unlikely' is more ambiguous than a precise, low probability number). They found no support for this prediction, which at the time raised question marks around the generality of ambiguity aversion as a phenomenon. If, as we maintain, comparison processes between numbers on a mental number line play a central role in the phenomenon of ambiguity aversion, the fact that ambiguity aversion does not emerge in comparisons between numeric and non-numeric information, appears as a logical boundary condition.

Importantly, some previous research provided process evidence for theories of ambiguity aversion by means of moderators which are correlated with numeric magnitude. In such cases, the principles of numeric cognition could provide an alternative explanation for parts of their results. In Web Appendix D, we discuss, for example, how empirical evidence for the "competency hypothesis" could be impacted by our theory (Heath and Tversky 1991). More generally, our research highlights the importance of disaggregating analyses for comparisons of CEs and ranges when they occur on different regions of the mental number line. Extant research often failed to do so, causing unexplained heterogeneity in the results (Du and Budescu 2005).

It's important to underscore that our perspective does not diminish the significance of prior theories on ambiguity aversion. These psychological explanations each likely contribute to the phenomenon in distinct ways. As such, our findings provide a new perspective to contextualize the large heterogeneity of ambiguity aversion in the literature and can help explain the recurring deviations from standard ambiguity aversion predictions in the loss domain. Yet, we explicitly do *not* want to claim that in the loss domain, only ambiguity seeking would be observed or that all sources of ambiguity aversion can be reduced to the properties of the mental number line. To the contrary, the interaction of the processes described in the current paper with those outlined in previous theories are expected to lead to a complex picture, especially in the domain of losses. Furthermore, the less-than-straightforward results of the supplementary studies described in Web Appendix C and E, reveal that in many situations (e.g., in daily life or in concrete consumer contexts), additional inferences will play a role which can significantly influence people's levels of ambiguity aversion. Thus, the two principles of numerical cognition we identified as important to understand ambiguity aversion merely pave the way for deeper exploration and understanding of the multifaceted nuances in the ambiguity aversion literature, across various CE magnitudes, left-digit asymmetries, domains, and range widths.

Implications for Practice

Our research provides guidance for marketers, policymakers, and professionals who need to communicate numerical information effectively. We provide new insights into the conditions under which a range of values can be as appealing—or even more so—to consumers than a single point estimate, thereby challenging the commonly-held view that ambiguity aversion typically makes precise estimates more attractive. To illustrate this, we presented choices between precise and imprecise options in six consumer contexts: vaccines, discounts, used car sales, investment products, product lifespans, and product ratings. When the uncertain option was upwards-elongated relative to the certain equivalent (i.e., when the range's upper bound was more left-digits removed from the CE than its lower bound), consumers ceased to be ambiguity averse in three out of six contexts and came close to ambiguity seeking in one. This shift in preferences signals that ambiguity aversion can be mitigated or even reversed, when giving proper attention to the width of the range of uncertainty and its relation to the CE's magnitude in the communication or presentation of the options.

In addition to the six contexts presented, these insights may also apply to various other sectors where managers can choose to communicate using ranges versus point estimates. This approach can help foster trust and establish more realistic expectations among consumers (Gaertig and Simmons 2023). For instance, utility companies could employ range estimates to provide more nuanced predictions of monthly energy bills. Manufacturing companies specializing in durable goods, such as electronics or home appliances, might opt for range estimates to indicate the product's lifespan. Educational institutions could use range estimates to depict test score improvements or job placement rates, thus setting more realistic expectations among students and parents.

The numerical cognition principles we highlight can inform marketers and communication professionals for which ranges and point estimates consumers are most likely to react positively to uncertainty. This knowledge, combined with understanding situations where consumers are generally open to ambiguity—such as perceived scarcity or exclusivity (Fan et al. 2019), negotiable pricing (Ames and Mason 2015), or when there is mutual trust between the company and consumer (Liu and Chang 2017)—paves the way for the most effective communication strategies. However, future work needs to more comprehensively understand how these effects play out in the real world, depending on contextual factors and other important moderators.

Limitations and Future Research

Future research is necessary to validate our findings in more externally valid settings (e.g., field data). The consumer-relevant studies in this paper (e.g., Study 2) still utilized somewhat abstract stimuli and studies in consumer contexts sometimes showed weaker effects (e.g. experiments C2-3 and E1) than studies in more abstract settings. Hence, there may be significant practical boundary conditions to the effects. Furthermore, our paper's predominant focus lay in the domain of gains while the domain of losses requires further exploration. Additionally, investigating how consumers' number reading and encoding behaviors influence ambiguity attitudes could be a fruitful avenue for understanding differences in behavior when ambiguity information is presented in different formats, verbally or in writing (Laurent and Vanhuele 2023).

Conclusion

Our research is the first to identify two principles in numerical cognition which appear to underlie and drive significant heterogeneity in ambiguity attitudes. We show how these two principles, 'the compression effect' and the 'left-digit effect' influence the perceived upside vs. downside of a range relative to a CE across various contexts (lotteries, vaccines, product reviews, lifespans, investment products etc.), domains (gains, losses), and numerical formats (probabilities, outcomes). Across 34 experiments with over 10,000 participants, our findings consistently substantiated these effects, illustrating their robustness. These discoveries have broad applicability, offering valuable insights for academics studying choice behavior under risk and uncertainty and to professionals aiming to communicate numerical data effectively.

DATA COLLECTION STATEMENT:

The first author conducted studies 1 and 3 on Prolific in 2023, and collected data for studies 2 (vaccine effectiveness study), 5, and 6 on Prolific in 2022. The first author collected data for study 4, which comprises 16 experiments, from both Prolific and the Erasmus University student panel during 2021-2022. For study 2, aside from the vaccine effectiveness study which was collected earlier, the first author conducted five additional experiments on Prolific in 2024. The first author also collected the data for all the other studies listed in the Web Appendix on Prolific in 2024. The only exception are the data in Web Appendix E, which were collected by an independent reviewer. The first author analyzed the data for all studies.

Preregistrations, materials, data, and code of the data collected by the authors are available on the Open Science Framework website at: https://osf.io/vcneh/?view_only=043a1f801d804308bbc0e7b00da9872f.

Materials and data collected by a reviewer are available at: https://osf.io/k4f7c/?view_only=8a1d0c01146e4b31b5b7943c0f546990

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How Numerical Cognition Explains Ambiguity Aversion

WEB APPENDIX

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WEB APPENDIX A

Study 2 Additional Information and Results

TABLE A1

RESULTS FOR EXPERIMENTS IN STUDY 2

Experiment	Condition*	Precise (CE) choice	Imprecise (Range) choice	% Choose precise (CE) option	Sample size	χ^2	*p*
Vaccine Effectiveness	DE UE	74% 76%	69-79% 71-81%	75% 40%	202	23.48	<.001
Discount Offers	DE UE	74% 76%	69-79% 71-81%	67% 55%	200	2.91	.08
Used Car Sales	DE UE	$74k $76k	$69-$79k $71-$81k	80% 74%	202	.70	.40
Investment Returns	DE UE	$74 $76	$69-$79 $71-$81	74% 53%	201	8.92	.002
Product Lifespans	DE UE	7.4 years 7.6 years	6.9-7.9 years 7.1-8.1 years	72% 54%	202	6.16	.01
Product Ratings	DE UE	7.4 (out of 10) 7.6 (out of 10)	6.9 – 7.9 (out of 10) 7.1-8.1 (out of 10)	74% 62%	201	2.93	.08

NOTE- * DE = downwards-elongated condition, UE = upwards-elongated condition

Heterogeneity of Effects in the Internal Meta-Analysis

We assessed the heterogeneity of the effect sizes across studies using the Q, I^2, and τ^2 statistics. The Q-statistic tests the null hypothesis that all studies in the meta-analysis share a common effect size. Under this null hypothesis, when considering only the main effect, the expected value of Q would be equal to its degrees of freedom (or less). In this analysis, which includes 6 studies and accounts for the main effect, the degrees of freedom are 5. The observed Q-value of 8.5, with a *p* value of .13, shows some evidence of heterogeneity across contexts due to the higher Q than degrees of freedom, but with a *p* value of .13, conclusions about heterogeneity should be drawn with caution. The observed I^2 of 41%, indicates that 41% of the observed variability can be attributed true variation (rather than sampling error) and the τ^2, which quantifies the variance of true effects across studies, is 0.06. Taken together, the three statistics suggest there is some evidence for heterogeneity in the range elongation effect across contexts.

WEB APPENDIX B

Study 4 Additional Information and Results

TABLE B1

RESULTS FOR THE INDIVIDUAL EXPERIMENTS IN STUDY 4

Experiment	Condition*	Tens-digit coding**	Precise (CE) choice	Imprecise (Range) choice	% Choose precise (CE) option	Sampl e size	χ^2	*p*	Data source
1	DE UE	1 0	€11 €9	€6-16 €4-14	64% 55%	202	1.3	.25	Prolific

2	DE	2	€21	€16-26	58%	200	2.8	.08	Prolific
	UE	1	€19	€14-24	45%				
3	DE	3	€31	€26-36	57%	202	7.1	.007	Prolific
	UE	2	€29	€24-34	38%				
4	DE	4	€41	€36-46	56%	200	8.0	.004	Prolific
	UE	3	€39	€34-44	35%				
5	DE	5	€51	€46-56	52%	202	1.9	.15	Prolific
	UE	4	€49	€44-54	42%				
6	DE	6	€61	€56-66	54%	200	4.5	.03	Prolific
	UE	5	€59	€54-64	38%				
7	DE	7	€71	€66-76	54%	200	8.1	.004	Prolific
	UE	6	€69	€64-74	33%				
8	DE	8	€81	€76-86	61%	203	13.5	<.001	Prolific
	UE	7	€79	€74-84	33%				
9	DE	9	€91	€86-96	60%	201	22.2	<.001	Prolific
	UE	8	€89	€84-94	26%				
10	DE	2	21%	16 - 26%	71%	168	0.02	.86	Prolific
	UE	1	19%	14 - 24%	69%				
11	DE	2	24%	19 - 29%	63%	171	0.47	.49	Student
	UE	2	26%	21 - 31%	56%				panel
12	DE	4	44%	39 - 49%	69%	168	3.05	.008	Prolific
	UE	4	46%	41 - 51%	54%				

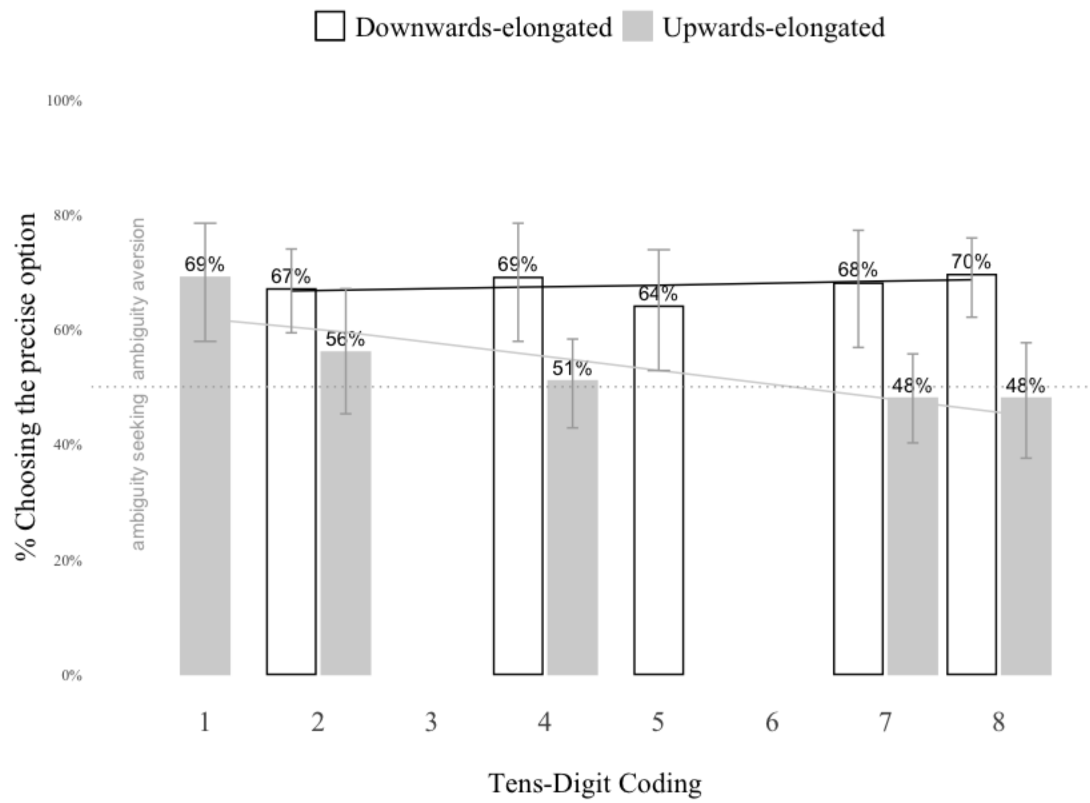
13	DE UE	5 4	51% 49%	46 - 56% 44 - 54%	64% 47%	172	4.60	.03	Student panel
14	DE UE	7 7	74% 76%	69 - 79% 71 - 81%	68% 47%	173	7.17	.007	Student panel
15	DE UE	8 7	81% 79%	76 - 86% 74 - 84%	69% 49%	167	5.88	.015	Prolific
16	DE UE	8 8	84% 86%	79 - 89% 81 - 91%	70% 48%	200	9.23	.002	Prolific

NOTE- The first 9 experiments are precise vs. imprecise outcomes and experiments 10-16 are precise vs. imprecise probabilities. * DE = downwards-elongated condition, UE = upwards-elongated condition ** The tens digit coding is the coding used for the moderating effect of tens-digit on the effect of range elongation.

FIGURE B1

CHOICE OF PRECISE PROBABILITY (CE) BY RANGE ELONGATION CONDITION

(STUDY 4)



NOTE- Experiments with the same tens-digit coding were combined in this graph. The solid black and gray lines in the figure represent the logistic regression predictions of choosing the precise probability by range elongation condition and number magnitude. The white and gray bars show the proportion of participants who choose the precise probability in each condition. The dotted line at 50% represents ambiguity neutrality (indifference between the precise (CE) and imprecise (range) options). When the proportion of participants choosing the precise option is above 50%, this reflects an overall propensity for ambiguity aversion. The grey error bars represent the 95% confidence interval for each condition.

Heterogeneity of Effects in the Internal Meta-Analysis

We assessed the heterogeneity of the range elongation effect across studies using the Q, I^2, and τ^2 statistics. These statistics reflect the variation among study effects that isn't explained by the tens-digit moderator. The Q-statistic tests the null hypothesis that all studies in the meta-analysis share a common effect size. Under this null hypothesis, when considering one moderator and the main effect in the meta-regression, the expected value of Q would be equal to its degrees of freedom (or less). In this analysis, which includes 16 studies and accounts for both the main effect and the moderator, the degrees of freedom are 14. The observed Q-value of 6.82, with a p-value of 0.94, allows us to retain the null hypothesis, suggesting that the true effect size of range elongation is the same across studies, after accounting the CE magnitude moderator. In line, the observed I^2 of 0%, indicates that all observed variability can be attributed to sampling error (rather than true variation) and the τ^2, which quantifies the variance of true effects across studies, is also 0. Taken together, the three statistics suggest consistent and stable effects for the range-elongation effect after accounting for CE magnitude.

WEB APPENDIX C

Supplemental Experiments C1-3: Interaction of Range Elongation Effect and CE Magnitude in Discount Offers

Here we report three additional experiments that test H2 & H3 in the consumer context of discount offers. The three experiments feature an identical design but variations in wording. The experiments aimed to test H3, like study 4 in the main paper, but in a consumer domain context. Table C1 shows scenarios for each of the three experiments as well as the choices participants had to make. The first experiment differed from the second and third only in asking people to select between coupons rather than stores, see table C1. Everything else was identical across the experiments except for sample size.

Method

Participants and design. The first (non-preregistered) experiment had 257 participants (149 females, M_{age}= 39). The second and third experiments were pre-registered and had 521 (286 females, M_{age}= 39) and 1,559 (864 females, M_{age}= 39) participants respectively. Participants for all experiments were recruited via Prolific and were based in the UK and US. Participants were randomly assigned to one of two range elongation conditions (downwards-elongated or upwards-elongated) and one of two CE magnitude conditions (low or high).

Procedure. In experiment C1, we informed participants that they would be choosing between two hypothetical coupons. In experiments C2 and C3, participants were told that their choice would be between two hypothetical stores. They were then presented with a choice between two coupons in experiment C1 and two stores in experiments C2 and C3. One option offered a precise (CE) discount, while the other offered an imprecise (range) discount. Variations in range elongation and CE magnitude were introduced between subjects. Table C1 presents the four conditions in the 2 (range elongation) x 2 (CE magnitude) design and their corresponding choices.

In all three experiments, we did not provide participants with any information on interpreting the imprecise (range) option or its distribution, thereby preserving the ambiguity of the option. Participants were informed that they would learn the value of the discount prior to shopping. The order in which the precise (CE) and imprecise (range) options appeared—first versus second—was counterbalanced.

Results

We conducted a logistic regression analysis to test the interaction of range-elongation and CE magnitude (H3) in each of the three experiments. Additionally, we also applied this test to the combined data from all three experiments. In the first experiment, we found a significant interaction between CE magnitude and range elongation (β = 1.47, SE = 0.5, z = 2.78, *p* = .005). The other two experiments had the predicted directional pattern of results but not a significant interaction, see table C1 and figure C1. When aggregated, the three experiments revealed a marginally significant interaction between CE magnitude and range elongation (β = 0.31, SE = 0.17, z = 1.83, *p* = .06).

TABLE C1

CONSUMER CONTEXT EXPERMENTS C1-3

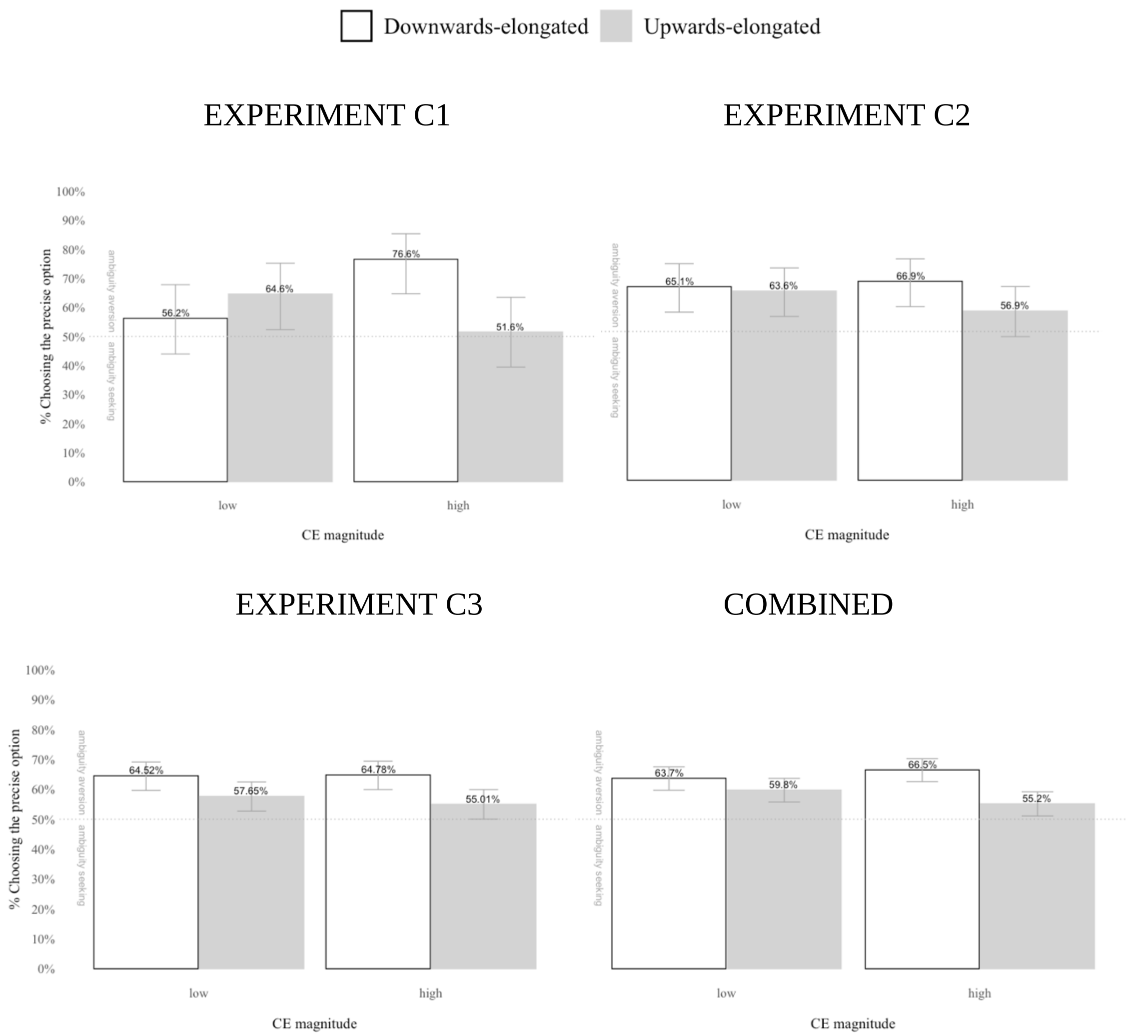
Experiment	Pre-registered	Sample size	Condition*	Description	Choice to make	Test for H3
C1	No	257	DE_low: X = 34, Y = 29, Z = 39 UE_low: X = 36, Y = 31, Z = 41 DE_high: X = 74, Y = 69, Z = 79 UE_high: X = 76, Y = 71, Z = 81	Imagine your favorite store is handing out coupons to loyal customers. Which of these coupons would you prefer.	Discount of X%. Discount of Y-Z%. You will know the exact value prior to shopping	β = 1.47, SE = 0.5, z = 2.78, p = .005
C2	Yes	521	Same as 1	Imagine your favorite stores are handing out coupons to loyal customers. Which of these stores would you prefer.	Store A: Discount of X%. Store B: Discount of Y-Z%. You will know the exact value prior to shopping.	β = 0.36, SE = 0.36, z = 0.991, p = .32

C3	Yes	1559	Same as 1	Same as 2	Same as 2	β = 0.11, SE = 0.20, z = 0.57, p = .56

Note -DE_low = downwards-elongated, low CE magnitude, UE_low = upwards-elongated, low CE magnitude, DE_high = downwards-elongated, high CE magnitude, UE_high = upwards-elongated, high CE magnitude.

FIGURE C1

CHOICE OF STORE BY DISCOUNT MAGNITUDE AND RANGE ELONGATION



NOTE- The gray bars show the proportion of participants who preferred the precise (CE) over the ambiguous (range) outcome in each condition. The dotted line at 50% represents ambiguity neutrality (indifference between the precise (CE) and imprecise (range) options). When the proportion of participants choosing the precise option is above 50%, this reflects an overall propensity for ambiguity aversion. The grey error bars represent the 95% confidence interval for each condition.

Discussion

Despite the non-significant results for H3 in experiments C2 and C3, we consider the three experiments collectively insightful. Across the three, the interaction was significant in some cases (experiment C1) but only directional (experiment C2 and C3) or marginally significant (combined data) in other. This could imply that the moderation of the range elongation effect by numeric magnitude (H3) might be weaker in more concrete consumer contexts than in the more abstract context of hypothetical lotteries (study 4). Why would this be the case?

Qualitative feedback suggests that in a retail context, consumers' assumptions about discounts are shaped by prior experiences. For instance, one participant favored a specific discount (74%) over a range (69-79%), citing distrust in business practices: "In my mind, it is clear and set...I therefore prefer the 74% one. No nonsense, no trickery, what you see is what you get." Another noted a preference for guaranteed discounts due to past experiences of often receiving the minimum discount. This indicates that individuals may interpret ambiguous scenarios based on past experiences rather than solely on the presented data. This link between data specificity and prior experience is important. Extant research indicates that while numerical data always impacts consumer choices, its influence varies with experience (Hsee et al. 2009). For example, a job applicant frequently receiving offers at the lower end of salary ranges might expect similar outcomes in the future, affecting their perception of ambiguity. In such cases, direct experiences play a significant role alongside provided data, complicating the identification of more complex effects, like interactions, in a consumer context compared to lottery scenarios.

This interpretation, while speculative, highlights the importance of considering the broader context in which numerical cognition and ambiguity aversion operate. As discussed in our main manuscript, companies must understand the circumstances under which consumers are receptive to range offers. For instance, this receptiveness could be influenced by factors such as the level of mutual trust between company and consumer (Liu and Chang 2017).

WEB APPENDIX D

Additional Implications for Theory

A prominent theory of ambiguity aversion, which might be influenced by our account of numeric cognition, posits that people are especially ambiguity-averse when they feel relatively incompetent or less knowledgeable in a domain (Heath and Tversky 1991). In a prototypical paradigm supporting this inference, participants are asked to assign a confidence value to a belief, such as estimating the likelihood of rain tomorrow. If an individual is 50% confident in their belief, they are offered a choice: a clear-cut lottery with a 50% chance of winning (the precise option), or they can bet on their own belief and see how it plays out. The latter is considered ambiguous because a subjective belief is assumed to have a certain degree of vagueness, unlike the lottery, which is based on a specific probability. Thus, participants who estimated it would rain with 50% probability tomorrow, would choose between the following two bets:

- Specific lottery bet: Enter a lottery with a precise 50% chance of winning.
- Ambiguous (belief) bet: Win if it rains tomorrow (which is assumed to have an inherent degree of vagueness, e.g., between 40-60%).

Heath and Tversky (1991) demonstrated in multiple experiments that as the degree of belief (i.e., the judged probability of the event) increases, people are more inclined to wager on their ambiguous beliefs compared to a specific lottery equivalent. Interestingly, this prediction would also have been made from the current theory, as ambiguity aversion for both outcomes and probabilities is predicted to decrease at higher numerical magnitudes (H1). It is of course entirely possible that competence perceptions have an additional, independent effect from numeric magnitude, and several findings in their experiments are in line with this idea (e.g., Heath and Tversky repeatedly show that ambiguity aversion is also attenuated in judgment areas where people rate their knowledge as higher).

The main point we wish to make here is that future research and theory formation on ambiguity aversion should account for the idea that points are compared with ranges on an implicit scale which obeys the principles of the mental number line (Dehaene 2003). As we argue more generally in the "Implications for Theory" section of this paper, this has explanatory value for many empirical findings, seeming inconsistencies and theoretical inferences in this literature.

WEB APPENDIX E

Supplemental Experiments E1-3 Conducted by Reviewer

We are deeply grateful to the entire editorial review team for their highly constructive approach in guiding this article. We would like to acknowledge our gratitude to one anonymous reviewer in particular who went beyond the call of duty and collected additional data testing predictions of our theory in consumer relevant contexts. The reviewer conducted three experiments and posted the complete datasets, stimuli, and results in the following repository: https://osf.io/k4f7c/?view_only=8a1d0c01146e4b31b5b7943c0f546990. The reviewer labeled their studies A, B and C, to which we will refer as experiments E1, E2 and E3 respectively. Experiments E1 and E2 were designed to test H1 in consumer contexts. As they shared a common design, we will comment on them together below. Experiment E3 was meant to test H3 in a consumer context, but was mis-specified in its design (see below).

Experiments E1-2: Testing H1 in Consumer Relevant Contexts

We present a summary of these studies in Table E1. Their complete datasets, stimuli and results can be found as studies A and B in the OSF link mentioned above. We conducted a logistic regression analysis on the reviewer's data to test H1 (see 'Test for H1' in the table).

TABLE E1

2 TESTS OF H1 IN CONSUMER CONTEXTS (EXPERMENTS E1-2)

Experiment	Sample size	Condition*	Description	Choice to make	Percent choosing CE	Test for H1
E1 (Reviewer Study A)	300	CE30: X = 30 , Y = 20, Z = 40 CE50: X = 50, Y = 40, Z = 60 CE70: X = 70, Y = 60, Z = 80	Please choose which of these two vaccines you would prefer. Imagine everything is equivalent except for effectiveness information.	Vaccine A: X% effective. Vaccine B: Y-Z% effective.	CE30: 68% CE50: 66% CE70: 66%	β = 0.06, SE = 0.15, z = 0.4, p = .68
E2 (Reviewer Study B)	301	CE20: X = 20, Y = 10, Z = 30 CE50: X = 50, Y = 40, Z = 60	Imagine it is Black Friday and you are shopping. Please indicate your preference of store based on the information below, assuming	Store A: Discount of X%. Store B: Discount of Y-Z%.	CE20: 63% CE50: 53% CE80: 37%	β = 0.54, SE = 0.14, z = 3.69, p < 0.001.

	CE80: X = 80, Y = 70, Z = 90	all other factors are equal.

Discussion

The two experiments provide an interesting pattern of results. While there was strong support for H1 in experiment 2 featuring store discounts, there was no support for H1 in the vaccine setting. Why might this be the case? We can only speculate but note that in our own experiments, we deliberately refrained from testing ambiguity in a vaccine setting at low CE magnitudes, even though the vaccine setting proved conducive to range elongation effects at higher CE magnitudes (see study 2). The reason was that we feared that the vaccine setting would lack consumer relevance at lower CE magnitudes. After all, vaccines with low effectiveness rates would be (rightfully) distrusted by consumers who, as we feared, would object to having to choose between a vaccine with an effectiveness rate of 30% or one with effectiveness between 20 and 40%. We also note that a vaccine needs an effectiveness rate of at least 50% to be approved by the WHO.[3] Hence, the lower CE magnitude conditions in experiment E1 should not be choices consumers can actually face. Admittedly, this rationale is post hoc and experiment E1 demonstrates that there may be many factors which influence ambiguity attitudes that are unrelated to numerical cognition.

In sum, we are grateful to the reviewer for the additional data they provided, which provide additional support for our thesis that ambiguity aversion decreases at higher values of outcomes (H1) in the consumer relevant context of store discounts (experiment E2). They also

[3] https://www.who.int/news-room/feature-stories/detail/vaccine-efficacy-effectiveness-and-protection

demonstrate that consumer preferences for ambiguity in other contexts might be influenced by idiosyncratic context-related factors other than numeric cognition principles (experiment E1).

Experiment E3: Testing H2 and H3 in Product Lifespan Decisions

The reviewer conducted a three-cell between subject experimental design that was meant to test H2 and H3 in the consumer relevant context of product lifespan decisions. The stimuli and results are represented in table E2:

TABLE E2

DESIGN AND RESULTS OF EXPERIMENT E3 (REVIEWER STUDY C)

Condition	Sample size	Description	Choice to make[4]	Percent choosing CE	Chi Square test against indifference between the options (50% choice)
1	100	Imagine you are deciding between two products. Which do you prefer, assuming all other factors are equal.	Store A: Has a lifespan of 18-24 months. Store B: Has a lifespan of 21 months.	CE21: 58%	$\chi2(1) = 2.56, p = 0.11$
2	100		Store A: Has a lifespan of 24-30 months. Store B: Has a lifespan of 27 months.	CE27: 54%	$\chi2(1) = 0.64, p = 0.42$
3	101		Store A: Has a lifespan of 78-84 months. Store B: Has a lifespan of 81 months.	CE81: 67%	$\chi2(1) = 12.13, p < .001$

[4] Note that the stimuli (somewhat confusingly) indicate ‘store A vs store B’ while the choice participants are asked to make is one between products, not stores. Here, we simply display the materials provided by the anonymous reviewer. This oversight might have occurred either in the experimental stimuli (i.e., as presented to participants) or merely in the description of the study.

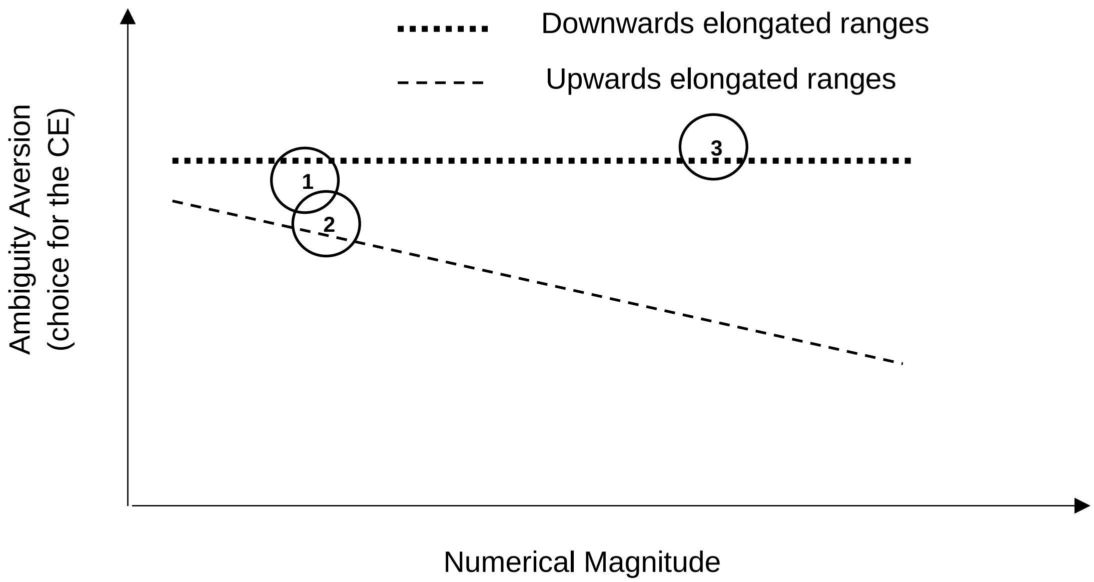
Discussion

The reviewer interpreted these results as follows: “My third study was a test of H2 and H3. H2 says a downward elongation (relative to upward elongation) of the range should amplify ambiguity aversion. Condition 1 has the downward elongation. The CE choice share is 58%. Condition 2 has upward elongation. The choice share is 54%. The z-test is .57. H3 says the downward elongation test should get stronger at higher CE magnitudes. Comparing condition 1 (58%) to condition 3 (67.3%) is not significant (z = 1.37). The data do not support H2 or H3.”

We are highly grateful to the reviewer for providing these data. We have a different interpretation, however, about the extent to which they support our theoretical predictions, arguing they are quite in line with our expectations. To aid our interpretation, we believe it useful to compare in figure E1 the reviewer’s pattern of results with our predictions resulting from the sum of H1 and H3 (as visualized in figure 10 and observed in study 4; see also figures 9 and B1).

FIGURE E1

CONDITIONS OF EXPERIMENT E3 RELATIVE TO THE COMBINED PREDICTIONS OF H1 AND H3 (SEE ALSO FIGURES 9, 10 AND B1)



NOTE- The figure presents the three conditions of experiment E3 (study C conducted by the reviewer) on a conceptual figure representing the summed impact of H1 and H3. Condition 1 features a downwards-elongated range versus a CE at a lower region of the mental number line. Condition 2 features an upwards-elongated range versus a CE at a lower region of the mental number line. Condition 3 features a downwards-elongated range versus a CE at a higher region of the mental number line.

The reviewer is right to argue that the comparison of conditions 1 and 2 represents a test of H2. While directionally in line with predictions, this test was not significant. We note, however, that there are a few additional considerations that could explain why this test was not significant. First, this test of H2 was conducted at a low region of the mental number line, where the effect of H2 is predicted to be the weakest (per H3). Second, it is possible that participants were puzzled by the wording in the study which confused stores with products (see footnote 2).

The reviewer also argues that the comparison of conditions 1 (featuring a downwards-elongated range low on the mental number line) and 3 (featuring a downwards-elongated range higher up the mental number line) represents a test of H3. This is incorrect. H3 stipulates that the effect of *downwards- versus upwards*-elongated ranges (i.e., H2) increases higher up the mental number line. To run the test of H3, the reviewer's study is missing a 4th condition (i.e., an upwards-elongated range higher up the mental number line). They should then test whether the difference between conditions 1 and 2 is smaller than the difference between conditions 3 and 4. When comparing only downwards-elongated ranges at lower versus higher regions of the mental number line, as one does by comparing conditions 1 and 3, no differences are expected to emerge, as the effects of H1 and H3 cancel each other out on downwards-elongated ranges (see figures 9, 10, B1 and E1).

WEB APPENDIX F

Supplemental Experiments F1-2 (Numbers Over 100 and Middle Digits)

During the review process, one reviewer posed intriguing follow-up questions to our theory: "What happens at values beyond 100(%)? And does the effect manifest with middle digits (e.g., 169% - 179% vs. 171% - 181%)?" We found these questions relevant and conducted two exploratory studies. Due to space constraints in the manuscript, we did not include this in the paper but wish to provide a brief overview for anyone wishing to further investigate this question for theoretical or practical purposes. The stimuli and complete datasets of these stimuli can be found in our OSF directory https://osf.io/vcneh/?view_only=043a1f801d804308bbc0e7b00da9872f

STUDY F1: NUMBERS OVER 100

In line with the reviewer's recommendation, we focused on a downwards-elongated and non-elongated condition. Participants were asked to imagine investing $1,000 and choose between two investment options. In the downwards-elongated condition, the options were Investment A with an expected one-year return of $204, and Investment B with a return of $199-$209. In the non-elongated condition, the options were Investment A with a return of $206, and Investment B with a return of $201-$211 (we don't call this condition upwards-elongated as there is only a digit change in the middle digits). We recruited 100 participants through Prolific for this study. In the downwards-elongated condition, 74% preferred the precise option, while in the non-elongated condition, only 40% did ($\chi2(1) = 22.22$, $p < 0.001$). These findings suggest that our theory is applicable for numbers greater than 100.

STUDY F2: MIDDLE DIGITS

We conducted a similar study focusing on middle digits, testing (awaiting better terms) middle-downwards-elongated and middle-upwards-elongated conditions. Participants chose between Investment A (with an expected return of $174) and Investment B ($169-$179 return) in the middle-downwards-elongated condition, and between Investment A ($176 return) and Investment B ($171-$181 return) in the middle-upwards-elongated condition. This study involved 101 participants from Prolific. In the middle-downwards-elongated condition, 71% chose the precise option, while in the middle-upwards-elongated condition, 62% did ($\chi2(1) = 1.43$, $p = 0.23$).

While these results are directionally in line with the range elongation effect (H2), they are not significant. They suggest that if changes in middle digits (i.e., tens digits in this case) influence choices in the same way, their influence is smaller than the effects of left-most digit changes, in line with established knowledge about the effects of left(most) digits changes more generally (Williams et al. 2023).

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