

CONTEXT DEPENDENCE IN PERCEPTUAL AND PREFERENTIAL CHOICE

A Dissertation Presented

by

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Many people.

ABSTRACT

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A large body of research in psychology has shown that context can systematically affect choice. These *context effects* are in violation of rational choice theory and are both practically and theoretically interesting. Recent work has demonstrated context effects in simple perceptual choice, interesting findings that suggest that these results are not restricted to high-level (e.g., consumer) choice. This dissertation explores the attraction and repulsion effects, two related context effects, with a particular emphasis on perceptual choice. Chapter 1 introduces the attraction and repulsion effects and reviews the empirical and theoretical literature surrounding them. Chapter 2 tests the ability of perceptual and decisional processes to account for these effects through the introduction of a Thurstonian choice model. Chapter 3 uses this model to make predictions about best-worst choice and test them empirically. Chapter 4 generalizes the model and paradigm from Chapter 2 to consumer choice. Chapter 5 tests the idea

that the repulsion effect can be generated through ease of comparability. Chapter 6 discusses and summarizes these results.

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CHAPTER 1

INTRODUCTION

1.1 Overview

Decades of decision-making research have shown that context can systematically affect choice. In decision-making experiments, researchers present participants with a finite set of options on each trial and ask them to select a single option based on either an internal (e.g., most preferable) or external (e.g., largest shape) criterion. Decision-making research spans multiple fields, including psychology, neuroscience, economics, marketing, and political science. In economics, for example, researchers have developed models based on the idea that people make choices that maximize their utility but are subject to resource constraints and noisy preferences. In psychology and marketing, however, decision-making researchers have identified a set of phenomena that violate such assumptions, by showing that choices can vary with the *choice set*, or the menu of available options. This class of phenomena is known as *context effects*.

One notable context effect, the attraction effect, occurs when the choice share of a *target* option increases upon the inclusion of a similar but inferior *decoy* option (Huber et al., 1982). Another finding, the repulsion effect, occurs when a decoy boosts the choice share of a dissimilar *competitor* option rather than the target (Simonson, 2014). The repulsion effect is an empirical reversal of the attraction effect.

Context effects, originally studied in preferential choice, have been recently demonstrated simple perceptual choice (Evans et al., 2021; Liao et al., 2021; Spektor et al., 2018, 2022; Trueblood & Pettibone, 2017; Trueblood et al., 2013; Turner et al., 2018;

Yearsley et al., 2022). This idea is theoretically interesting because it suggests that context effects are a theoretical primitive rather than simply a feature of high-level consumer choice (Trueblood et al., 2013).

As suggested by the title, this dissertation explores various forms of context dependence in both perceptual and preferential choice. Specifically, the dissertation explores the attraction and repulsion effects. The goal of this dissertation is to further understand why these effects occur in perceptual and preferential choice, by employing well-studied statistical models from the psychology literature. Additionally, this dissertation sets out to differentiate perceptual processes from decision-making processes in context effects (specifically, the attraction and repulsion effects).

As discussed throughout this dissertation but particularly in Chapter 2, recent work has demonstrated inconsistency in context effects, particularly in perceptual choice. This dissertation uses behavioral experiments and statistical modeling in an attempt to reconcile these inconsistencies.

This dissertation is structured as follows. Chapter 2, develop and tests a statistical (Thurstonian) model of choice within the domain of perceptual choice. In Experiment 1, it is shown that the types of stimuli used in perceptual choice context effects experiments are easily confusable and vary systematically with theoretically relevant properties of the stimuli. In Experiment 2, the results of a high-powered psychophysics experiment show that the repulsion effect, but not the attraction effect, is naturally predicted by this Thurstonian model. In Chapter 3 further tests the Thurstonian model by applying it to best-worst choice. In Chapter 4 generalizes the paradigm and model to preferential choice. Finally, Chapter 5 uses a perceptual choice experiment to show that stimulus comparability affects choice, even when the decoy is equally similar to both focal options. Chapter 6 summarizes the findings of the dissertation, their implications, and discuss future directions for research in this domain.

Below, the attraction and repulsion effects are introduced, and the empirical and theoretical literature is reviewed.

1.2 The Attraction Effect

This section formally defines the attraction effect. See Figure ?? (left panel), which shows a graphical configuration of various choice options. These options vary on two dimensions (or attributes), where higher values of an attribute are always preferred. These dimensions are named generically to emphasize the generality of the attraction effect.

Let A , B , D_A , and D_B be discrete choice options, $[]$ denote the options in a choice set, and $P(A|[A, B])$ denote the probability of choosing option A from a set consisting of A and B , for example.

In Figure ?? (left panel), options A and B trade off on attributes. A is high on dimension 2 but low on dimension 1, while B is high on dimension 1 but low on dimension 2. A decision-maker who assigns equal importance to both dimensions should be indifferent between both options when presented with choice set $[A, B]$. Now, however, consider option D_A , which is inferior to A and B , but more similar to A than to B . This *decoy* option is dominated by A , so no rational agent who perceives this dominance relationship should intentionally select the decoy over the target. Similarly, D_B is inferior to both A and B but more similar to B . The attraction effect is the finding that choice for A over B is greater given set A, B, D_A than given set A, B, D_B .

The attraction effect was first demonstrated by Huber et al. (1982)¹, who tested participants with sets of choice options, using products such as cars, beers, and TV sets. Participants first completed hypothetical choice tasks where they chose their

¹These authors referred to this finding as the asymmetric dominance effect. Contemporary researchers have adopted the term attraction effect.

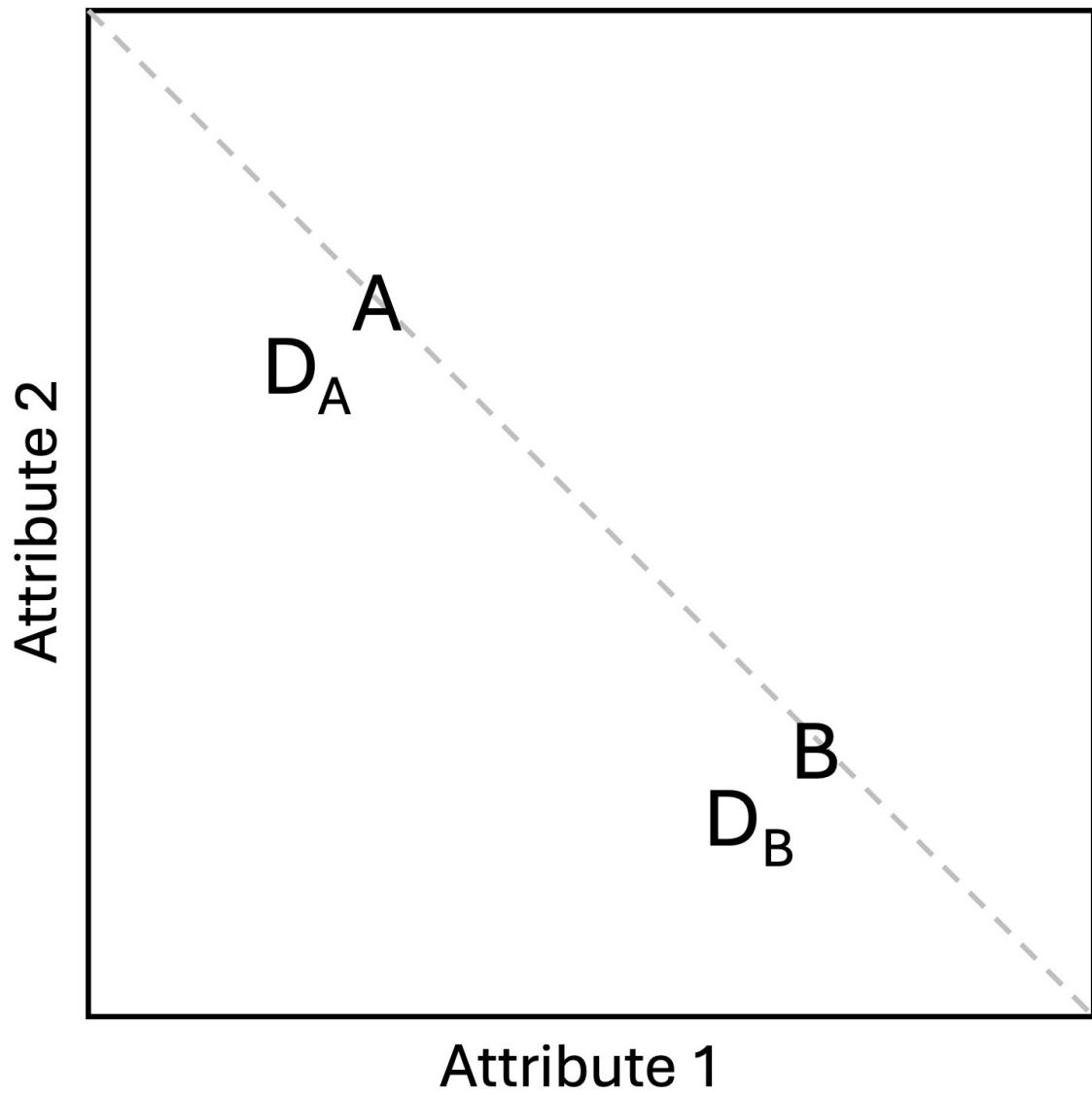


Figure 1.1. A graphical depiction of choice options in the attraction/repulsion effect. Attributes are named generically.

most preferred option from ternary choice sets, each containing a target, competitor, and decoy option. Participants then returned two weeks later to choose from the same choice sets but with the decoy removed from all trials. Participants chose the target at a higher proportion when the decoy was present than when it was absent. The results of Huber et al. (1982) violate the regularity principle, which states that the choice proportion for a particular option cannot increase when more options are added to the choice set. According to regularity, the following inequality should hold:

$$P(A|[A, B]) \geq P(A|[A, B, D_A]) \quad (1.1)$$

Thus, the binary-ternary form of the attraction effect demonstrated by Huber et al. (1982), where $P(A|[A, B, D_A]) \geq P(A|[A, B])$, violates regularity.

The attraction effect also violates the *Independence of Irrelevant Alternatives* (IIA) principle. IIA states that the relative likelihood of choosing a particular option over another is invariant of the choice set (Ray, 1973).

Written in the context of the above example, IIA requires the follow equality to hold²:

$$\frac{P(A|[A, B])}{P(B|[A, B, D_A])} = \frac{P(A|[A, B])}{P(B|[A, B])} \quad (1.2)$$

However, in the attraction effect, this equality is violated:

$$\frac{P(A|[A, B, D_A])}{P(B|[A, B, D_A])} > \frac{P(A|[A, B])}{P(B|[A, B])} \quad (1.3)$$

The attraction effect is often demonstrated by a ternary-ternary comparison (Trueblood et al., 2013), where participants choose from two choice sets each containing a target, competitor, and decoy option (e.g., $[A, B, D_A]$ and $[A, B, D_B]$ in Figure ??). In the attraction effect, participants are more likely to choose A given $[A, B, D_A]$ than

²This is often referred to as the constant ratio rule.

given $[A, B, D_B]$, and they are also more likely to choose B given $[A, B, D_B]$ than given $[A, B, D_A]$. This effect can be written using the following inequality, which also violates IIA:

$$\frac{P(A|[A, B, D_A])}{P(B|[A, B, D_A])} > \frac{P(A|[A, B, D_B])}{P(B|[A, B, D_B])} \quad (1.4)$$

Thus, IIA is violated by the attraction effect in this ternary-ternary example.

In the context effects literature, it is common to refer to the similar, dominated option as the *decoy*, the similar dominating option as the *target*, and the dissimilar dominating option as the *competitor*. For example, in the choice set $[A, B, D_A]$, A is the target, B is the competitor, and D_A is the decoy. This terminology will be adopted throughout this dissertation.

Cataldo and Cohen (2019) showed that, in preferential choice, context effects can be reversed or eliminated simply by altering stimulus presentation format. For example, they showed that if participants can easily compare pairs of options (e.g., target and decoy) on each dimension, the attraction effect occurs quite strongly, but without this ease of comparison the attraction effect becomes negligible. Hasan et al. (2025) failed to replicate this effect, albeit with different decoys than those of Cataldo and Cohen (2019).

Chang and Liu (2008) also varied option display, in either a by-alternative format, where option names are listed as columns while attribute values are listed as rows, or a by-attribute format, where option attributes are columns while option names are rows. The former display makes it more difficult to compare options on a single attribute, while the latter makes it easier. They found that listing options by-attribute increased the choice share of the compromise option, relative to a by-alternative display.

Hayes et al. (2024) manipulated attribute commensurability in a context effects experiment. When two dimensions are commensurable, they vary on a common unit (e.g., user ratings from 0-10), while incommensurable units exist on incomparable

units (e.g., RAM and CPU speed in laptops). They found that when dimensions are commensurable, the attraction effect vanishes, while it still exists strongly when dimensions are incommensurable. This suggests that the attraction effect occurs more strongly when the representation of options encourages between-option comparisons on a single attribute.

Theoretically, the attraction effect is particularly interesting because in violating IIA and regularity, it is not predicted by many classical models of choice. Luce's Choice Model (Luce, 1959), for example, is a well-known model of choice which states that the probability of choosing option x from set K can be written as:

$$P(x|K) = \frac{v_x}{\sum_{y \in K} v_y} \quad (1.5)$$

where v_i is a ratio scaled variable indicating value, or utility, of option i . Luce's model is highly influential in psychology and has been used to account for data in areas such as categorization (Nosofsky, 1986) and identification (Townsend, 1971). However, given that the model satisfies both IIA and regularity, the model cannot predict the attraction effect.

The attraction effect is not the only context effect to be demonstrated empirically; Tversky (1972) demonstrated that a similar, but not necessarily inferior, option can decrease choice for a focal option. For example, an option closer to A than to B on the diagonal line in Figure ?? can cause a decrease in the choice proportion for A . Simonson (1989) demonstrated the compromise effect, where the placement of an intermediate option between two extremes decreases choice for the extremes.

Context effects such as the attraction effect have strong theoretical implications. Traditional models of choice, as used in economics and marketing research (McFadden, 2001), treat the *utility*, or value, of each option as a random variable whose parameters are estimated from choice data. According to these models, on each trial of a decision-making experiment, the participant samples option values from

these distributions and deterministically chooses the option with the highest sampled value. These models are known as *Random Utility Models* (RUMs). When utilities are assumed to follow a Type 1 Generalized Extreme Value distribution, the logit or softmax model is used (Gensch & Recker, 1979). The probit model, another popular model, assumes Gaussian distributed utilities (Bolduc, 1999). Typically, though not necessarily, these models assume independently distributed errors, which typically implies IIA. Typically, these models are used to estimate the inherently unobservable utility values for each option.

With the large body of published empirical data and the inadequacy of existing models to explain context effects, many researchers have developed process models that attempt to explain the mental processes that lead to context effects.

One notable model is Roe et al. (2001)'s Multialternative Decision Field Theory (MDFT) model. Building on other research in cognitive psychology which casts the decision-making process as an evidence accumulation process indexed by time (Ratcliff, 1978), where evidence here is preference. According to MDFT, the valence \mathbf{V} of each option at time t is computed as:

$$\mathbf{V}(t) = \mathbf{C}\mathbf{M}_1\mathbf{W}_1(t) + \epsilon(t) \quad (1.6)$$

where \mathbf{C} is a (symmetric) contrast matrix defining the comparison process, \mathbf{M} is a matrix of attribute values, \mathbf{W} is a vector of attention weights (defining which attribute is being attended to), and ϵ is the random error term.

The valences are then combined into a preference state vector $\mathbf{P}(t)$ and a new state is formed at time $t + 1$ by:

$$\mathbf{P}(t + 1) = \mathbf{S}\mathbf{P}(t) + \mathbf{V}(t + 1) \quad (1.7)$$

\mathbf{S} is a feedback matrix where the diagonal elements allow memory decay for previous preference states, but the off-diagonal elements allow options in a choice set to

influence one another through lateral inhibition. Roe et al. (2001) stated that this influence should be negative and its strength should be a decreasing function of distance in attribute space. They did not specify a form to this function, but Hotaling et al. (2010) amended the model to specify a Gaussian function for the distance, where the value of S_{ij} is computed as:

$$S_{ij} = \delta_{ij} - \varphi_2 \cdot e^{-\varphi_1 \cdot D_{ij}^2} \quad (1.8)$$

where $\delta_{ij} = 0$ if $i \neq j$ (indicating lateral inhibition), D_{ij}^2 is distance in attribute space between options i and j ³, and the φ are free parameters.

MDFT can produce the attraction effect because of the strong connection between target and decoy (e.g., A and B in Figure ??), where the mutual negative inhibition cancels (via multiplication) to cause the decoy to boost the preference state for the target, relative to the competitor.

RUMs often have difficulty accounting for context effects. For example, Berkowitzsch et al. (2014) tested the independent logit and independent probit models against Roe et al. (2001)'s Multialternative Decision Field Theory (MDFT), a cognitive process model of decision-making. According to MDFT, choice is the end result of a stochastic evidence accumulation process, where preferences for each option in a choice set accumulate value through a series of comparisons on each dimension. In Berkowitzsch et al. (2014)'s experiment participants chose between digital cameras from choice sets designed to elicit context effects. Berkowitzsch et al. (2014) found that MDFT, but not the logit or probit models, could account for the attraction effect (and other related context effects). Furthermore, according to model comparison measures, the majority of participants were best described by MDFT. Participants whose data were best described by MDFT were also more likely to exhibit context

³Hotaling et al. (2010) also specify that distance should be weighted differently depending on whether one option dominates another.

effects. Independent RUMs, such as the logit and probit model, assume each option's utility is independently sampled, so these models cannot account for context effects.

Often, though not necessarily, RUMs assume IIA. This assumption can be relaxed, however. Paetz and Steiner (2018) showed, via simulations, that the probit model can violate IIA by allowing non-zero off-diagonal elements in the variance-covariance matrix. IIA can also be relaxed by estimating choice set or alternative specific coefficients (Rooderkerk et al., 2011) or allowing correlations between options and/or attributes (Haaijer et al., 1998). Without such modifications, RUMs are unable to account for context effects.

Huber and Puto (1983) replicated the results of Huber and Puto (1983) and also showed that if the decoy has a relatively high value, it can actually take choice shares away from the target.

CHAPTER 2

CORRELATED VALUATIONS AS A MECHANISM FOR THE REPULSION EFFECT

2.1 Introduction

As discussed in Chapter 1, the attraction effect is a well-studied choice phenomenon where an asymmetrically dominated decoy option increases the choice share of a similar, but superior, target option (Huber et al., 1982). The attraction effect is an example of a context effect, where the relative choice share of an option varies systematically with the choice set.

Though context effects originally were originally demonstrated in preferential choice, recent work has generalized these results to simple, perceptual choice. This result has important theoretical and practical implications for decision-making research. See Chapter 1 for a review of relevant literature on the attraction effect.

Numerous researchers have since demonstrated the attraction effect in preferential choice, including in real-world scenarios. Doyle et al. (1999) found an attraction effect in real world supermarket choices by adding a decoy option to an existing product set, where the decoy option was the same brand and price as the target, but of a lower volume. van den Enden and Geyskens (2021) showed that the attraction effect can be used to induce people to choose healthier food items. Slaughter et al. (1999) showed that the attraction effect can be found even without the explicit attribute descriptions commonly used in laboratory experiments, when participants must infer option attributes.

The attraction effect is not solely limited to consumer choice. Researchers have also demonstrated the attraction effect in risky choice (Mohr et al., 2017), policy

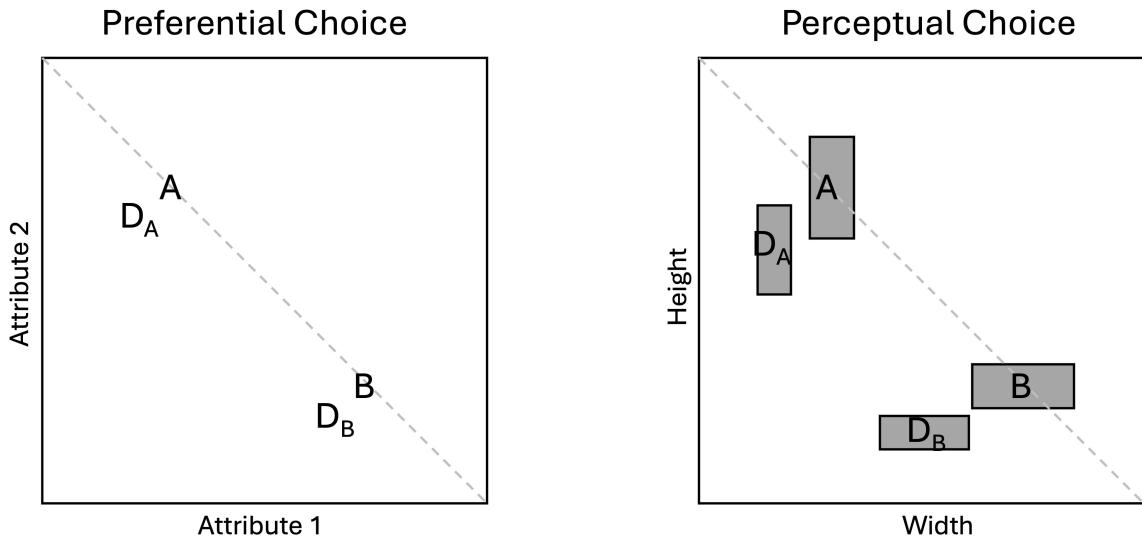


Figure 2.1. A graphical depiction of choice options in the attraction/repulsion effect. Left panel: preferential choice. Right panel: perceptual choice.

choice (Herne, 1997), intertemporal choice (Marini et al., 2020), probability judgment (Cai & Pleskac, 2023), medical decision-making (Schwartz & Chapman, 1999), episodic memory judgment (Maylor & Roberts, 2007), charitable donation (Pittarello et al., 2020), inference (Trueblood, 2012), job candidate selection (Highhouse, 1996), political choice (Pan et al., 1995), sports prediction (Fang et al., 2024), and, as will be the focus of much of this dissertation, perceptual choice (Evans et al., 2021; Liao et al., 2021; Spektor et al., 2018, 2022; Trueblood et al., 2013, 2015; Turner et al., 2018; Yearsley et al., 2022).

2.1.1 From Preferential to Perceptual Choice

Choplin and Hummel (2005) and Yearsley et al. (2022) first demonstrated the attraction effects in perceptual choice. In these experiments, participants saw various perceptual stimuli (i.e., ovals, swirled lines, vertical lines) and chose the option most similar to a reference option. The researchers showed that participants were more

likely to choose the option paired with a similar (but less similar to the reference stimulus) decoy option.

Trueblood et al. (2013) also demonstrated the attraction effect in perceptual choice. In their experiments, participants saw three rectangles on each trial, arranged in a horizontal array, and selected the option they perceived to have the largest area. For an example stimulus set, see Figure ?? (right panel). Note that options A and B have equal area but trade off in height and width. The decoy options (D_A and D_B , respectively) are smaller in area but are more similar to their respective targets than to their respective competitor. In Trueblood et al. (2013)'s experiments, participants chose the target option more than the competitor option, on average.

Notably, the title of Trueblood et al. (2013)'s paper was "Not Just for Consumers: Context Effects Are Fundamental to Decision Making", and in their General Discussion, Trueblood et al. (2013) argued "our experiments suggest that these context effects are a general feature of human choice behavior because they are a fundamental part of decision-making processes. As such, our results challenge explanations of these effects exclusively in terms that are unique to high-level decision making and thus call for a common theoretical explanation that applies across paradigms." (p. 907). According to Trueblood et al. (2013), context effects are not idiosyncratic to high-level decision-making but are a fundamental feature of choice. Trueblood et al. (2013) also used these perceptual results to argue against the context-dependent advantage (CDA) model (Tversky & Simonson, 1993) as well as the Leaky Competing Accumulators (LCA) model (Usher & McClelland, 2004), as these models use loss aversion - the idea that an option's disadvantages on an attribute are weighted more strongly than its advantages on other attributes - to account for context effects. Trueblood (2012) demonstrated context effects in an inference task and argued similarly against loss aversion.

Frederick et al. (2014) failed to replicate Trueblood et al. (2013)'s finding of the attraction effect in perceptual choice. Frederick et al. (2014) collected data online, which may have resulted in less precision than a laboratory task, potentially leading to the null finding.

Turner et al. (2018) replicated Trueblood et al. (2013)'s results and performed a large scale modeling analysis, comparing the ability of various model mechanisms to account for context effects. For example, Turner et al. (2018) concluded that pairwise comparisons on individual attributes greatly improves models' ability to account for context effects. This may not be appropriate, however, given a perceptual domain where dimensions may not be separable. Specifically, in a consumer choice experiment, participants may very well compare options on a single dimension at a time, e.g. comparing cars on their fuel efficiency. However, in a perceptual choice task, it is unlikely that participants are able to separately compare rectangles on the height dimension and on the width dimension and then arrive at an overall judgment. Rather, it is more plausible that participants compare these stimuli holistically.

Spektor et al. (2018) followed up on this work and demonstrated the *repulsion effect* in a similar perceptual choice experiment. In the repulsion effect, the competitor's choice share is higher than the target's choice share. In Spektor et al. (2018)'s experiments, the target and competitor options varied in area, such that one option was always larger, though on average they were the same size. The researchers also varied the *target-decoy attribute distance* (TDD), the percentage difference between the target and decoy areas. For example, if TDD is 2%, the decoy is 2% smaller than the target.

Spektor et al. (2018) ran a total of five experiments. All experiments showed similar results, so the current focus is on their experiments 3 and 4a, which are the most representative of the article's conclusions. In Experiment 3, the authors varied TDD at four levels: 2%, 5%, 9%, and 14%. The rectangles were arranged

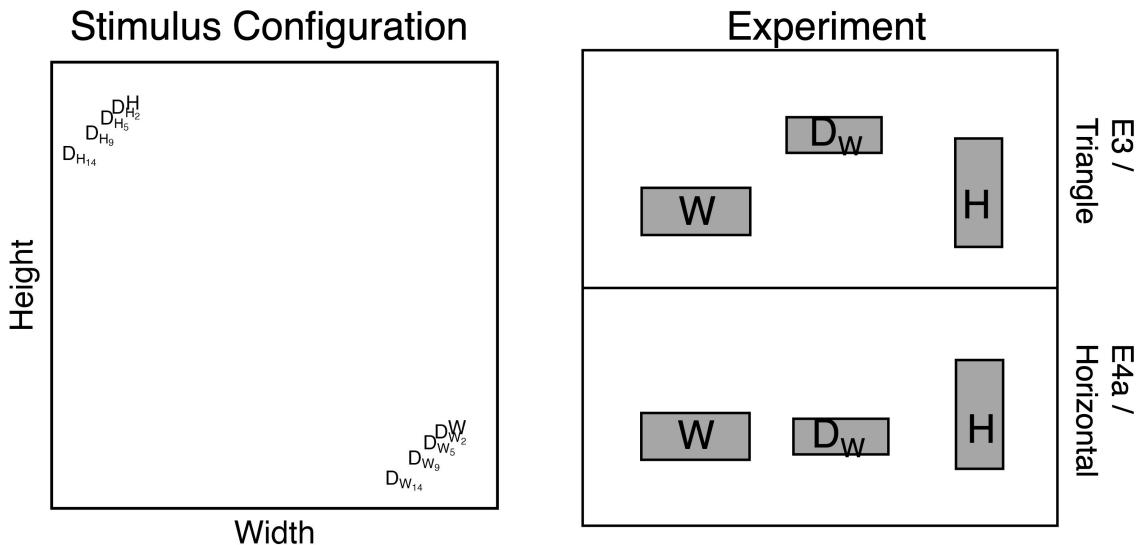


Figure 2.2. Stimulus configuration and example trials from Spektor et al. (2018), Experiments 3 and 4a. Decoy subscripts indicate TDD. Note that the stimulus in the righthand plot were not shown in the experiment; these are solely for the benefit of the reader.

in a triangular display on the screen (see Figure ??, Experiment 3), in contrast to Trueblood et al. (2013)'s horizontal display. Spektor et al. (2018) found a repulsion effect, such that the competitor was selected more than the target at all levels of TDD (see Figure ??).

Spektor et al. (2018)'s Experiment 4a, however, used the horizontal display of Trueblood et al. (2013) (see Figure ??, Experiment 4a). Here, they varied TDD at 5%, 9%, and 14%. In Experiment 4a, the data show a slight repulsion effect at low TDD levels that eventually becomes an attraction effect at high TDD levels.

Trueblood and Pettibone (2017) demonstrated a "phantom decoy" effect in perceptual choice. Phantom decoys are options that are similar to the target, but also superior in value, and are initially presented but made unavailable at the time of choice. They showed that participants chose the target less than the competitor, a result at odds with phantom decoy effects in preferential choice (Pettibone & Wedell, 2000; Pratkanis & Farquhar, 1992).

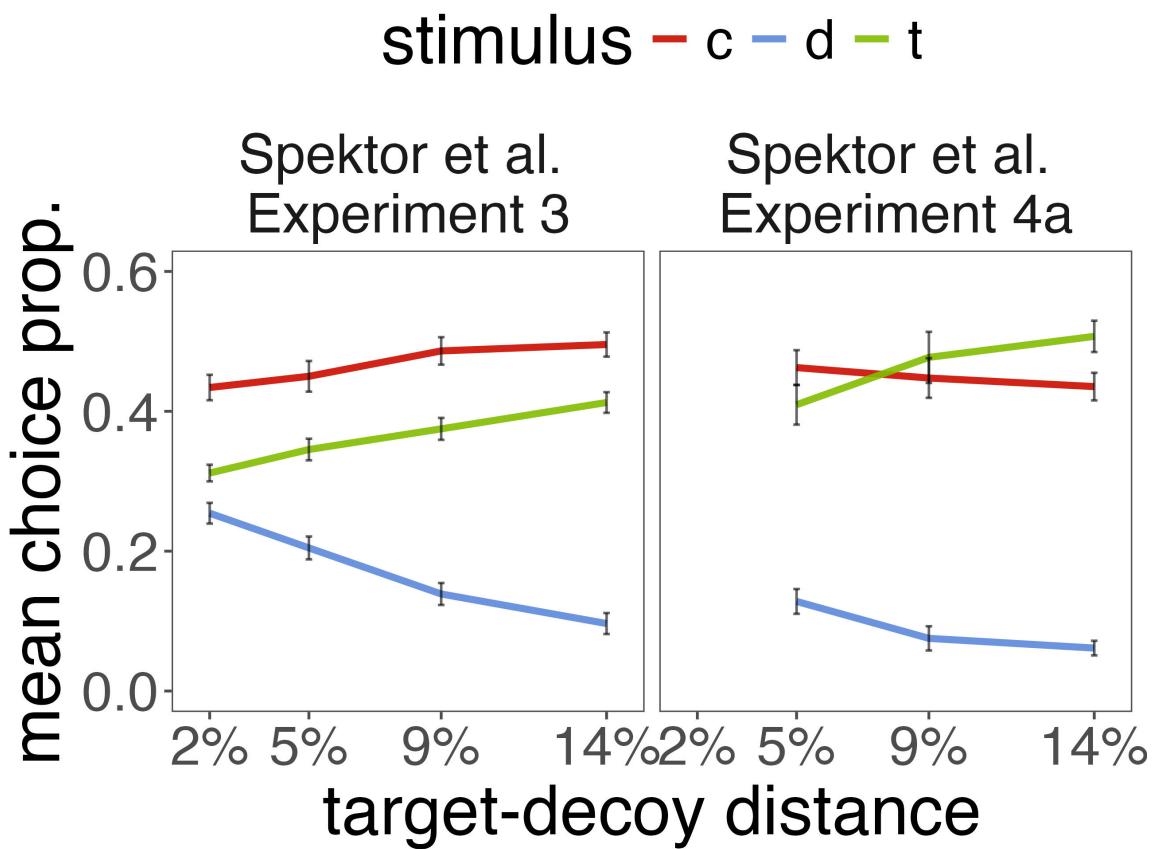


Figure 2.3. Data from Spektor et al. (2018), collapsed across choice set. Error bars are 95% CIs of the mean, computed using the within-participants error correction from Morey et al. (2008). Dashed lines are drawn at .5 and .33.

Liao et al. (2021) also replicated the general pattern of Spektor et al. (2018)'s results and also found a an inverse U-shaped relationship between TDD and the attraction effect. Low and high TDD values created a repulsion effect, while intermediate TDD values created an attraction effect.

Spektor et al. (2022) demonstrated the repulsion effect in both preferential and perceptual choice, using similar stimuli and a similar display configuration to Spektor et al. (2018) and Liao et al. (2021). Here, the stimuli were squares containing two bars filled to varying degrees with color. In perceptual choice, participants were to select the stimulus with the largest cumulative filled area. In the preferential choice scenario, participants were told that each filled bar represented one possible outcome of a 50-50 gamble, and they were to select the gamble with the highest expected value. Their results were similar to those of Spektor et al. (2018), however, where both target and competitor choices increased with TDD.

In a review of the recent context effects literature, Spektor et al. (2021) identified *attribute concreteness* as a crucial moderating factor on context effects. They defined attribute concreteness as the degree to which observers would agree on the true value of options' attributes. For example, in a preferential choice experiment where attributes are presented numerically, e.g. RAM and Screen Resolution for laptops, attribute concreteness is high. In a perceptual rectangle choice experiment, where observers must rely on their own perception of height and width, attribute concreteness is low. They noted that high attribute concreteness tends to lead to robust context effects while low attribute concreteness has led to mixed results. According to their explanation, the lack of concreteness in perceptual choice is a crucial reason for the varied context effects data.

Researchers are clearly using perceptual experiments to demonstrate context effects and test theories of choice. These results are clearly informative and theoretically interesting. However, there are distinct differences between these perceptual choice

experiments and the preferential choice experiments in which the attraction effect was originally demonstrated. In preferential choice tasks, participants are typically shown a set of options (e.g., laptops, apartments, washing machines), along with the attribute values associated with each option (e.g., 10 GB RAM, 1500 square feet, 2.7 cubic feet capacity). These attributes are typically represented numerically (Banerjee et al., 2024; Hayes et al., 2024) or with easily discriminable graphical representations (Cataldo & Cohen, 2019). The decoy option, therefore, is rarely selected (e.g., < 5% of all trials in many studies), and these selections are assumed to be the result of inattention or accidental responses. Though participants' preferences may be noisy, researchers can generally assume that participants are able to detect the dominance relationship between target and decoy. Perceptual choice tasks, on the other hand, complicate participants' ability to detect this dominance relationship.

In Spektor et al. (2018)'s experiments, the decoy is selected as often as 25% of all trials in some conditions (see Figure ??), far more often than is common in preferential context effect experiments. The decoy is also selected less often in experiment 4a (triangle display) than in experiment 3 (horizontal display). Decoy selections also decrease as TDD increases. Finally, though both target and competitor increase in choice share as TDD increases, the target choice share increases at a higher rate than does the competitor, suggesting a strong trade-off between target and decoy choices; stronger, indeed, than the competitor-decoy trade-off. That is, the mean *Relative Choice Share of the Target*, or RST (Berkowitzsch et al., 2014) increases with TDD in both experiments.

Spektor et al. (2018) found that a relatively small change in stimulus display (arranging stimuli in a triangle rather than a horizontal line) reverses the attraction effect. Why is it that a relatively subtle change in stimulus display led to a qualitative shift in the data? To answer this question, it is worth considering the differences between Spektor et al. (2018)'s data and previous context effect experiments.

Clearly, perceptual discriminability plays a role in Spektor et al. (2018)'s results. Participants clearly are better able to discriminate the target and competitor from the decoy as TDD increases. Any reasonable account of these data should parse value discriminability from genuine context effects.

Below results from a two-alternative forced-choice experiment show that these stimuli are easily confusable and that the triangle display of Spektor et al. (2018) decreases discriminability relative to the horizontal display.

2.2 Experiment 1

The goal of Experiment 1 was to test participants' ability to discriminate between rectangles in the perceptual choice tasks of Trueblood et al. (2013) and Spektor et al. (2018). On each trial, participants saw three options (target, competitor, and decoy). After a short delay, two of the rectangles were highlighted and participants chose which of the two rectangles was larger. This two-alternative forced choice (2afc) task allows testing discriminability between all pairs of options.

This experiment also included a within-participants manipulation to compare discriminability in both the triangle display of Spektor et al. (2018), Experiment 3, and the horizontal display of Spektor et al. (2018) Experiment 4a and Trueblood et al. (2013). Otherwise, with a few exceptions discussed below, the experiment followed the stimulus construction and experimental design of Spektor et al. (2018), Experiments 3 and 4a.

2.2.1 Methods

2.2.1.1 Participants.

Data collection took place at the University of Massachusetts Amherst. 86 undergraduate students participated in exchange for course credit. 1 participant who achieved less than 80% accuracy on catch trials (see below) was excluded from all

analyses. 1,280 and 1,296 trials from the triangle and horizontal conditions, respectively, with response times (RTs) $< 100\text{ms}$ or $> 10000\text{ms}$ were also excluded from all analyses, leaving 18,069 and 18,054 trials remaining in the triangle and horizontal conditions, respectively.

2.2.1.2 Stimuli.

Stimuli were gray scale rectangles based on Trueblood et al. (2013) and Spektor et al. (2018).

Stimuli varied based on trial type. The experiment had two types of trials: critical trials and catch trials.

On each critical trial, the target and competitor had the same area¹ but differed on orientation, with one stimulus being wide and the other tall. The decoy always had the same orientation as the target. TDD was varied so that the decoy was always 0%, 2%, 5%, 9%, or 14% of the target area. Because the target and competitor always had the same area, this means that the decoy was also 0%, 2%, 5%, 9%, or 14% of the competitor area. These are the TDD values from Spektor et al. (2018), plus a 0% level which acted as a baseline².

On each catch trial, there was one large rectangle and two much smaller rectangles. The large rectangle was $260 \pm U(-40, 40)\text{x}200 \pm U(-40, 40)\text{px}^2$, with a random orientation. The smaller rectangles were $180 \pm U(-40, 40)\text{x}120 \pm U(-40, 40)\text{px}^2$, one wide and one tall.

2.2.1.3 Design.

There were 5 blocks of trials. In each block there were 60 critical trials, 12 at each TDD level, and 30 catch trials. Of the 12 critical trials at each TDD level,

¹Here Spektor et al. (2018)'s design was simplified as both focal stimuli had the same area.

²When TDD=0%, the target and decoy are identical, so labeling is arbitrary.

6 trials were presented in the triangle display and 6 trials were presented in the horizontal display. Finally, 3 of the 6 targets in each display condition at each TDD level were wide and 3 were tall. Of each of these 3 trials, one trial was a target-decoy comparison, one trial was a target-competitor comparison, and one trial was a competitor-decoy comparison. Trial order and rectangle order within each trial were randomized. Thus, this was a 5 (TDD: 0%, 2%, 5%, 9%, 14%) x 2 (display: triangle, horizontal) x 2 (target-decoy orientation: wide, tall) x 3 (comparison: target-decoy, target-competitor, competitor-decoy) within-participants design.

2.2.1.4 Procedure.

On each trial, participants saw three rectangles, labeled 1, 2, and 3 (from left to right). The horizontal distance between all rectangles was constant, but 25 pixels of jitter was added to each rectangle's vertical location. The rectangles appeared for 1825ms total, but after 500ms, two of the rectangles changed to a darker shade. Next, all three rectangles disappeared from the screen, and participants were asked to select which of the two darker rectangles had the larger area. The procedure was identical for critical trials and catch trials.

Stimuli were presented on computer monitors with a resolution of 1920 x 1080 pixels. The experiment was programmed in jsPsych (De Leeuw, 2015).

2.2.2 Results

2.2.2.1 Catch Trials.

Participants performed well on the catch trials. The mean percentage correct in the triangle display was 92.6%($SD = 3.77$), and the mean percentage correct in the horizontal display was 93.2%($SD = 3.52$).

2.2.2.2 Critical Trials.

First the baseline TDD level data (TDD=0%) are presented to demonstrate that participants were indifferent between pairs of options when they had identical area. The mean percentage of target choices in target-competitor trials was 48.99% (SD=10.18, 95% CI [46.80, 51.20]). The mean percentage of competitor choices in competitor-decoy trials was 49.80% (SD=11.30, 95% CI [47.40, 52.20]). The mean percentage of target choices in target-decoy trials was 49.47% (SD=12.06, 95% CI [46.90, 52.10]). Participants were indifferent between all pairs of options in the TDD = 0% trials, so these are not considered further.

Next, the target-competitor trials are presented. Note that in these trials, because both stimuli had the same area, there is no correct response. The results are plotted in Figure ??, with the y axis (arbitrarily) showing the mean proportion of target selections. Though participants were occasionally biased to select either the target or competitor, there was no systematic pattern to their choices, and these data are not discussed further.

The primary analysis was performed on the target-decoy and competitor-decoy trials, excluding all TDD=0% trials and the target-competitor trials. Note that participants were to select the option with the largest area. Because the target and competitor were always equal in size, and larger than the decoy, a correct response was one in which the decoy was not chosen.

Mean choice proportions across conditions are shown in Figure ???. Participants' performance indeed improves with TDD. Furthermore, their performance is better when stimuli are displayed in the horizontal configuration than in the triangle configuration, and it is also better in target-decoy trials compared to competitor-decoy trials. Finally, there is an interaction, such that as TDD increases, the target-decoy performance is even better than the competitor-decoy performance. See the Appendix for inferential statistics which support these conclusions.

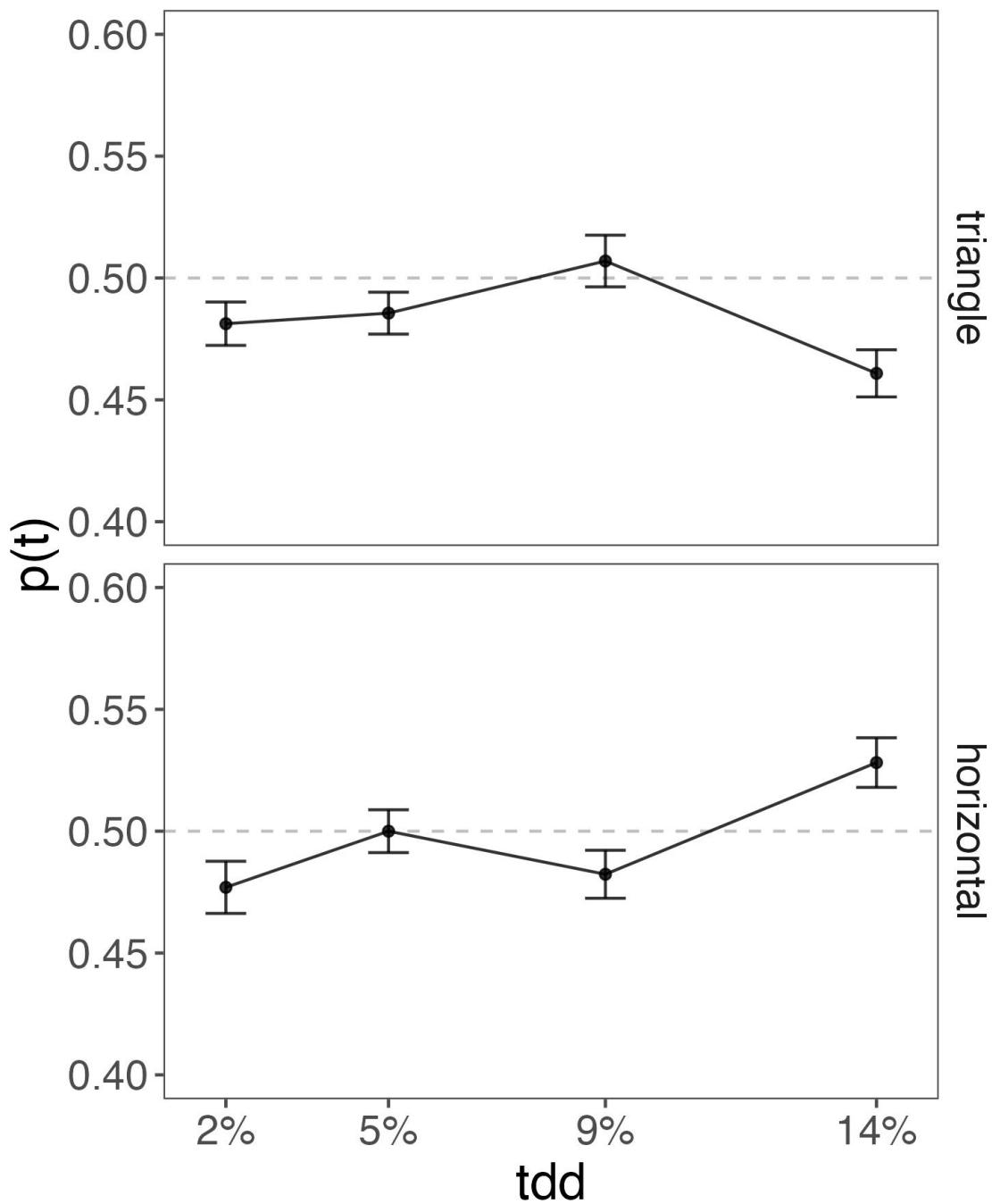


Figure 2.4. Experiment 1, mean target choice proportions by stimulus display and TDD for all target-competitor trials. Dashed line is shown at .5.

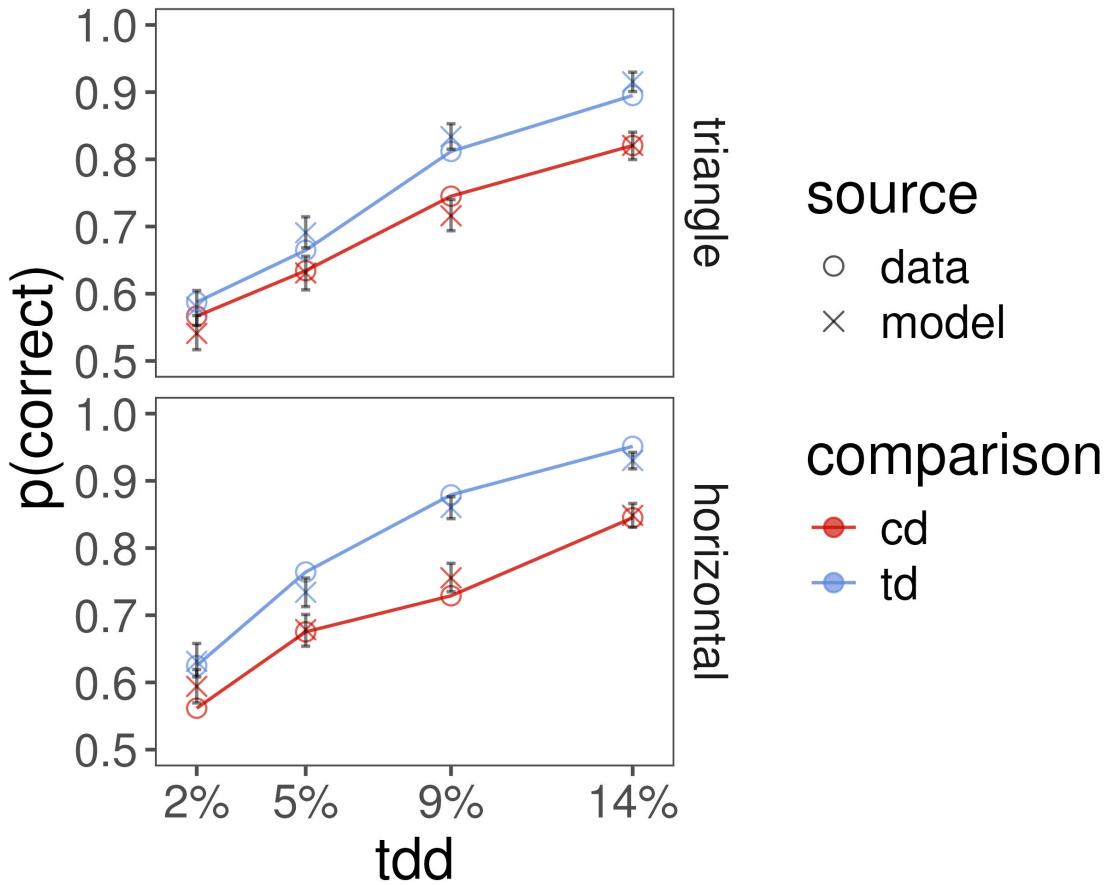


Figure 2.5. Experiment 1, mean choice proportions by stimulus display, TDD, and comparison. td=target-decoy trials, cd=competitor-decoy trials. Model predictions come from the Bayesian hierarchical logistic regression presented in the Appendix and are presented to demonstrate that the model used for inference adequately fits the data. Error bars are 95% HDIs on the mean.

2.2.3 Discussion

The goal of Experiment 1 was to test participants' ability discriminate between target-decoy and competitor-decoy stimuli in binary perceptual choice. Though participants choose the decoy at non-trivial rates in ternary choice (see Figure ??), previous researchers have not tested participants' binary discriminability.

Experiment 1 showed that participants are not always able to discriminate between target-decoy and competitor-decoy stimuli. Additionally, this discriminability increases with TDD and that overall discriminability is better in the horizontal compared to the triangle display. Finally, through the interaction of comparison and TDD, it was shown that target-decoy discriminability increases with TDD at a higher rate than competitor-decoy discriminability.

These results are important because they show that target-decoy (and indeed, competitor-decoy) discriminability cannot be taken as a given in perceptual context effect experiments. Researchers must carefully consider how perception of the decoy affects choice. The role of perception is theoretically important because any conclusions about context effects being fundamental to choice (Trueblood et al., 2013) rely on the assumption that context effects are qualitatively similar across choice domains.

In the next section, a Thurstonian perceptual choice model is introduced, with the goal of using it to understand the attraction and repulsion effect.

2.3 Modeling Context-Dependent Perceptual Choice

Spektor et al. (2018) argued that their work provides partial evidence in favor of the tainting hypothesis, the idea that decoys sometimes "taint" the value of nearby targets, leading to a repulsion effect. They argued that this is supported by the decrease in competitor choice share as TDD increases. They did note that this high level explanation seems implausible for a perceptual rectangle task.

Another plausible account of Spektor et al. (2018)'s data is that participants occasionally perceive the decoy to be at least as large as, or larger than, the target. Indeed, the target and decoy are perceptually similar, more so than the decoy and competitor. Their results may be another form of the similarity effect (Tversky, 1972), where a similar decoy causes a decrease in the choice share of a target option. Simply put, participants may occasionally select the decoy over target, and they do so more often than they select it over the competitor. This account is consistent with the data shown in Figure ???. As TDD increases, decoy choices decrease while target choices increase. Though competitor choices also increases with TDD, the target choice shares increase at a higher rate. There appears to be a strong tradeoff between target choices and decoy choices. This explanation is, however, distinct from theoretical accounts of the attraction effect. Spektor et al. (2018) dismiss such an account because the target was always chosen more often the decoy. This does not, however, rule out that possibility that, on the trials where the decoy was chosen, it was more likely to be chosen over the target than the competitor. In other words, participants do not always select the decoy; however, when they do, they more often select it over the similar target than the dissimilar competitor.

One goal of this work is to separate the role of perceptual and decisional processes in context effects. To do so, we begin with an extreme stance - that such experiments are solely perceptual experiments rather than decision-making experiments and that no high level decision processes are occurring. This extreme assumption is quite likely incorrect, but it may be helpful in understanding existing data. For example, if a perceptual model can account for the repulsion effect without incorporating higher-level decision processes, (such as loss aversion or attribute weighting, as invoked by some cognitive models of context effects), this provides evidence that the repulsion effect is not a decision-making phenomenon, but a perceptual one. On the other hand, if perceptual processes explain part, but not all, of the repulsion effect, this

provides evidence that higher-level decision processes must be invoked in a complete theoretical account of these data.

There is a large body of psychological research, beginning with the work of Thurstone (1927), which treats the stimulus perception as a random variable. In his famous "Law of Comparative Judgment" paper, Thurstone (1927) showed that researchers can use binary choice proportions to estimate the psychological distance between stimuli, by treating perceptual intensity as a Gaussian random variable. According to Thurstone's models, given a proportion of the trials on which participants were able to discriminate between two stimuli, researchers can estimate the average psychological distance between these perceptions, scaled by their standard deviations. Thurstone considered multiple forms of this model, but the most relevant model is his Case *II* model, which allows for correlations between perceptions. Models of this class are often called *Thurstonian*.

Thurstone's work has been particularly influential on the choice modeling literature. In marketing and economics, researchers treat the utilities of choice options as random variables, which are often assumed to be Gaussian or Extreme Value Distributed and estimate choice models known as Random Utility Models (RUMs) (Hausman & Wise, 1978; McFadden, 2001; Train, 2009). Often, though not necessarily, these models share the common property that value - be it the utility of a consumer product, the perception of magnitude in a perceptual task, or memory signal in a recognition task - is stochastic while choice is deterministic (c.f. Benjamin et al. (2009)).

Based on this research, we consider the Thurstonian choice model which will be applied to perceptual choice. This model treats the experiments of Trueblood et al. (2013) and Spektor et al. (2018) as perceptual tasks, rather than decision tasks. This assumption may be incorrect, but the extent to which it can explain existing data can still be highly informative. According to this model, the perceived areas

of each rectangle on each trial are sampled from an underlying multivariate probability distribution. Participants then deterministically choose the option with the largest perceived area. Thus, while perception is stochastic, choice is deterministic.

2.3.1 A Thurstonian Choice Model

In a perceptual choice task such as that of Spektor et al. (2018), the value/utility of each option is its perceived area. According to the model, on each trial i with choice set K , the perception \mathbf{X}_i of all 3 stimuli is sampled from a multivariate Gaussian distribution:

$$\mathbf{X}_i \sim \mathcal{N}(\boldsymbol{\mu}, \boldsymbol{\Sigma}) \quad (2.1)$$

where $\boldsymbol{\mu}$ is the column vector:

$$\begin{pmatrix} \mu_T \\ \mu_C \\ \mu_D \end{pmatrix} \quad (2.2)$$

where the subscripts T , C , and D indicate target, competitor, and decoy, respectively.

$\boldsymbol{\Sigma}$ is a positive semi-definite 3x3 covariance matrix computed by:

$$\boldsymbol{\Sigma} = S\boldsymbol{\Omega}S \quad (2.3)$$

where S is a diagonal matrix consisting of:

$$\begin{pmatrix} \sigma_T & 0 & 0 \\ 0 & \sigma_C & 0 \\ 0 & 0 & \sigma_D \end{pmatrix} \quad (2.4)$$

with σ_T , σ_C , σ_D denoting the standard deviations for target, competitor, and decoy, respectively. These parameters reflect the extent to which area perception varies from trial to trial for each stimulus type. Ω is a 3x3 correlation matrix:

$$\begin{pmatrix} 1 & \rho_{TC} & \rho_{TD} \\ \rho_{TC} & 1 & \rho_{CD} \\ \rho_{TD} & \rho_{CD} & 1 \end{pmatrix} \quad (2.5)$$

with ρ_{TD} , for example, denoting correlation between target and decoy perception. These parameters measure the extent to which area perceptions "move" together for certain pairs of stimuli. For example, as will be shown below, the target and decoy perceptions are strongly positively correlated, meaning that on trials where the target is perceived to be relatively large, the decoy will also tend to be perceived relatively large.

As mentioned above, the model assumes that value is stochastic while choice is deterministic³. The model always chooses the option perceived as largest, regardless of the magnitude of the difference between the "winner" and "runners-up". That is, given a vector \mathbf{X}_i of perceived areas on trial i with set K , the probability a participant selects stimulus j as largest is:

³This also assumes ties are not possible, which is true if and only if perceived area is absolutely continuous.

$$P(j|i, K) = P(\mathbf{X}_{ij} > \mathbf{X}_{ik}), \forall k \in K, j \neq k \quad (2.6)$$

If all correlations = 0 and $\sigma_T = \sigma_C = \sigma_D$, the model collapses to a trivariate version of the standard Thurstonian Case V model (Thurstone, 1927) often used by cognitive psychology researchers. Models of this form have closed form solutions and their predictions are easy to compute.

On the other hand, if any correlations are non-zero, the closed form solution of this model does not exist, and to compute predictions and estimate model parameters, researchers must use simulation or numerical integration methods (Train, 2009).

This model is easily capable of generating a(n) attraction (repulsion) effect by assuming $\mu_T > \mu_C$ ($\mu_C > \mu_T$), i.e., that on average target and competitor stimuli differ in their perceived areas. This is an ad hoc assumption that may describe the data well but will generate limited theoretical insight.

On the other hand, the correlations between perceived area, may allow the model to predict context effects. Other researchers have considered correlations in RUMs as a mechanism for context effects. Kamakura and Srivastava (1984) argued that the correlation between a pair of options in the multinomial probit model reflect their similarity, or substitutability. They implemented a model where the correlation between options is parameterized as a decreasing function of their distance in attribute space. They showed, via simulations, that this model is able to successfully predict the similarity effect. They also fitted the data to risky choice data, which were collected using stimuli designed to elicit the similarity effect, and found that the fitted model could successfully account for the data.

Natenzon (2019) implemented a Bayesian probit model, in which participants are assumed to sample from a multivariate normal distribution on each trial, with the correlation between options being related to their similarity in multiattribute space.

Natenzon (2019) also suggested that similarity is related to ease of comparability. They fitted the model to frog mating choice data and showed that not only can the model explain choice reversals (i.e., context effects), but the estimated correlations between pairs of options were greater for options closer in multiattribute space.

It is worthwhile considering then, the role of correlations (i.e., ρ_{TC} , ρ_{TD} , and ρ_{CD}) in predicting the attraction and repulsion effects in perceptual choice.

ρ_{TD} and ρ_{TC} were varied from -1 to 1; in other words, all rectangles oriented the same way (i.e., target and decoy) shared one correlation and those oriented differently (i.e., target and competitor, decoy and competitor) shared another correlation. These model predictions are shown in Figure ???. It was assumed that $\mu_T = \mu_C > \mu_D$ and that $\sigma_T = \sigma_C = \sigma_D$ ⁴. It is difficult to assess how all parameters may interact if these assumptions are incorrect.

Figure ??? shows model predictions in the form of RST⁵, where RST values above .5 indicate an attraction effect and values below .5 indicate a repulsion effect. The model can, depending on the relationship between ρ_{TD} and ρ_{TC} , predict a repulsion, attraction, or a null context effect.

First, if $\rho_{TD} = \rho_{TC} = \rho_{CD}$, the model predicts a null effect. In this case, no pair of stimuli are more correlated than any other pair, so the predictions are identical to a model where $\rho_{TD} = \rho_{TC} = \rho_{CD} = 0$. The decoy will still be chosen occasionally (depending on the relative difference between μ_D and μ_T / μ_C), it does not differentially take choice shares away from the target or competitor.

If $\rho_{TD} > \rho_{TC}$, the model predicts a repulsion effect. The correlation between target and decoy causes them to "move" together. If, on a particular trial, the perceived target area is relatively high, the perceived decoy area will also be relatively

⁴Experiment 2 presents evidence supporting these assumptions.

⁵Recall that RST is *Relative Share of the Target*, reflecting the proportion of trials in which the target is chosen over the target, conditional on not having selected the decoy.

high. Though the decoy is chosen at a lower rate than target or competitor, the ρ_{TD} parameter causes it to be chosen over the target more often than it is chosen over the competitor.

Lastly If $\rho_{TC} > \rho_{TD}$, the model predicts an attraction effect. The logic here is the similar to the above logic; the decoy and competitor tend to move together, and the decoy is more likely to exceed the competitor than the target.

2.3.2 Perceptual Correlations as Mechanism for the Repulsion Effect

These perceptual correlations, which cause the decoy to occasionally exceed the target in perceived area, may be, at least partially, driving the repulsion effect in Spektor et al. (2018)'s data.

Experiment 1 demonstrated that participants do not always discriminate between the target and decoy (or indeed, competitor and decoy). Experiment 1 also demonstrated the triangle display decreases discriminability relative to the horizontal display.

The target and decoy, however, are quite perceptually similar and easier to compare. Simultaneously, however, the fact that target and decoy share an orientation (i.e., both wide or both tall) makes the comparison of these two options easier. At lower levels of TDD, when discriminability is quite difficult (i.e., the difference between μ_D and μ_T/μ_C is small), the similarity of target and decoy makes it more likely the decoy is occasionally perceived as larger than the target, than the competitor. I

In statistical terms, the perception of the decoy is more strongly correlated with the perception of the target than with perception of the competitor. These correlations are measured with the ρ_{TD} and ρ_{CD} parameters. According to this account, if $\rho_{TD} > \rho_{CD}$, the perceived areas of target and decoy "move" together, allowing the competitor to exceed the target at a higher rate than the target exceeds the competitor, particularly if perceptual discriminability is low. This account explains

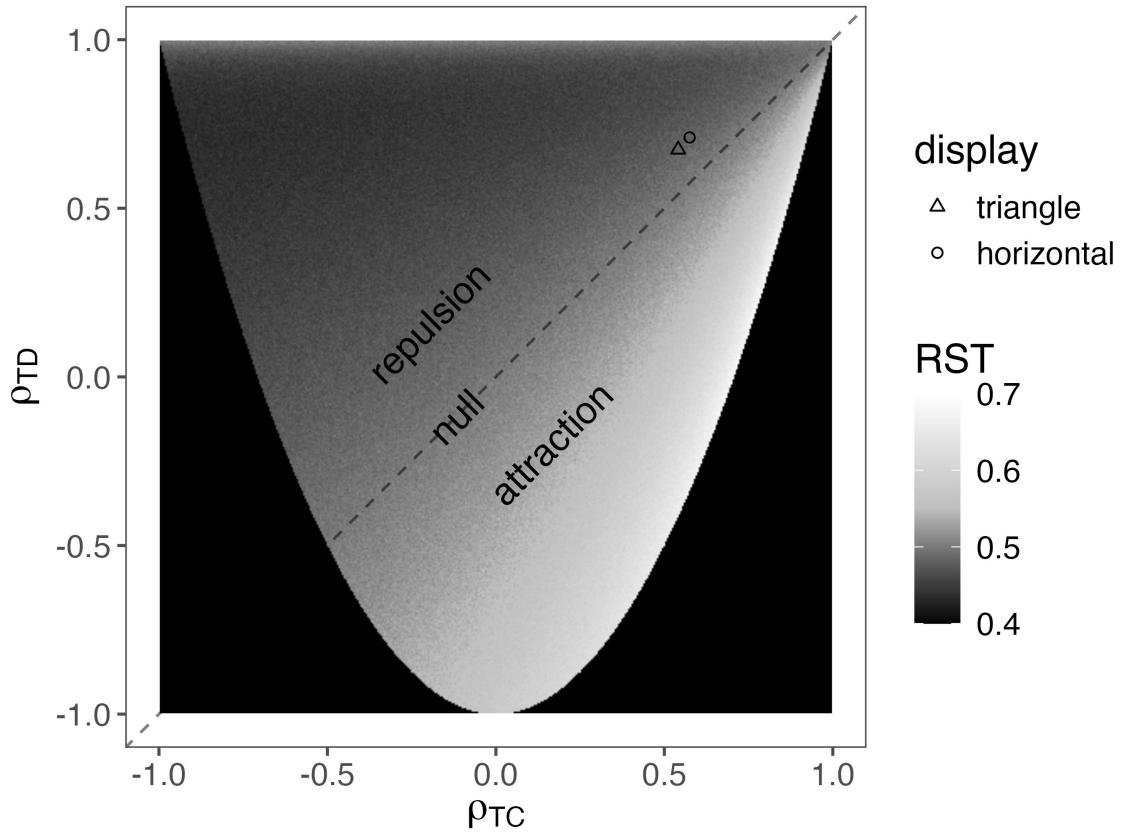


Figure 2.6. Model simulations for the attraction and repulsion effects based on the variation of ρ_{TD} and ρ_{TC} . "Regions" of the plot are labeled based on their qualitative predictions for attraction, null, and repulsion effects. The black region is the area where, due to extreme correlations, a positive semi-definite variance-covariance matrix could not be formed and predictions are unavailable. The triangle and circle mark the estimated mean correlations from the Experiment 2 triangle and horizontal conditions, respectively (see below for details).

the repulsion effect as a perceptual phenomenon rather than a decision-making phenomenon.

Experiment 2, shown below, combined a psychophysics task with a choice task to estimate the parameters of the Thurstonian perceptual model outlined in the beginning of this chapter. In the first phase of the experiment, participants estimated the size of target, decoy, and competitor rectangles on each trial. The second phase of the experiment was a standard choice exxperiment, replicating Spektor et al. (2018)'s results. The data from the first phase of Experiment 2 were used to obtain stable estimates of μ and Σ for the Thurstonian perceptual model. Finally, the model, conditioned on these parameter estimates, naturally predicts a repulsion effect but not an attraction effect.

2.4 Experiment 2

The goal of this experiment was to estimate the parameters of the model presented above and to clarify the role of perception and decision in producing the repulsion and attraction effects. The Thurstonian model introduced above can predict the repulsion effect and the attraction effect through the perceptual correlation parameters. However, this model can produce many different data patterns (as shown in Figure ??), some of which may be consistent with existing choice data but many others which are not. Thus this experiment allows us to estimate the model parameters using a non-decision task.

Furthermore, participants also separately completed a choice task, replicating Spektor et al. (2018). This allows us to estimate the parameters of the model using the judgment task and then test the model's ability to predict the results of the choice task.

Experiment 2 utilized the *method of cross-modal matching* (Stevens & Marks, 1965), where participants estimate the intensity of a stimulus presented in one modal-

ity using a different response modality (e.g., estimating the loudness of a tone by adjusting the brightness of a light). Participants adjusted the size of a circle to match the perceived area for each rectangle.

The experiment Spektor et al. (2018)'s choice data in the second phase of the experiment. In both phases, there was between-participants manipulation to display the rectangle stimuli in either the horizontal or triangle displays of Spektor et al. (2018).

2.4.1 Methods

2.4.1.1 Participants.

Data collection took place at the University of Massachusetts Amherst. 521 undergraduate students participated in exchange for course credit. 68 participants did not complete the full experiment within the 1 hour time limit and were removed from all analyses. 10 additional participants were failing at least 2/8 catch trials from the circle adjustment phase (see below).

After removing participants, this left 218 participants in the horizontal display condition and 225 participants in the triangle display condition.

Choice trials with RTs < 100ms or > 10,000ms were removed from analysis.

2.4.1.2 Stimuli.

Stimuli were gray-scale rectangles, based on the experiments of Spektor et al. (2018) and Trueblood et al. (2013).

Both the circle adjustment phase and the choice phase (see below) had critical trials, the main focus of the experiment. On each critical trial, there was a target, competitor, and decoy rectangle. The target and competitor rectangles were always oriented differently (i.e., one wider than tall and the other taller than wide), while the decoy was oriented the same as the target. Target-decoy distance (TDD) also varied, with the decoy being either 2%, 5%, 9%, and 14% smaller than the target

and competitor. For example, if TDD=2%, then the decoy’s area is $\approx 98\%$ the area of the target and competitor. Decoys were created by reducing both the height and width. For example, on the lowest diagonal (see below), the target and competitor had dimension values of 60 and 135 px, and the TDD=2% decoy had dimension values of 59 and 134 px. Decoys where both dimension values are lower than that of the target are known as range-frequency decoys in the context effects literature (Wedell, n.d.).

To introduce variation in the stimuli, the absolute area of the target and competitor also varied. The target and competitor were either 8100, 14850, or 23400 px² (with the decoy area changing proportionally based on TDD), falling along one of three diagonals when plotted. See Figure ?? for a plot of all critical stimuli. In pixels, the smaller/larger dimension values on the lower, middle, and upper diagonals were 60/135, 90/165, and 120/195, respectively.

Participants were randomly assigned to either the triangle or horizontal display condition, where, on each trial both rectangles and circles were either arranged in a triangle or in a horizontal array.

The experiment also contained filler trials (see below). On filler trials, stimuli were randomly generated by independently sampling three rectangles’ dimension values from the distribution $U(56, 195)\text{px}$, the full range of dimension values from the critical trials, where 56px is the smallest decoy dimension value and 195 is the largest target/competitor dimension value.

On the catch trials, one larger stimulus was generated by sampling uniformly from the upper diagonal line from the critical trials (see Figure ??). Two additional smaller stimuli were generated by sampling uniformly from the lower diagonal line from the critical trials (see Figure ??). This ensured that one rectangle was always larger than the other two rectangles and allowed for the removal of participants who could not complete the task. Specifically, on a given trial, a participant who did not judge the

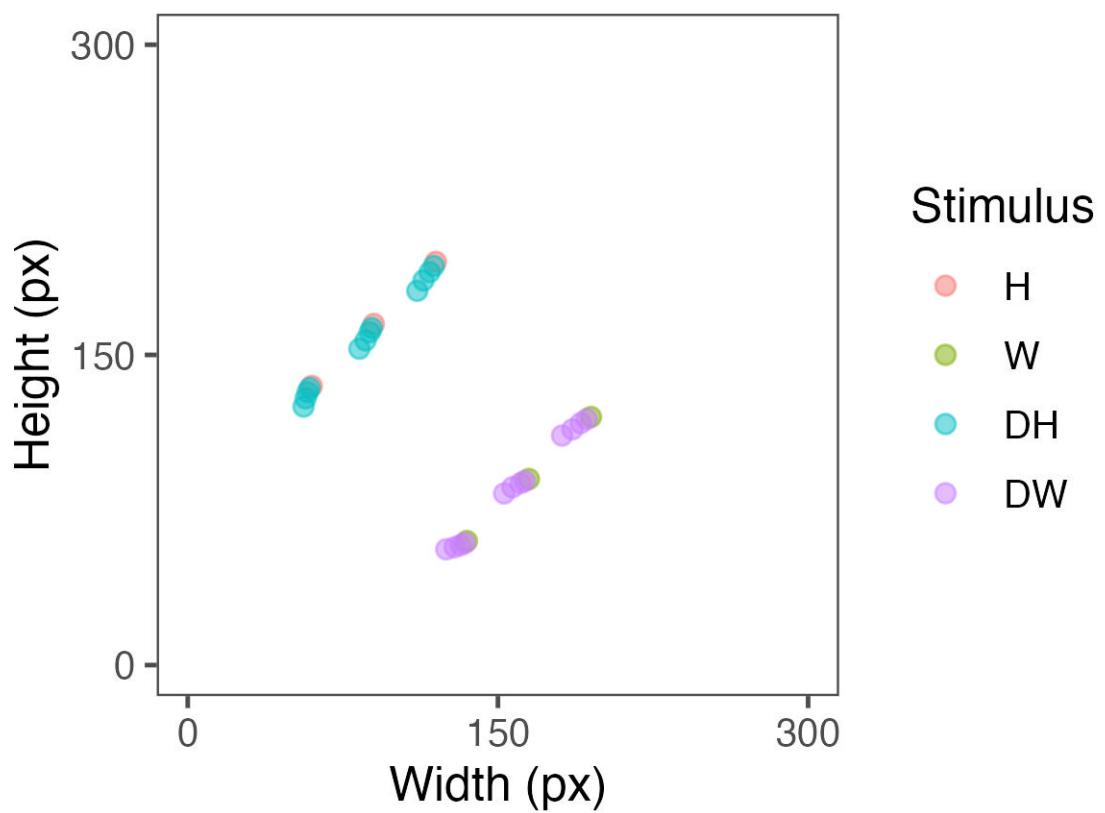


Figure 2.7. Stimulus configuration for Experiment 2.

larger rectangle to be greater in area than the other two rectangles was considered to have "failed" this trial. Only participants who passed 6/8 judgment catch trials were retained in the analysis (see above).

The choice phase had identical stimuli with the exception that there were no catch trials, only critical and filler trials. Additionally, there were no circles in this phase (see below).

2.4.1.3 Design.

Across both phases, display condition (triangle, horizontal) varied between-participants and TDD (2%, 5%, 9%, 14%), diagonal (lower, middle, upper), and target-decoy orientation (wide, tall) varied within-participants.

In the circle adjustment phase, there were 4 blocks, each with 40 trials. Each block consisted of 24 critical trials, 14 filler trials, and 2 catch trials. Within the critical trials, there were 6 trials at each level of TDD. In 3 of these 6 trials the target and decoy were oriented wide (choice set $[W, H, D_W]$), and in the other 3 target and decoy were oriented tall (choice set $[W, H, D_H]$).

In the choice phase, there were 4 blocks, each with 34 trials. 24 of these trials were critical trials and 10 were filler trials. Of these 24 critical trials, there were 6 trials at each level of TDD. Within each 6, there were 3 trials where target and decoy were oriented wide and 3 were target and decoy were oriented tall.

2.4.1.4 Procedure.

The experiment was presented on computer monitors with a resolution of 1920 x 1080 pixels and programmed with GNU Octave (Eaton et al., 2021) and PsychoPhysics Toolbox (Brainard, 1997).

The experiment took place in two phases: a circle adjustment phase, followed by a choice phase:

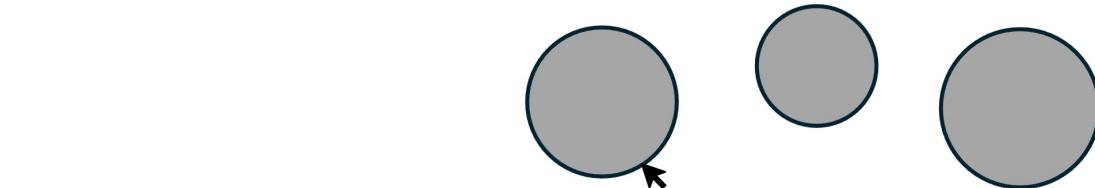
On each circle adjustment trial, participants saw three rectangles and three circles, each labeled 1, 2, and 3. The rectangles appeared in the lower left corner of the screen, either in a triangle or horizontal display, depending on the condition to which the participant was assigned. The circles appeared in the upper right of the screen, in the same display as the rectangles (see Figure ?? for a sample trial). Stimuli were positioned this way to ensure that participants could not easily compare the circles to the rectangles. A small amount of jitter ($U(-15, 15)px^2$) was also added to the vertical position of each rectangle and the corresponding circle. Each circle appeared with an area of $78px^2$, the minimum size allowed in the experiment.

Participants were told to adjust the size of each circle until it had the same area as the rectangle with the corresponding label. They used the mouse to adjust the circles. They were not given instructions on the order they should adjust the circles in or the time they were to spend on the adjustments. The maximum circle area allowed was $65144px^2$ ²⁶, and the minimum area was $78px^2$. When a participant finished adjusting the circles on a trial, they clicked the "Submit" button located on the lower right hand corner of the screen and advanced to the next trial.

The circle adjustment phase began with three calibration trials. Calibration trials were identical to filler trials, with the caveat that participants received feedback after their responses. After participants submitted their responses on a calibration trial, a red circle appeared around each adjusted circle, showing the true area of the corresponding rectangle.

²⁶This was the maximum area the circles could be while only appearing on the right half of the screen and maintaining the same horizontal distance from each other as the corresponding rectangles. The minimum possible rectangle area in the experiment was $3136px^2$, while the maximum possible area was $38025px^2$. Thus the range of possible responses was well within the true area of all rectangles.

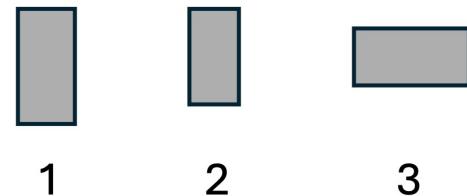
A



1

2

3



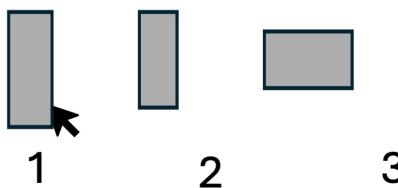
1

2

3

SUBMIT

B



1

2

3

Click on the rectangle with the
largest area.

Figure 2.8. Example trials from Experiment 2. A: Circle adjustment phase. B: Choice phase. This is an example from the horizontal display condition.

After the calibration trials, the experimental circle adjustment trials began. There were 4 blocks of experimental trials. At the beginning of each block, participants completed 3 calibration trials.

At the end of each block, participants were told that they were either over or under-adjusting, on average, based on the current mean deviation of their responses from the true areas. They were not told the magnitude of their over/under-estimation.

After the circle adjustment phase, the choice phase began. During the choice phase, participants were shown three rectangles on each trial and asked to select the rectangle with the largest area. They were told that they would know their percentage of correct choices at the conclusion of the experiment.

The choice phase began with 3 practice trials, which were identical to the filler trials but separate from the experiment. Participants did not receive feedback during choice practice trials.

At the end of the choice phase, participants were told their percentage of correct choices. Note that in a critical trial, a correct response is one where the participant did not select the decoy, given that the target and competitor rectangles always had the same area.

In both the circle phase and the choice phase, stimulus order was randomized on each trial.

2.4.2 Results

2.4.2.1 Data Processing

These data required processing to ensure that no outliers influenced estimates of μ or Ω , as it is widely known that outliers can detrimentally influence correlation estimates.

The most substantial data processing occurred in the circle phase data, so these are discussed first.

First, all trials where at least one circle was not adjusted (i.e., at least one circle was left at the starting size) were removed. Given the discrepancy between the starting circle area (78px^2) and the smallest rectangle area shown in the experiment ($3,136\text{px}^2$), these are unlikely to be representative of any participant's true perception of rectangle area.

Next, outlier participants were removed, followed by outlier trials from the remaining participants. An outlier participant is a participant whose responses are substantially different from most other participants, while an outlier trial is a trial, from a valid participant, which differs substantially from the rest of a given participant's trials. Outlier participants were first removed, and then outlier trials were removed from the remaining participants.

Outlier participants were identified and removed using the following procedure:

Each individual participant's data were log-transformed⁷. Each participant's data were then fit to a linear regression, regressing each log circle area on each corresponding log rectangle area. Participants whose corresponding R^2 value fell below the 5% quantile for all R^2 s (.3975 in this case) were removed from all analysis. The 5% quantile was chosen arbitrarily as a conservative threshold to ensure maximum participant retention while removing outliers.

This procedure removed 23 participants, leaving $N = 420$ participants, 213 in the triangle display condition and 207 in the horizontal display condition. Of the remaining participants, R^2 values were high ($M = .67, SD = .12$), indicating that participants could generally perform the task.

Next, outlier trials were identified and removed using the following procedure:

From the 420 participants whose data were analyzed, outlier trials were removed from the critical trial data. All data points were then z-transformed within each

⁷This was done to reduce the skewness observed in the raw data.

participant and diagonal⁸. All critical trials with at least one z-score with an absolute value above 3.5 were dropped, removing a total of 102 trials. This removed 0, 1, 2, and 4 critical trials from 339, 62, 18, and 1 participants, respectively. This left 20371 data points in the triangle display condition and 19809 data points in the horizontal display condition, where a data point is a vector of the participant’s estimated target, competitor, and decoy areas on a given trial.

Only those participants whose data were retained in the circle adjustment phase were retained in the choice phase.

2.4.2.2 Circle Adjustment Phase Results

First, it is important to show that participants could adequately perform the adjustment task. The mean difference between actual log area and estimated log area was computed for each participant, stimulus pair (i.e., target-competitor, target-decoy, competitor-decoy), and actual difference. These results are plotted in Figure ???. The x axis shows the actual difference between areas, while the y axis shows the estimated difference in areas according to participants’ judgments. Participants’ judgments varied considerably along the y axis, but on average, the estimated difference increased with the actual difference.

Next scatterplots of all pairwise circle area estimations are shown in Figure ???.

Correlation coefficients in each display condition were also computed. For the triangle condition, $r_{td} = .61$, $r_{cd} = .54$, and $r_{tc} = .55$. For the horizontal condition, $r_{td} = .66$, $r_{cd} = .56$, and $r_{tc} = .57$. In both conditions, the target-decoy correlation is stronger than both the competitor-decoy and the target-decoy correlations.

Bayesian hierarchical modeling was used to estimate the parameters of the Thurstonian perceptual model introduced earlier, as well as perform inference on the means and correlations. Though the descriptive parameter estimates are also reported, the

⁸This was done solely for the removal of outliers, not for the substantive analysis that followed.

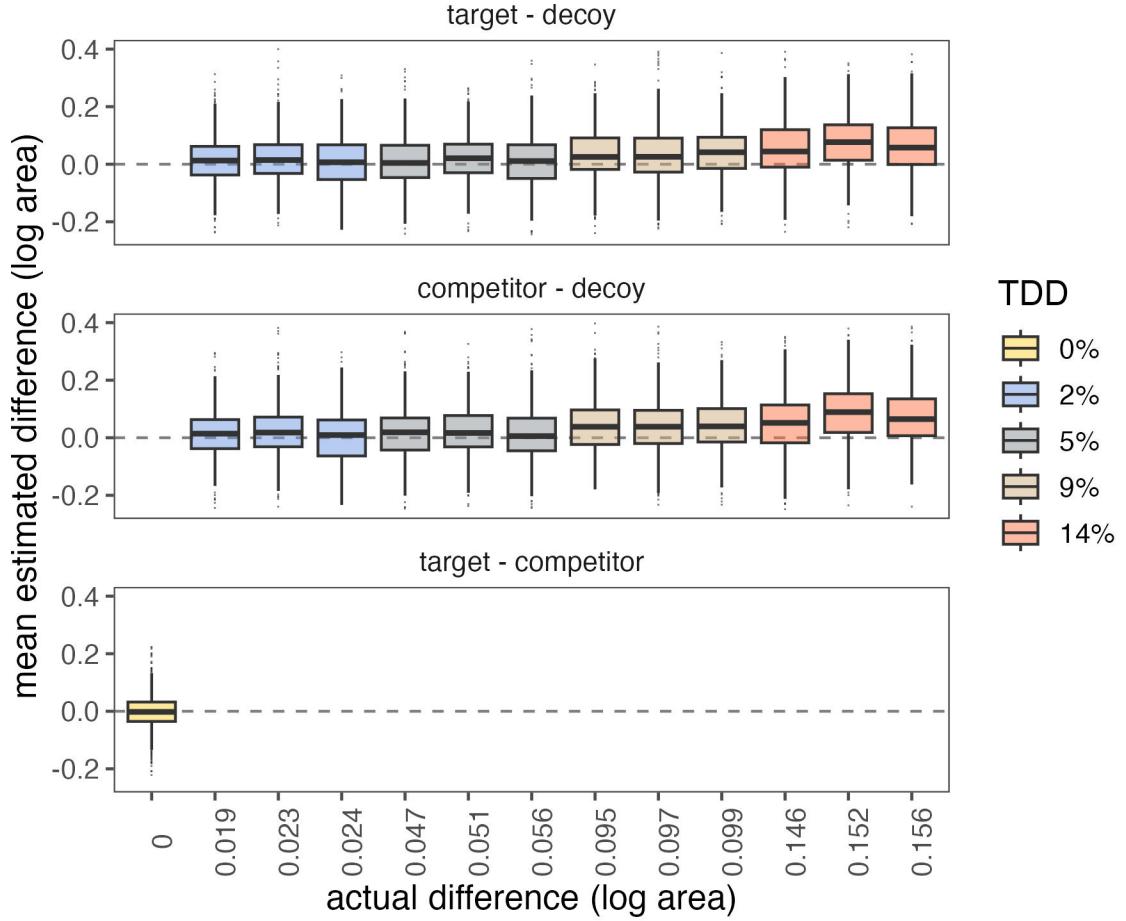


Figure 2.9. Experiment 2 plots of subject-level mean error in log-transformed area estimations, split by stimulus pair (e.g., target-decoy), TDD, and actual difference in rectangle area. Because the difference in physical area at a given TDD differed across the three diagonals, there are three plots per each TDD level. Note that because the target and competitor rectangles always had equal areas, the true difference is always 0.

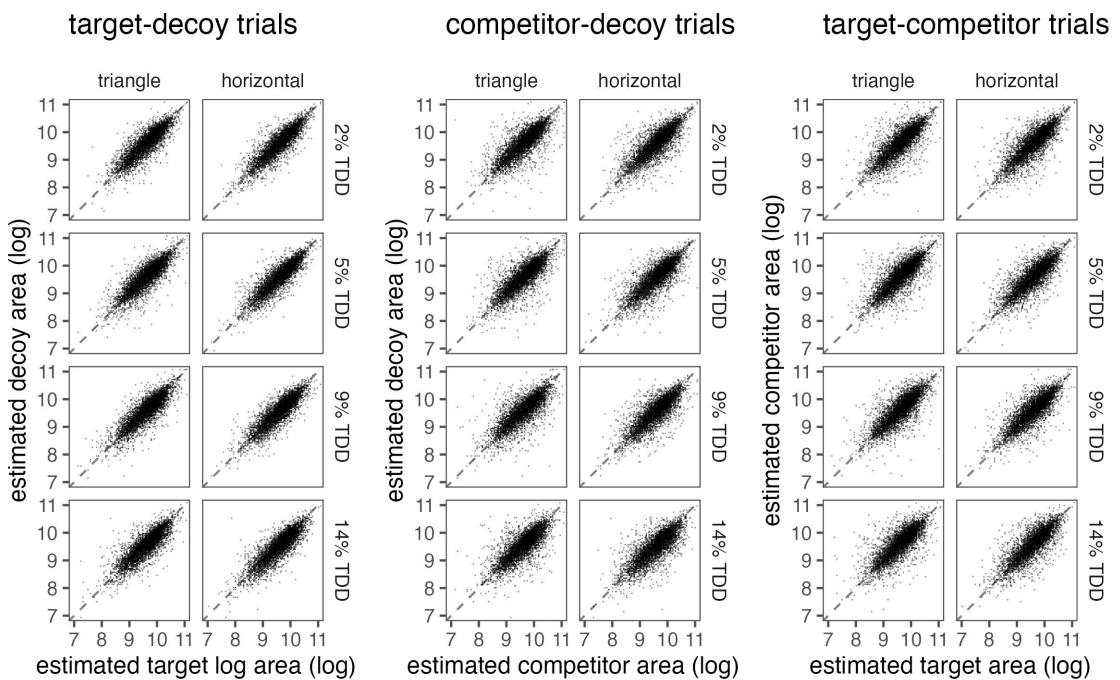


Figure 2.10. Scatterplots of target-decoy (left), competitor-decoy (middle), and target-competitor (right) log estimated areas, split by display condition (columns) and TDD (rows).

Bayesian analysis allows estimating the posterior distributions on each relevant parameter and comparing the range of plausible values across parameters and conditions. Furthermore, the Bayesian hierarchical modeling also takes into account participant-level differences in area estimation.

As an alternative to computing descriptive statistics for the relevant components of a multivariate Gaussian (i.e., computing raw means, variances, and correlations), the Bayesian analysis allows us to model the obtained trial-level area judgments as coming from a single joint Gaussian distribution of estimated areas. Additionally, this is also a novel application of the multinomial probit (MNP) model, whose parameters are usually estimated by inferring utilities from choice data (Train, 2009). In the current application, the parameters are estimated from the judgment data using Bayesian modeling and used to predict choice data, which were collected from the same participants.

The main text contains estimates of μ and Σ (the vector of means and the variance-covariance, respectively), while the details of the estimation procedure are found in the Appendix. As discussed above Σ is a positive semi-definite variance-covariance matrix, computed as $\Sigma = S\Omega S$, where S is a vector of standard deviations and Ω is a 3x3 correlation matrix.

The estimates of S suggest no systematic differences in the variance of area judgments variance across target, decoy, and competitor rectangles. In the triangle condition, the parameters were as follows: $\sigma_T: M = 0.34, SD = 0.002, 95\% \text{ HDI} [0.332, 0.338]$, $\sigma_C: M = 0.34, SD = 0.002, 95\% \text{ HDI} [0.335, 0.341]$, $\sigma_D: M = 0.34, SD = 0.002, 95\% \text{ HDI} [0.331, 0.338]$. In the horizontal condition, the parameters were as follows: $\sigma_T: M = 0.34, SD = 0.002, 95\% \text{ HDI} [0.334, 0.340]$, $\sigma_C: M = 0.34, SD = 0.002, 95\% \text{ HDI} [0.338, 0.345]$, $\sigma_D: M = 0.34, SD = 0.002, 95\% \text{ HDI} [0.333, 0.340]$.

Estimates of the μ components at each TDD level (averaged across participants) are plotted in Figure ???. First, note that the decoy mean is always lower than

that of the target and competitor. Furthermore, as TDD increases, the decoy mean decreases, indicating that participants were sensitive to decreases in absolute area, judging smaller rectangles as having smaller areas. Both target and competitor mean areas also decrease with TDD, suggesting that participants somewhat adjusted these areas relative to the decoy.

Focusing solely on the target and competitor means, an interesting pattern emerges. The competitor mean is always larger than the target mean, albeit only slightly (see Appendix for details). This pattern is somewhat consistent with the tainting hypothesis, the idea that nearby decoys can taint the value of target option (Simonson, 2014). However, the tainting hypothesis predicts that tainting is a decreasing function of distance in attribute space, and the current observed difference between target and competitor means appears to be constant. There is also limited statistical evidence for this difference, as the 95% HDIs overlap considerably at each TDD level in both display conditions (see Figure ??).

There is, however, evidence from the Bayesian Hierarchical Regression (see Appendix), via the competitor-specific regression coefficient β_{comp} , that the competitor is rated higher than the target, at least in the triangle condition. The β_{comp} parameter captures the tendency for participants to rate the competitor higher than the target, regardless of the TDD or target orientation. In the triangle condition, this parameter was reliably above 0, $M = 0.005$, $SD = 0.0023$, 95%HDI [0.0001, 0.009]. Note that this effect is quite small. Given that the data were transformed via the natural logarithm, this estimate corresponds to a $e^{0.005} = 1.005px^2$ difference in mean judged area, a considerably small effect size. In the horizontal condition, this parameter was not reliably different from zero, $M = 0.003$, $SD = 0.002$, 95%HDI [-0.002, 0.007].

The estimates of Ω (the correlations) are plotted in Figure ???. First, it is worth noting that all correlations are positive. This means that in general, there are strong trial-level dependencies between area judgments. However, the crucial pat-

tern emerges when comparing the correlations to one another within each display condition. As predicted, in both display conditions, ρ_{TD} is larger than both ρ_{CD} and ρ_{TC} , while ρ_{CD} and ρ_{TC} do not differ from each other. This shows that there is a stronger dependency between judgments of the target and decoy (which are perceptually similar to one another) than of the target and competitor or the competitor and decoy.

The relatively high ρ_{TD} estimate predicts that the target and decoy tend to "move" together. On trials where the target is judged relatively large, the decoy is also judged to be relatively large. Furthermore, because $\rho_{TD} > \rho_{CD}$, this means that the decoy is more likely to be judged larger than the target than it is to be judged larger than the competitor. This provides a plausible mechanism for the repulsion effect; the decoy is more likely to steal choice shares away from the target than from the competitor. This can generate a data pattern where $P(C) > P(T)$ without requiring $\mu_C > \mu_T$.

Furthermore, all ρ parameters from the horizontal condition are larger than the corresponding parameters from the triangle condition. This suggests that the difference between area judgments for target, competitor, and decoy rectangles in the horizontal condition can be more attributed to the true differences between their means than to general noise, when compared to the triangle condition. However, given that the model was fit separately to each display condition, these inferences should be considered cautiously.

2.4.2.3 Choice Phase Results

In each trial of the choice phase, participants saw three rectangles and selected the rectangle with the largest area. This was a replication of Spektor et al. (2018).

Mean choice proportions across display condition and TDD are plotted in Figure ??, collapsed across choice set (i.e., ignoring whether the target was wide/tall).

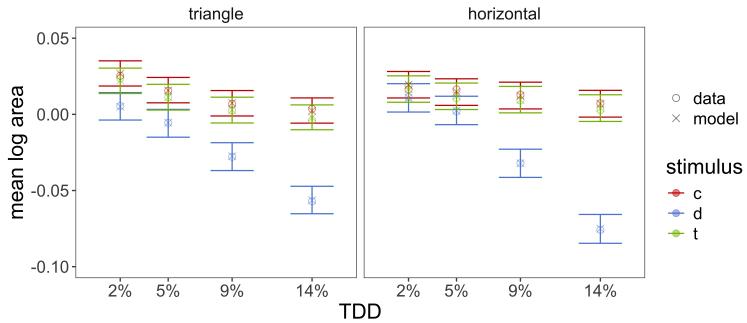


Figure 2.11. Experiment 2 μ estimates. Model values are means, and the error bars are 95% HDIs.

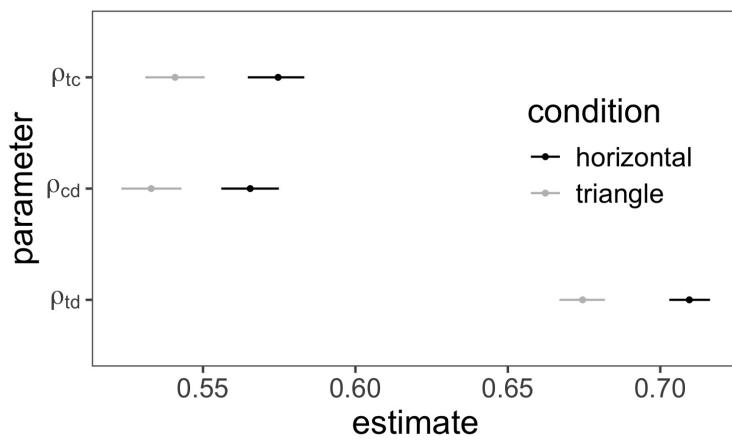


Figure 2.12. Experiment 2 posterior estimates of Ω off-diagonal parameters across display conditions. Lines show 95% HDIs. Dots indicate means.

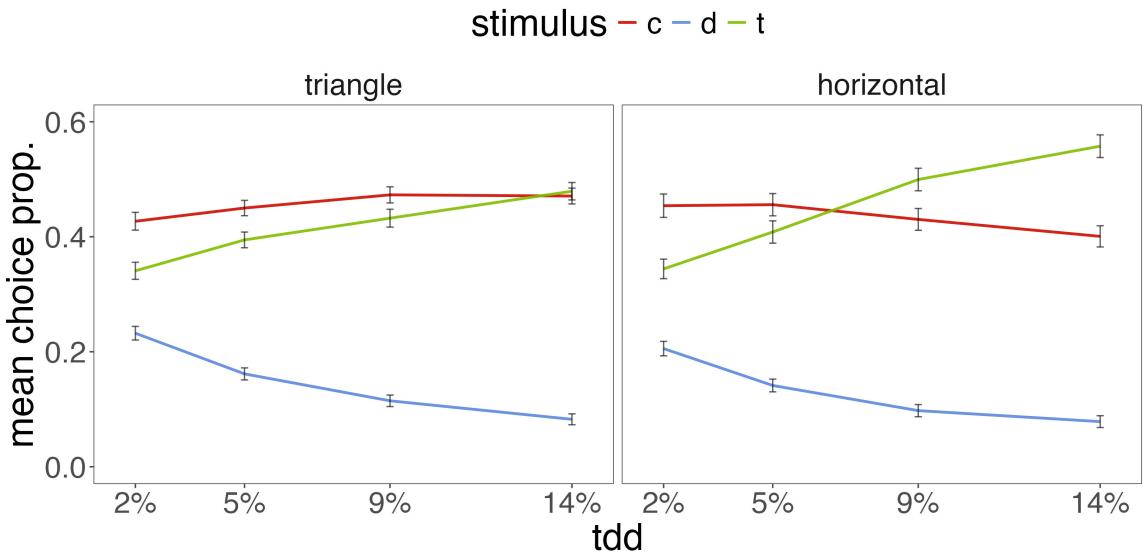


Figure 2.13. Experiment 2 mean choice proportions for target, competitor, and decoy options, by TDD and display condition. Error bars are 95% CIs on the means.

First, in both display conditions, note that decoy choice decreases with TDD. Participants were sensitive to the absolute size of the decoy and chose it less often as the decoy decreased in area.

In the triangle condition (Figure ??, left panel), at the first three levels of TDD (i.e., 2%, 5%, and 9%), the data show a fairly strong repulsion effect, as the competitor was clearly chosen more often than the target. Though this figure suggests a null effect at $TDD = 14\%$, inferential statistics on AST (Absolute Share of the Target) show that there is also a slight repulsion effect at $TDD = 14\%$ (see Appendix).

In the triangle condition (Figure ??, left panel), at the first two levels of TDD (i.e., 2% and 5%), the data show a fairly strong repulsion effect, as the competitor was clearly chosen more often than the target. Though this figure suggests an attraction effect at $TDD = 9\%$, inferential statistics on AST (Absolute Share of the Target) show that there is a null effect at $TDD = 9\%$ (see Appendix). The data clearly show, however, a strong attraction effect at $TDD = 14\%$. See the Appendix for inferential statistics which support these conclusions.

These data show that the repulsion effect, at least in the current paradigm, is strongly related to the similarity between target and decoy along with participants' ability to discriminate the target/competitor from the decoy. As TDD increases, the repulsion effect either decreases in magnitude (triangle condition) or reverses entirely, to an attraction effect (horizontal condition). The results are also consistent with the overall discriminability difference between display conditions. The results of Experiment 1 showed that participants are better at discriminating the target and competitor in the horizontal condition than in the triangle condition.

To demonstrate the strong relationship between discriminability and the repulsion/atraction effects, the choice data from Experiment 2 are plotted against the two-alternative forced choice data from Experiment 1 (see Figure ??). The y axis is identical to that of Figure ???. However, rather than the TDD - the physical difference between target and decoy - the x axis is now the mean target-decoy discriminability. In other words, the x axis is now the psychological target-decoy difference as rather than the physical difference.

When the data are plotted this way, a critical pattern emerges. The crossover point - the point at which the repulsion effect becomes null - occurs at lower discriminability levels in the horizontal condition compared to the triangle condition. This strongly suggests that the target-decoy relationship is crucial for generating the repulsion effect.

2.4.3 Model Simulations

Earlier in this chapter, it was shown the Thurstonian Choice Model could generate a repulsion effect, an attraction effect, or a null effect, depending on the correlation parameters. However, it was open question whether, conditioned on actual estimated parameters, the model could generate data that match empirical choice data. The goal of the following analysis is to test the model's ability to predict the data.

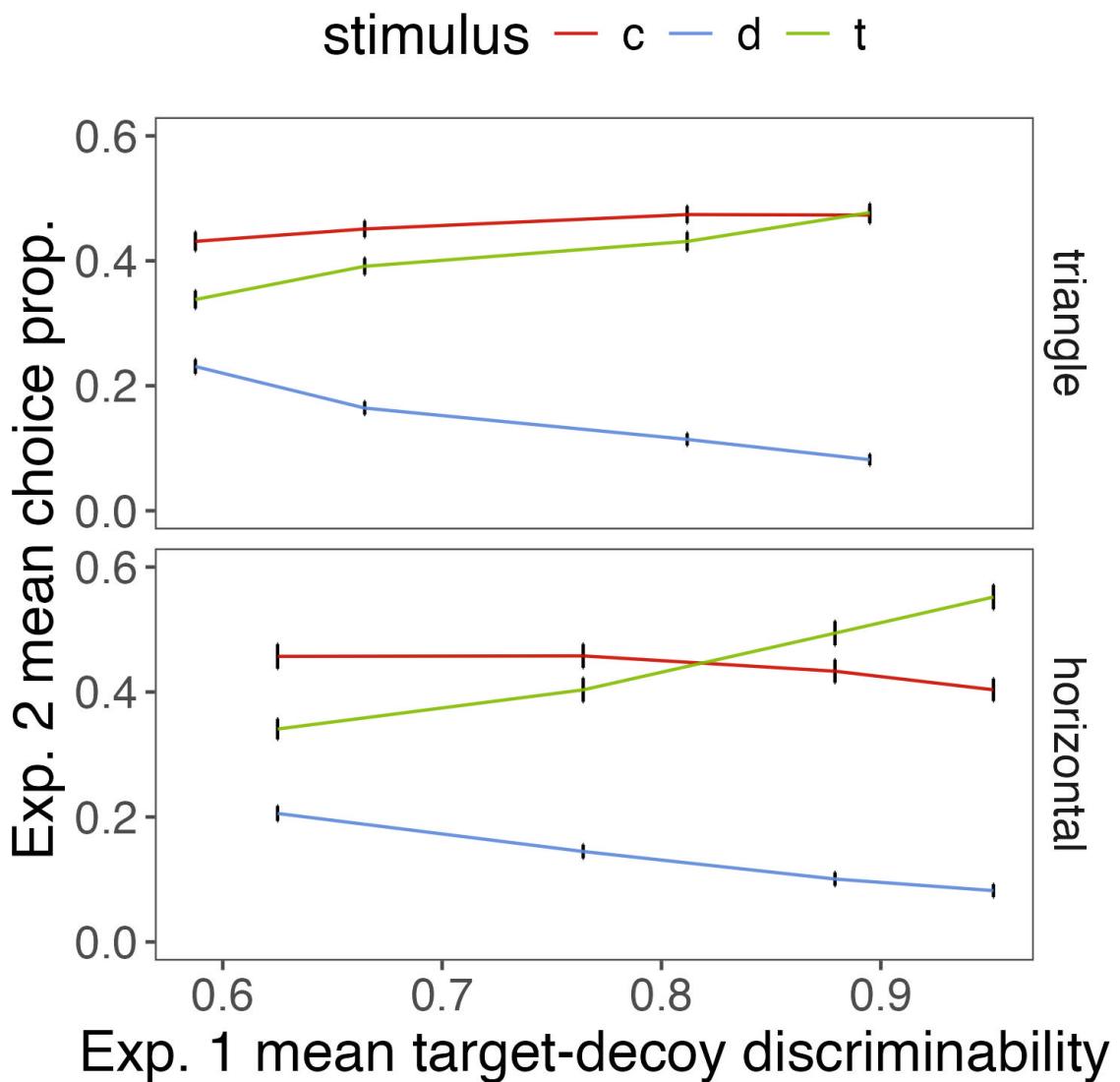


Figure 2.14. Mean target, competitor, and decoy choice proportions (y axis) at each TDD level in Experiment 2, plotted against mean target-decoy discriminability for each TDD level from Experiment 1 (x axis). The y axis error bars are 95% CIs on the mean.

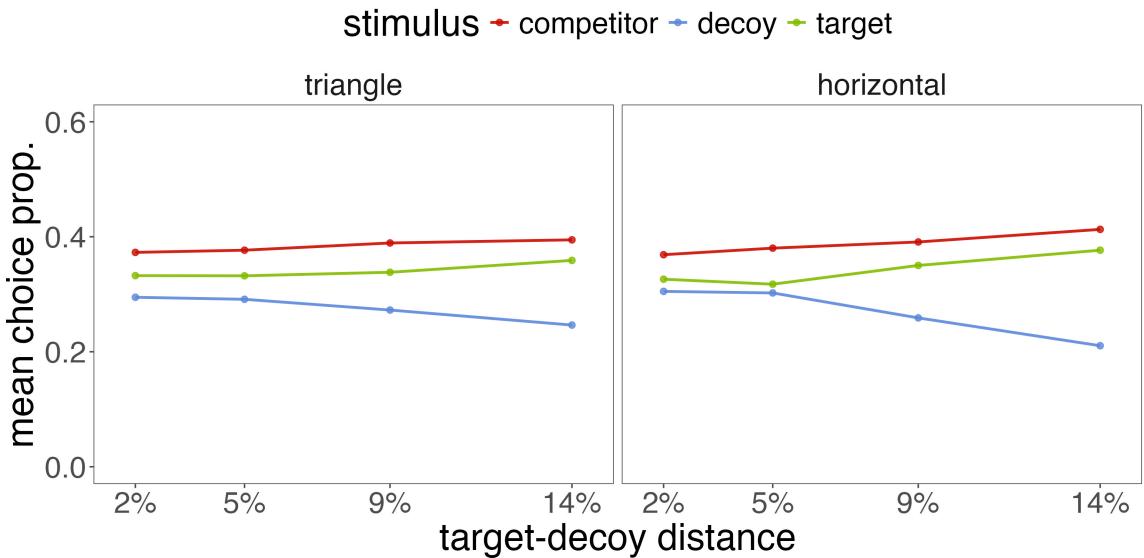


Figure 2.15. Model predictions for the choice data, conditioned on the mean estimated parameters from Experiment 2.

Predictions were generated at each level of TDD using the mean estimates of μ ⁹ and Σ , in each display condition. For simplicity, the mean estimates for each parameter were used, rather than the full distribution of parameter values.

To generate predictions, at each TDD level in each display condition, 1,000,000 samples were drawn from a multivariate Gaussian distribution with parameters μ and Σ , where a sample is a vector of perceived target, competitor, and decoy areas. The choice proportion for each rectangle is simply the proportion of times that a particular rectangle was perceived to be the largest in that sample. The results are plotted in Figure ?? at each TDD level in each display condition. The reader can also see Figure ?? to examine where these predictions fall, though Figure ?? was generated by making assumptions about the mean and variance parameters (see above).

Conditioned on the estimated parameters, the model is able to produce a repulsion effect. This result aligns with our predictions; the repulsion effect, at least in

⁹Given the considerable overlap in HDIs(see Figure ??), the μ_T and μ_C parameters were constrained to be equal at each level of TDD.

some forms, can be generated by the Thurstonian perceptual choice model if the correlation between target and decoy perceptions is greater than the target-competitor and competitor-decoy correlations. In other words, the dependence between target and decoy perceptions is sufficient to produce the repulsion effect.

The model fails in predicting the null effect found at high TDD levels in the triangle condition, and it also fails completely in predicting the attraction effect. This is unsurprising, as to produce the attraction effect the model requires either $\mu_T > \mu_C$ or $\rho_{CD} > \rho_{TD}$, patterns not shown in the current parameter estimates.

The model can produce the repulsion effect solely based on perceptual factors. That is, the model predicts the repulsion effect because the decoy is more likely to exceed the target in perceived area, than it is to exceed the competitor in perceived area.

Conditioned on the observed parameter estimates, the model cannot predict the attraction effect. Assuming the validity of the Thurstonian model, additional processes are needed to explain the attraction effect.

2.5 Discussion

The goal of Experiments 1 and 2 was to test the mechanisms generating the repulsion effect in perceptual choice.

In Experiment 1, participants performed a two-alternative forced choice task, where on each trial they first saw a ternary set of target, competitor, and decoy rectangles before selecting the largest option from a particular pair (i.e., target/decoy, competitor/decoy, or target/competitor). The results showed that participants were not always able to discriminate between stimuli of differing areas (i.e., they selected the decoy a non-trivial proportion of the time). Furthermore, participants performed worse when the rectangles were arranged in the triangle display of Spektor et al. (2018) than in the horizontal display of Trueblood et al. (2013). Finally, participants were

better at discriminating the target from the decoy than they were at discriminating the competitor from the decoy.

Experiment 2 was designed to estimate the parameters of a Thurstonian perceptual model and test the model’s ability to predict the empirical results of a choice experiment. The experiment took place in two phases: a judgment phase, followed by a choice phase. On each trial in the judgment phase, participants saw a set of target, competitor, and decoy rectangles and estimated the areas of each rectangle by adjusting the size of corresponding circles. In each trial of the choice phase, participants saw three rectangles and were told to choose the rectangle with the largest area. The choice phase was a replication of Trueblood et al. (2013) and Spektor et al. (2018).

The results of Experiments 1 and 2 show that participants are not always able to discriminate the decoy from the target and the competitor, and, that target-decoy perceptions are highly correlated. The observed correlations can, when embedded in a Thurstonian perceptual choice model, naturally produce the repulsion effect but not the attraction effect. This result is highly informative for decision-making research, as it shows to what extent the effects reported by Trueblood et al. (2013) and Spektor et al. (2018) can be explained by valuation noise alone, and to what extent researchers must invoke higher-level decision processes to explain them. This finding does not rule out the possibility that the Thurstonian model is incorrect, but the model provides a parsimonious and empirically validated account of the repulsion effect.

To understand how these correlations produces the repulsion effect, consider the following simulation.

First, two sets of parameters were generated. In each set, the μ and S values were similar to those estimated in Experiment 2, $\mu_T = \mu_C = 0$, $\mu_D = -0.1$, $\sigma_T = \sigma_C = \sigma_D = \frac{1}{3}$. However, for the first set of parameters, all correlations were set equal, $\rho_{TC} = \rho_{CD} = \rho_{TD} = .75$, which were not observed in Experiment 2. For the second

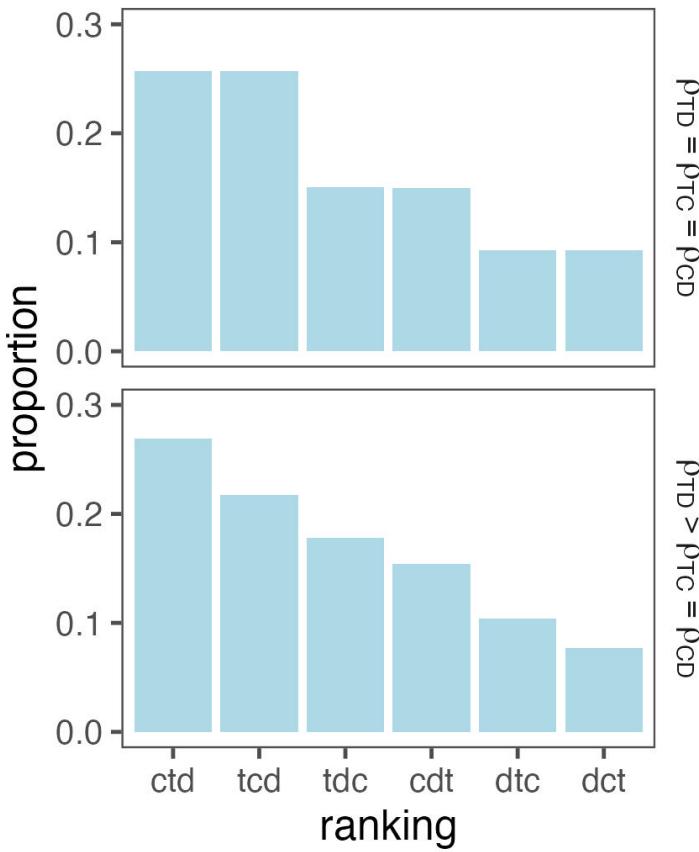


Figure 2.16. Model-simulated ranking proportions, in the order of largest to smallest.

set of parameters, the correlations were set to comparable values from Experiment 2, $\rho_{TC} = \rho_{CD} = .65$, and $\rho_{TD} = .75$.

Next, the Thurstonian model was simulated using each set of parameters. 1,000,000 samples were drawn from the model (where, as above, a sample is a vector of target, competitor, and decoy perceived areas). For each sample, rankings were computed; for example, a ranking of TCD indicates that the target was perceived as largest, the competitor as second-largest, and the decoy as smallest. The simulation results are plotted in Figure ??.

First, consider the parameter set where all correlations are equal (Figure ??, top panel). The results show that $P(CTD) = P(TCD) > P(TDC) = P(CDT) >$

$P(DTC) = P(DCT)$. The decoy is most likely be perceived smallest, least likely to be perceived largest, and the perceived size of the decoy does not influence the relative perception of target and competitor; The target and competitor are equally likely to be perceived as largest (e.g., $P(CTD) = P(TCD)$).

Now consider the parameter set where $\rho_{TD} > \rho_{TC} = \rho_{CD}$ (Figure ??, bottom panel). Here, $P(CTD) > P(TCD)$, because the target and decoy tend to move together, making it easier for the competitor to exceed both options. Furthermore, $P(DTC) > P(DCT)$, because the relatively large ρ_{TD} also allows the decoy to be pulled up with the target. These correlations also cause $P(TDC) > P(CDT)$. In simple terms, if the decoy is in the middle, it is more likely that the target is the largest than it is that the competitor is largest. Note that if we sum up these orderings we can obtain the marginal choice proportions for T , C , and D which will show a repulsion effect, i.e., $P(C) > P(T) > P(D)$.

Thus far the research provides a statistical account of these data, but a process account is (one) ultimate goal of cognitive psychology research. I argue that the target and decoy, which are inherently more similar to one another than either is to the competitor, are more likely to be compared to one another. This ease of comparison leads to correlated valuations which in turn affects choice. This account is plausible based both on this research and on prior decision-making research.

Other researchers have suggested that correlated valuations may be a measure of similarity between choice options. Kamakura and Srivastava (1984) and Natenzon (2019) both estimated correlations indirectly from choice data, by applying constraints to variants of the multinomial probit model. The current research is, to the author's knowledge, the first to directly estimate these correlations through trial-level valuations.

Multialternative Decision Field Theory (MDFT) (Roe et al., 2001) relies on within-trial correlations between similar options to produce the similarity effect, though this

mechanism is distinct from the current model, which relies on *across-trial* correlated valuations.

Bhui and Xiang (2021) showed that target and decoy valuations may be correlated, and they further argued that the repulsion effect is rational given a consumer's belief that the target and decoy come from the same distribution (e.g., two products from the same brand). Bhui and Dubey (2024) similarly argued that context effects can be rational given limited information about options in a choice set.

The results of Experiments 1 and 2 have important methodological implications. Trueblood et al. (2013) and Spektor et al. (2018) designed their studies to test the interesting hypothesis that context effects occur even in low-level, perceptual decision-making. They designed experiments similar to other attraction effect experiments, with two equally viable focal options and an inferior decoy option which is similar to a focal target option. While acknowledging that participants may occasionally fail to perceive the dominance relationship, Spektor et al. (2018) dismissed the possibility that their repulsion effect may be a form of the *similarity effect*, where two similar options split choice shares, but they dismissed this hypothesis because participants chose the target more often than they chose the decoy. They did not consider the possibility, however, that the target-decoy comparability could cause perceptual correlations which manifest themselves in the choice data. Experiment 2 showed that, even though $P(T) > P(D)$, the decoy is systematically chosen over the target more than it is chosen over the competitor. Thus, the correlation between target and decoy can generate a repulsion effect that is qualitatively different from a reversal of the attraction effect.

Researchers have also argued in favor of the "tainting hypothesis" (Simonson, 2014; Spektor et al., 2018), where the inferior decoy "taints" similar options (i.e., the target). On average, participants did generally rate the competitor as larger than the target in Experiment 2. These results were, however, quite small and not always

statistically apparent. Moreover, the model does not require this tainting to produce the repulsion effect.

Researchers should be careful in assuming that an empirical context effect is generated solely by decision processes whenever the choice environment precludes full stimulus discriminability. Though data from Spektor et al. (2018) showed an empirical repulsion effect (i.e., competitor chosen less than the competitor), this chapter has presented evidence that the data are generated from a fundamentally different process than the attraction effect.

There are some limitations to the current experiment. Due to the large amount of data required to estimate a variance-covariance matrix (Martin, 2021; Merkle et al., 2023), The correlation parameters were estimated by collapsing across participants. The aggregation of data may obscure individual differences, an area of increasing concern in context effect research (Davis-Stober et al., 2023; Liew et al., 2016; Trueblood et al., 2015). Future studies should collect enough participant-level data (perhaps by asking participants to return for multiple experimental sessions) to allow participant-level variation in correlation estimates. It would be of great theoretical interest if individual differences in the correlation parameters could explain individual variation in the attraction and repulsion effects. If the repulsion effect in perceptual choice is truly generated by target-decoy similarity, then, at an individual participant level, the strength of the repulsion effect should be positively related to the value of ρ_{TD} . Participants who are more prone to confusing target and decoy should show a stronger repulsion effect.

Participants also appeared to use both relative and absolute judgment processes when judging the areas of the rectangles. Mean judgments of decoy sized decreased with TDD, but mean target and competitor judgments decreased as well. Thus, the measurements of area perception are not ideal, though these measurements were sufficient for the current purposes.

As discussed in the Appendix, there was a wide bias during the choice phase but a tall bias during the judgment phase. In the choice phase, participants chose wide rectangles more than tall rectangles. In the judgment phase, however, they judged tall rectangles to be larger than wide (at least in the triangle condition). The latter effect is quite small (i.e., smaller than that of the difference between the target and the smallest decoy), but it is nonetheless present in the data. There is currently no clear explanation for this result. Gronau et al. (2023) compared participants' ability to perform a perceptual discrimination task based on whether they responded via an ordinal rating scale or a choice. The authors concluded that participants relied on the same representation in both cases, but the participants were more sensitive to stimulus-level differences when choice responses were collected. It may be that, in Experiment 2, the relative lack of perceptual sensitivity caused participants to slightly underestimate their reported responses to stimuli they actually *perceived* as larger. This inconsistency may also be idiosyncratic statistical variation which may not appear in future samples.

This chapter shows that the repulsion effect in perceptual choice can be explained by target-decoy similarity alone, but the attraction effect may require invoking higher-level decision processes. To explain the repulsion effect, a Thurstonian perceptual choice model was developed and tested. In particular, the means, variances, and correlations of multivariate Gaussian distribution of area perception were jointly estimated from participants' judgments of perceptual stimuli. This model was then tested on its ability to explain choice data collected from the same participants. This research furthers the study of context effects, provides a new experimental paradigm for testing them, and helps explain inconsistencies in prior results.

CHAPTER 3

VIOLATIONS OF INDEPENDENCE IN BEST-WORST CHOICE

3.1 Introduction

Chapter 2 introduced a Thurstonian Perceptual Choice model and showed how, conditioned on estimated parameters, this model can systematically predict the repulsion effect, but not the attraction effect. This chapter tests another prediction of the model while demonstrating an important empirical result in another choice domain: best-worst choice.

3.1.1 Introducing Best-Worst Choice

Best-worst choice is an experimental paradigm where participants select their most and least preferred options from a choice set. Originally proposed by Finn and Louviere (1992), best-worst choice is widely used in a number of applied fields, such as transportation (Beck & Rose, 2016) and healthcare economics (Cheung et al., 2016; Flynn et al., 2007a; Mühlbacher et al., 2016). One key advantage, when compared to standard choice research, is that researchers can use best-worst choices to gain information about participants' ranking of options while never requiring them to complete a full ranking task (Flynn & Marley, 2014).

Researchers have developed theoretical models to account for best-worst choice data. These models relate best-worst choices to an underlying utility function (or functions). Marley and Louviere (2005) developed a class of models known as the

maxdiff (maximum difference) models of best-worst choice¹. According to the maxdiff model, the joint probability of selecting both option j as best and also option k as worst (denoted $BW(j, k|K)$) from set K , where $j \neq k$, is defined computed as:

$$BW(j, k|K) = \frac{e^{u_j - u_k}}{\sum_{\substack{p,q \in K \\ p \neq q}} e^{u_p - u_q}} \quad (3.1)$$

where u_i is the utility of option i . This model proposes that a single utility scale determines the selection of both the best option and the worst option in a choice set. It assumes that best-choice probabilities are an increasing function of u , while worst-choice probabilities are a decreasing function of u . Furthermore, the maxdiff model relies on the differences of utilites; From a given choice set, the most likely pair is the pair with the largest difference in utility values. Note that the use of the exponential function means that the maxdiff model is another form of the widely used multinomial logit (MNL) choice model (Hausman & McFadden, 1984). Utilities are also assumed to be independent of each other. There are several variants of the maxdiff model, along with other best-worst choice models (Flynn & Marley, 2014; Flynn et al., 2007b; Marley & Louviere, 2005; Marley & Pihlens, 2012; Marley et al., 2008), though the maxdiff model from Equation ?? remains the dominant model for analyzing best-worst choice data.

The marginal probability $B(j|K)$ of selecting option j as best from set K can be written as:

$$B(j|K) = \frac{e^{u_j}}{\sum_{p \in K} e^{u_p}} \quad (3.2)$$

while the marginal probability $W(k|K)$ of selecting option k as worst from set K can be written as:

¹Note that the term maxdiff is sometimes erroneously used to refer to best-worst experiments in the generic sense. Following Marley and Louviere (2005), maxdiff refers to a specific class and parameterization of a best-worst choice model.

$$W(j|K) = \frac{e^{-u_j}}{\sum_{p \in K} e^{-u_p}} \quad (3.3)$$

Thus, best-choice probabilities are an increasing function of u , while worst-choice probabilities are a decreasing function of u .

The maxdiff model predicts a decreasing monotonic relationship between best-choice probabilities and worst-choice probabilities (Hawkins et al., 2014a). Options most likely to be chosen as best are necessarily least likely to be chosen as worst, and vice versa.

To demonstrate this, consider the following simulation. 500 ternary (three-option) best-worst choice trials were simulated, by sampling 3 utilities from the standard normal distribution ($N(0, 1)$). For each trial, the marginal best and worst choice probabilities were computed using the maxdiff model. These probabilities were then plotted against each other in a state-trace plot. (Bamber, 1979). In a state-trace plot, the analyst plots two dependent variables against one another in each experimental condition. In Figure ??

That is, if we assume all options' utilities are independent, the model predicts that best-choice probabilities are negatively, monotonically related to worst-choice probabilities.

Researchers have explored whether this monotonicity holds empirically. Hawkins et al. (2014b) tested both preferential and perceptual best-worst choice data using response time modeling. They used the linear ballistic accumulator model (LBA) (Brown & Heathcote, 2008), which casts the decision process as a race between evidence accumulators towards a threshold, where the average accumulation across trials is captured by the drift rate parameter. Modeling both preferential and perceptual best-worst choice data, they were able to successfully account for choice data by assuming a parallel race between best and worst accumulators for each option. Furthermore, they showed that the utility values estimated for each option using a MNL

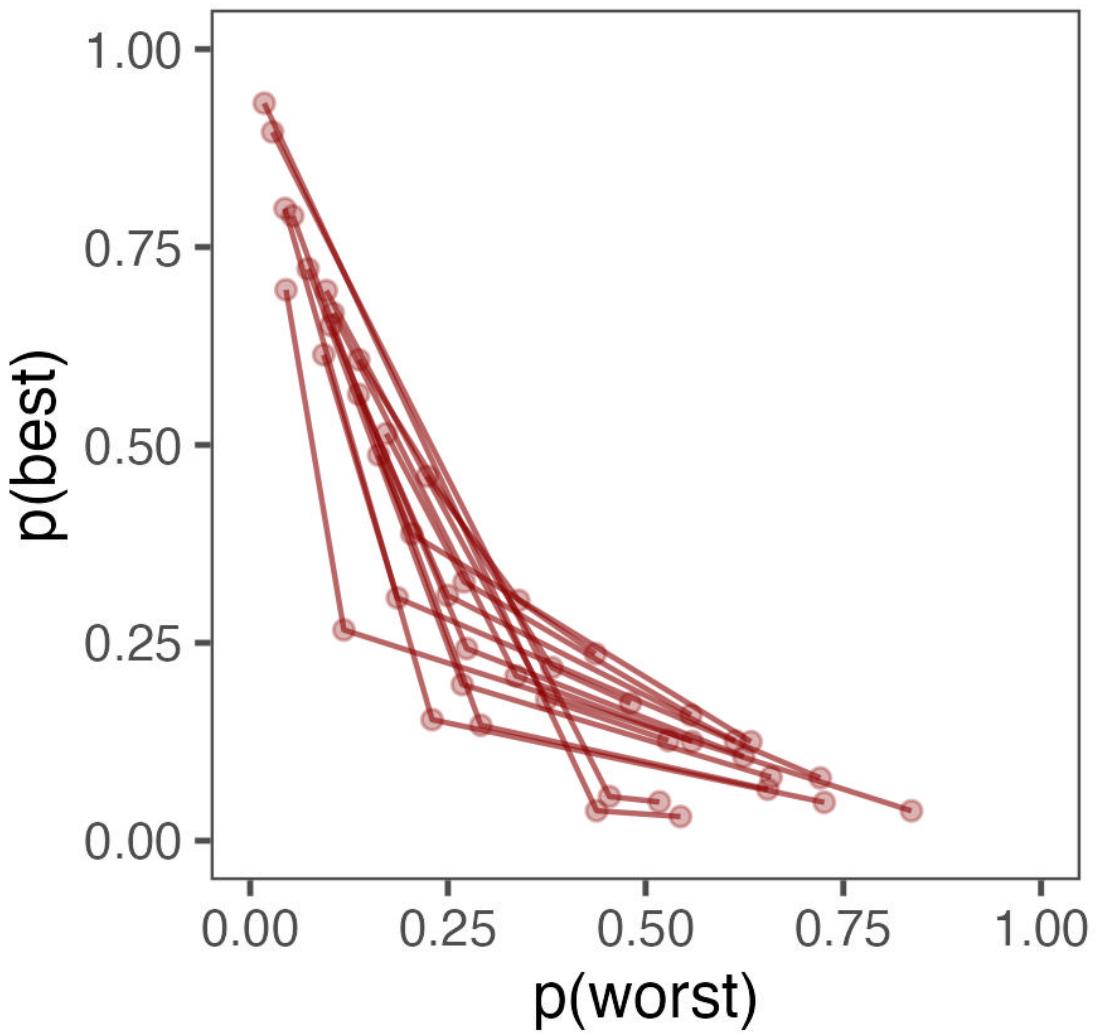


Figure 3.1. Best-worst choice simulations using the maxdiff model. Each curve is a separate simulation. The model predicts a negative, monotonic relationship between the marginal best-choice and worst-choice probabilities.

model were positively linearly related to the log drift rate values from the LBA, suggesting an underlying utility representation that explains both best and worst choices.

In a follow-up article, Hawkins et al. (2014a) found that, collapsing across choice sets, best-choice probabilities are monotonically related to worst-choice probabilities. Options that were most likely to be selected as best were least likely to be selected as worst, and vice versa. This finding held for perceptual choice and consumer choice. They also showed that, using the parallel best-worst LBA as a model, the drift rate parameter for worst choice can be parameterized as the reciprocal of the best choice drift rate.

Both the parallel best-worst LBA and the maxdiff model assume that the utilities of all options presented are independent. However, as shown below, the Thurstonian perceptual model from Chapters 1 and 2 predicts, under certain conditions, a dissociation between best and worst choices inconsistent with this assumption.

3.1.2 Model-Based Dissociations in Best-Worst Choice

Below, the Thurstonian perceptual model from Chapter 2 is used to make a prediction regarding a dissociation between best choices and worst choices.

Let K be a choice set consisting of options T , C , and D (i.e., target, competitor, and decoy). As in Experiments 1 and 2, the options are rectangles in a perceptual choice experiment. As in Chapter 2, it is assumed that on each trial i with choice set K , the vector \mathbf{X}_i of perceived areas is sampled from a multivariate Gaussian distribution with a mean vector $\boldsymbol{\mu}$ and variance-covariance matrix $\boldsymbol{\Sigma}$:

$$\mathbf{X}_{ij} \sim \mathcal{N}(\boldsymbol{\mu}, \boldsymbol{\Sigma}) \quad (3.4)$$

Given a vector \mathbf{X}_i of perceived areas on trial i with set K , according to model, the probability a participant selects stimulus j as best and option k as worst is:

$$BW_K(j, k) = P(\mathbf{X}_{ij} - \mathbf{X}_{ik} > \mathbf{X}_{ip} - \mathbf{X}_{iq}), \forall p, q \in K, p \neq q \quad (3.5)$$

Simply put, on any given trial, the option with the largest perceived area is always selected as best, while the option with the smallest perceived area is always selected as worst.

Applied to best-worst choice the Thurstonian Perceptual Choice model is quite similar to the maxdiff model. There are two main differences between these models, however. First, the Thurstonian model is a version of the Multinomial Probit (MNP) model, while the maxdiff model is a variant of the MNL model. Crucially, however, the Thurstonian model provides a distribution for option utilities and allows for correlations between these utilities, while the maxdiff model assumes that these utilities are independent of one another.

However, given the correlations (i.e., Ω components) estimated from Experiment 2, the Thurstonian predicts that, in the best-worst choice paradigm, there is a non-monotonic relationship between marginal best choices and worst choices. This dissociation is explained below.

The model, conditioned on the mean parameters ($\boldsymbol{\mu}$ and $\boldsymbol{\Sigma}$) estimated from Experiment 2 was simulated for 1,000,000 trials². As in Chapter 2, results are collapsed over choice set (i.e., whether the target is wide or tall). Marginal choice proportions for the target, competitor, and decoy options were computed at each level of TDD. These results are presented in Figure ??, in a series of state-trace plots.

The model, conditioned on the estimated parameters, predicts a theoretically informative data pattern. Although the competitor is most frequently chosen as best (as in the empirical results from Experiment 2), it is not, however, least frequently chosen as worst. Specifically, $B(C) > B(T)$, while $W(T) < W(C)$. At lower levels

²Only the correlations estimated from the triangle condition (See Experiment 2) were used here, as the parameters estimated from the horizontal condition made identical predictions.

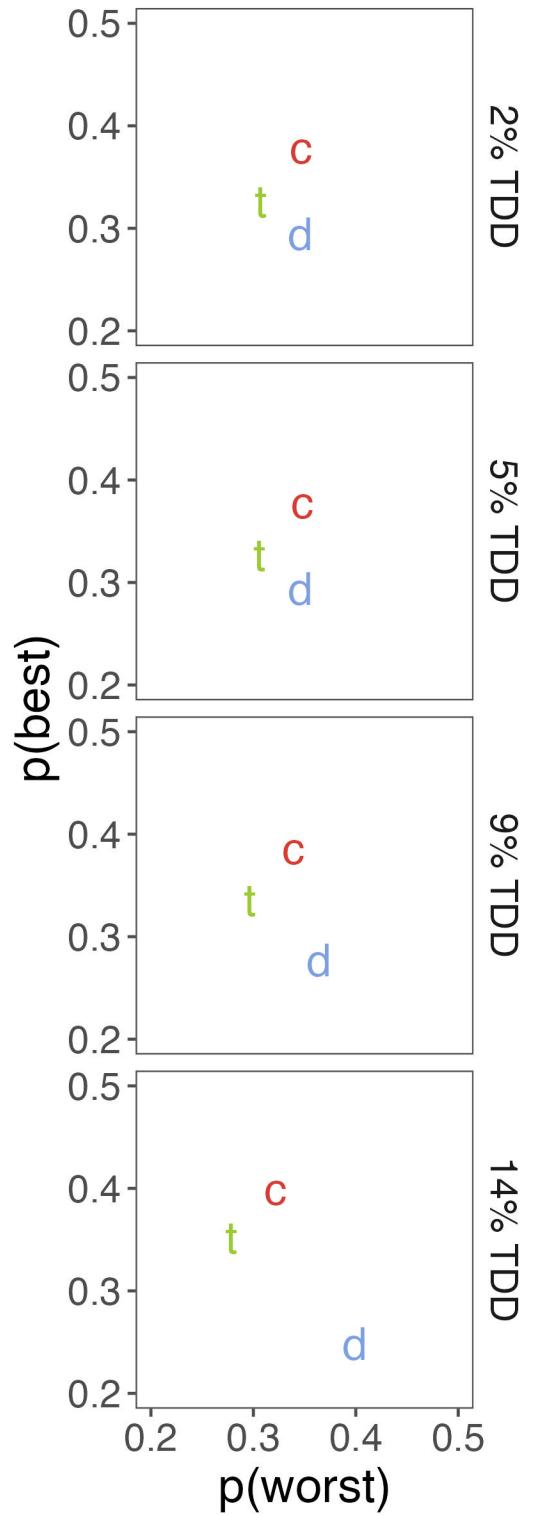


Figure 3.2. Simulated best-worst predictions per the Thurstonian perceptual model. Each row is a different level of TDD..

of TDD , the model even predicts that competitor and decoy are chosen as best at similar rates, a prediction likely due to the fact that participants are generally less sensitive to perceptual differences when providing ratings than when making choices (Gronau et al., 2023).

The Thurstonian perceptual model predicts this because $\rho_{TD} > \rho_{CD} \approx \rho_{TC}$. On the (relatively few) trials where X_{iD} is largest, it is more likely that $X_{iD} > X_{iT} > X_{iC}$ than $X_{iD} > X_{iC} > X_{iT}$. In other words, the high ρ_{TD} value "pulls up" the target more than the competitor. Though the similarity, and comparability, of target and decoy thus entail that the competitor is chosen more as best compared to the target (as in Experiment 2), this does not necessarily entail that the competitor is chosen less than the target as worst.

This effect is subtle, and the predicted effect size is small. Indeed, all differences in predicted $W(C) - W(T)$ values were $< .05$. Experiment 3 contains the empirical and modeling results from a best-worst choice experiment designed to test this prediction. The dissociation between best and worst choices does indeed occur empirically. Here, the assumption of monotonicity, required by the independent utilities typically assumed by the maxdiff model, also fails empirically.

3.2 Experiment 3

The goal of Experiment 3 was to test the predictions of the Thurstonian perceptual choice model. Specifically, the perceptual model predicts that $B(C) > B(T)$ but $W(T) < W(C)$. To test this prediction, the stimuli were identical to those of Experiment 2, including the triangle display. The aforementioned prediction holds empirically and the maxdiff model (with independent utilites) cannot account for these results.

3.2.1 Methods

3.2.1.1 Participants.

Data collection took place at the University of Massachusetts Amherst. 392 undergraduate students participated in exchange for course credit. 23 participants who achieved less than 80% accuracy on catch trials (see below) were excluded from all analyses.

From the remaining 369 participants, 2,604 trials with first-choice response times (RTs) < 100ms or > 10000ms were also excluded from all analyses, leaving 107,727 trials across all participants.

Participants were randomly assigned into one of two conditions: best-worst or worst-best. On each trial, participants in the best-worst condition first chose the largest rectangle and then chose the smallest rectangle. Participants in the worst-best condition chose in the opposite order. Condition was included to account for the possibility that best-worst choice order impacts choice, though results were qualitatively identical across conditions, so all results are collapsed across this factor.

After removing participants, there were 185 participants in the best-worst condition and 184 participants in the worst-best condition.

3.2.1.2 Stimuli.

The experiment had three types of trials: critical trials, filler trials, and catch trials.

Stimuli on critical trials were identical to those of Experiment 2. On each critical trial, the target and competitor had the same area but differed on orientation, with one stimulus being wide and the other tall. The decoy always had the same orientation as the target. TDD varied at 2%, 5%, 9%, and 14%. Target, competitor, and decoy rectangles along three diagonals, as in Experiment 2 (see Figure ??).

On each filler trial, three stimuli were uniformly sampled from the space between the largest and smallest diagonals (see Figure ??).

On each catch trial, one stimulus was sampled from the largest diagonal, while two stimuli were sampled from the smallest diagonal.

3.2.1.3 Design.

There were 8 blocks of trials. In each block there were 24 critical trials, 6 at each TDD level. There were 8 trials per diagonal. In addition to the critical trials, there were 10 filler trials and 3 catch trials per block.

Participants were randomly assigned into one of two conditions: best-worst or worst-best, as described above.

Stimuli were presented on computer monitors with a resolution of 1920 x 1080 pixels. The experiment was programmed with GNU Octave and Psychtoolbox (Brainard, 1997; Eaton et al., 2021).

3.2.1.4 Procedure.

The experiment began with three practice trials, which were identical to the filler trials.

On each trial, participants saw three rectangles, labeled 1, 2, and 3 (from left to right), arranged in a triangle display. Participants in the best-worst (worst-best) condition saw a prompt asking them to select the largest (smallest) rectangle on screen. Participants used the mouse to select their choice. After they made their choice, this rectangle changed color to indicate that it was no longer available as an option. Next, participants in the best-worst (worst-best) condition selected the smallest (largest) rectangle, at which point the trial ended. See Figure ?? for an example trial.

Stimulus order was randomized on each trial.

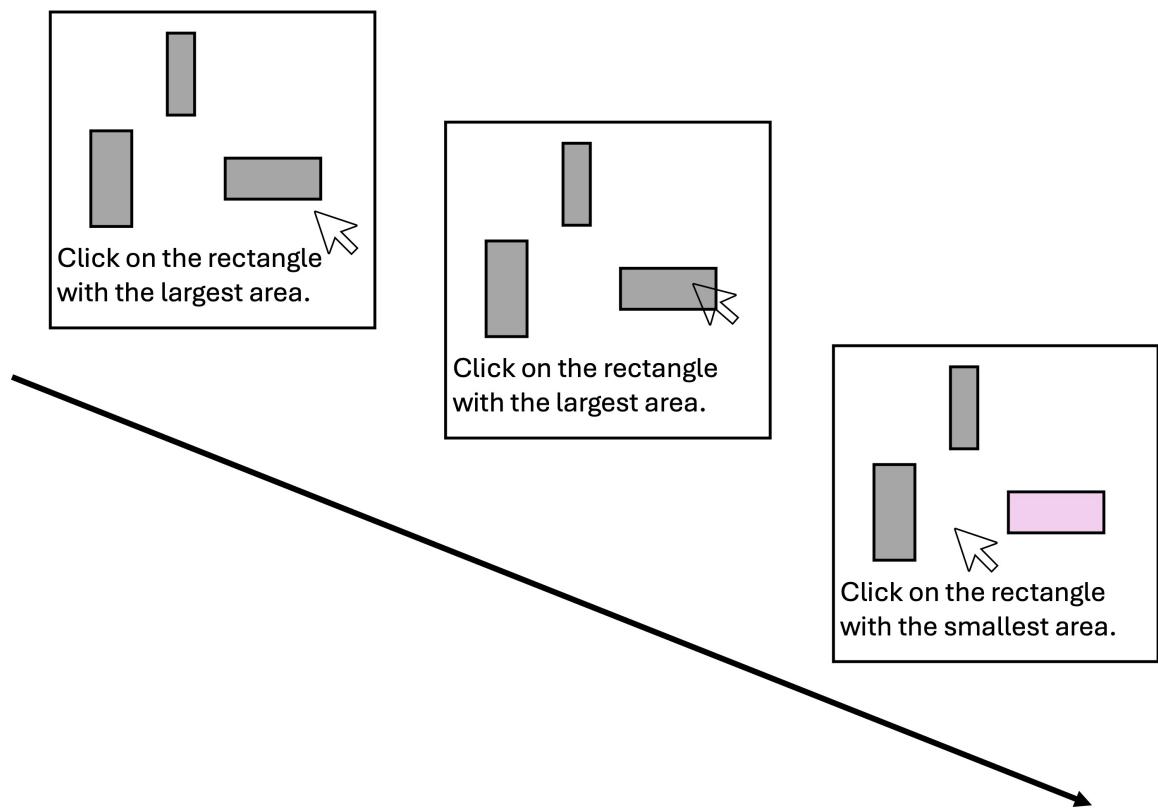


Figure 3.3. A sample experimental trial from Experiment 3. Note that this is a trial in the best-worst condition.

Participants were told their percentage correct of best choices, worst choices, and overall choices at the end of the experiment.

3.2.2 Results

3.2.2.1 Catch Trials.

Participants performed well on the catch trials. The mean percentage correct for best choices was 97.97%($SD = 14.09$), and the mean percentage correct for worst choices was 98.26%($SD = 13.09$). The mean percentage correct for both best and worst choices (i.e., the mean percentage of the trials on which participants were able to correctly identify the largest and smallest rectangles) was 96.98%($SD = 17.12$).

3.2.2.2 Filler Trials.

Participants performed worse on the filler trials compared to the catch trials, but still well above chance. The mean percentage correct for best choices was 89.83%($SD = 30.23$), and the mean percentage correct for worst choices was 88.95%($SD = 41.35$). The mean percentage correct for both best and worst choices was 80.95%($SD = 39.37$).

3.2.2.3 Critical Trials.

First, data were analyzed by computing choice proportions by TDD and choice set. Mean choice proportions for these data are plotted in Figure ?? (left and middle columns).

Participants showed a consistent bias to choose w (the wider rectangle) as largest, a finding also shown in Experiments 1 and 2. Participants also (on average) regularly choose the decoy rectangle as smallest, with the exception of the choice set h, w, d_w and $TDD = 2\%$, where they selected the h rectangle as smallest, on average. This can be attributed to the difficulty of the $TDD = 2\%$ condition and the overall wide rectangle bias. However, consistent with the predictions of the model, the target

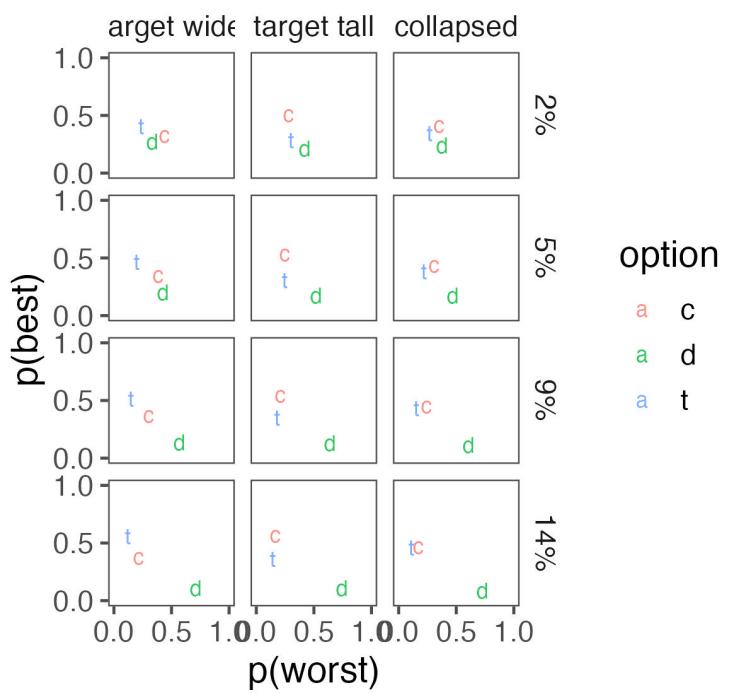


Figure 3.4. Experiment 3 mean best and worst-choice proportions, conditioned on TDD (rows) and choice set (columns). The first col.

was still less likely to be chosen as worst than the competitor, $W(h|[h, w, d_h]) < W(h|[h, w, d_w])$ and $W(w|[h, w, d_w]) < W(w|[h, w, d_h])$, while the competitor option was more likely to be chosen as best, $B(h|[h, w, d_w]) > B(h|[h, w, d_h])$ and $B(w|[h, w, d_h]) > B(w|h, w, d_w)$.

These results are more easily understood by plotting mean target, competitor, and decoy choice proportions across TDD levels, collapsed over choice set. See Figure ?? (right column) for these data.

The best-choice proportions replicated the repulsion effect initially found by Spektor et al. (2018) and replicated in Experiment 2, where the competitor was more likely to be chosen as best at low TDD levels, while the target and competitor were chosen equally often at high TDD levels. Decoy best-choice proportions also decrease systematically with TDD.

Furthermore, the target is always more likely to be chosen as worst, compared to the competitor and decoy, at all TDD levels, $W(T) < W(C)$, as predicted by the Thurstonian perceptual model outlined in Chapter 2. This model still cannot predict the null best-choice repulsion effect when $TDD = 14\%$, as discussed in Chapter 2, which suggests that the Thurstonian model may need incorporate to higher-level decision processes to account for the repulsion effect.

3.2.2.4 Maxdiff Modeling

Now consider the maxdiff model (Marley & Louviere, 2005), which was outlined in the introduction to this chapter. This model predicts that the probability of choosing options x as best and y as worst, $x \neq y$, increases monotonically with the difference in their estimated utilities (see Equation ??). This model is the most commonly used analysis technique for best-worst choice data. This model was applied to the current experiment and show that it is unable to predict the observed dissociations in best-worst choices, even with its best fitting parameters.

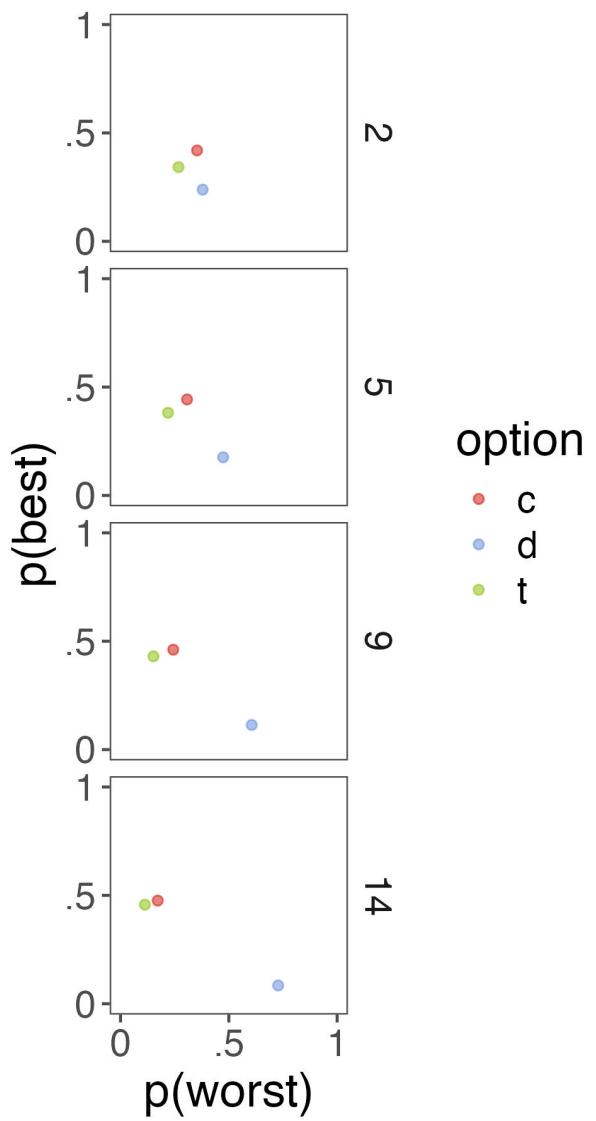


Figure 3.5. Experiment 3 mean best and worst-choice proportions for the target, competitor and decoy rectangles, conditioned on TDD (rows).

Bayesian hierarchical model was used to fit the model. For the fitting procedure, including parameterization, parameter estimates, and all priors in the Appendix and focus on the model predictions in the main text. The model predictions for the mean best and worst choices are shown in Figure ??.

The model clearly mispredicts the data. The model predicts that the target and competitor are chosen at roughly equal amounts for both best and worst choice. Furthermore, note that the model predictions fall on a straight line rather than the curve shown by the data. This misprediction stems from the fact that the model choices are a function of the utility of each option, in this case calculated through a linear combination of experimental factors multiplied by model coefficients, including target/competitor/decoy status. The model could, if the data suggest it, predict that the target has greater utility than the competitor or vice versa. However, because best-choice proportions are positively related to utility and worst-choice proportions are negatively related to utility, the model cannot simultaneously predict $B(C) > B(T)$ and $W(T) < W(C)$. Instead, the mostly likely parameter set is that which predicts $B(C) \approx B(T)$ and $W(T) \approx W(C)$

Participant-level data and model predictions are shown in Figure ???. The model generally does a poor job at accounting for participant worst-choice proportions.

3.3 Discussion

Experiment 3 demonstrated that correlated valuations can induce dissociations in best-worst choice. Specifically, given a target, competitor, and decoy option (borrowing the terminology of the attraction effect), the competitor is more likely than the target to be selected as best ($B(C) > B(T)$), but the competitor is also more likely than the target to be selected as worst ($W(C) > W(T)$). This prediction was made using the Thurstonian perceptual choice model of Chapter 2, conditioned on

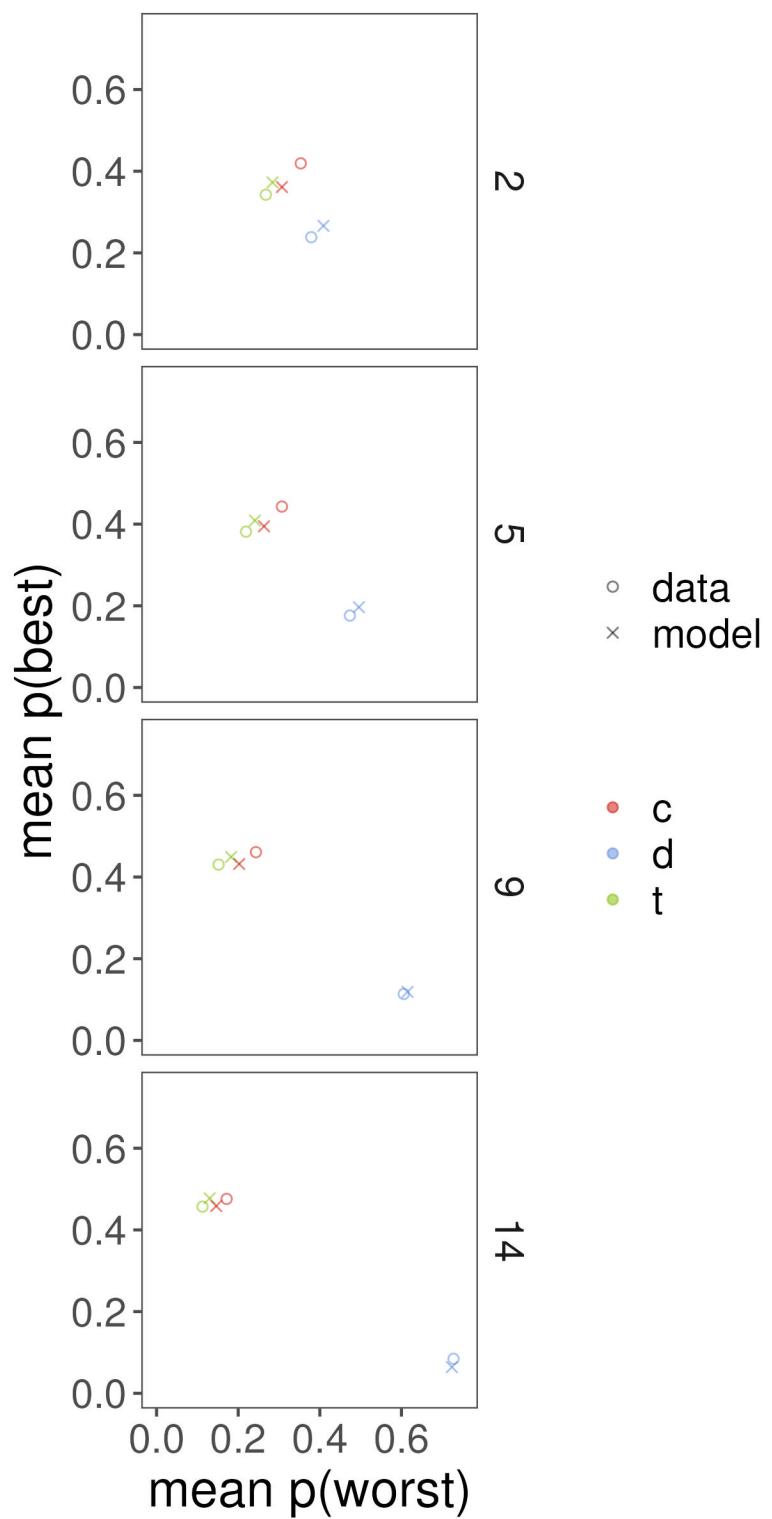


Figure 3.6. Experiment 3 maxdiff model predictions for the mean target, competitor, and decoy best-worst choice proportions.

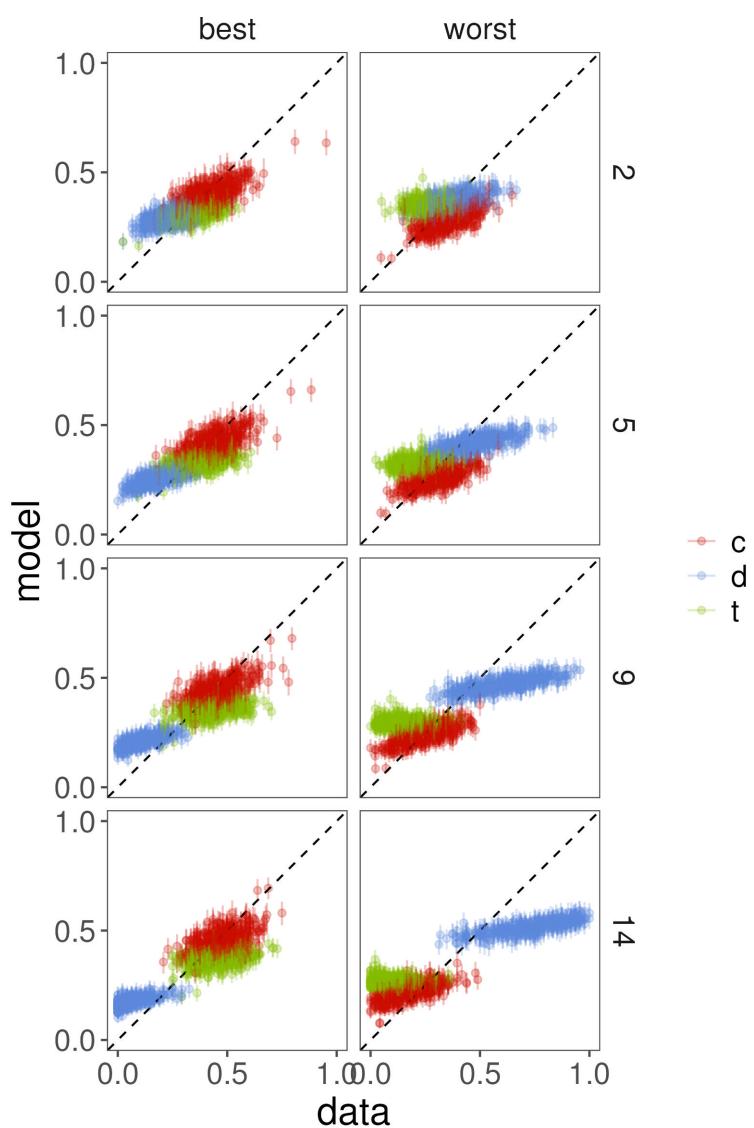


Figure 3.7. Experiment 3 maxdiff model predictions for the mean target, competitor, and decoy best-worst participant-level choice proportions, conditioned on TDD (rows) and choice type, i.e. best v. worst (columns). Vertical error bars are 95% HDIs.

the parameters estimated from Experiment 3. Furthermore, the prediction was made with different set of participants and a completely different experimental task.

The maxdiff model, the most common model for best-worst choice analysis cannot predict both that $B(C) > B(T)$ and $W(C) > W(T)$.

The maxdiff model assumes that, when selecting the best and worst option, the decision-maker picks the option with the highest and lowest utility, respectively. Most applications of the model assumes that these utilities are independently distributed (Flynn & Marley, 2014), and that the decision-maker uses the same utility for both best and worst choices. The use of a single utility scale is to some extent a convenience assumption. Marley and Louviere (2005) explored several theoretical models, including the case where best and worst utilities exist on independent ratio scales, though such a model does not seem to have been adopted by substantive researchers. Marley et al. (2008) introduced set-dependent best-worst choice models, which allow for context dependence based on choice set, albeit with best and worst choices still a function on a common underlying utility scale.

Hawkins et al. (2019) also argued that best and worst choices rely on a common utility representation, i.e., that the best option is chosen because it is highest in utility and the worst option is chosen because it is lowest in utility. They fit the maxdiff model to 5 best-worst datasets and showed, via Bayesian mixture modeling, that the overwhelming majority of participants were best fit by a model with a single utility representation.

Geržinič et al. (2021) argued (and provided evidence for) the claim that while best and worst choices rely on a common utility scale, people use two distinct decision rules for best choices and worst choices. They argued that the former is compensatory (i.e., allowing tradeoffs between attributes), while the latter is non-compensatory (i.e., disallowing tradeoffs to minimize future regret).

The Thurstonian perceptual model, used for the current predictions, also employs a common utility scale for both best and worst choices. However, the model does not assume independently distributed utilities, as assumed by the maxdiff model. Thus, the claims of Hawkins et al. (2014a) and Hawkins et al. (2019) are not necessarily falsified; rather, they are amended to account for correlations between option utilities.

Due to the small effect size, this experiment required a large amount of data to estimate these dissociations. Most best-worst choice research is applied (for example in transportation and healthcare economics), where researchers do not typically have access a large amount of data, at least at the individual participant level. Thus, researchers are unlikely to observe the dissociations in best-worst choice and will analyze the data using the maxdiff model. They may then arrive at incorrect conclusions regarding participants' preferences.

The Thurstonian perceptual model was not fit to the data from Experiment 3. In Experiment 2, participants judged the size of the rectangles, and these judgments were used to estimate the model parameters. It also seems unreasonable to expect researchers to fit a multivariate Thurstonian model to most best-worst choice studies, given limitations in data and potential issues with parameter identifiability.

The central purpose for conducting best-worst choice studies is to identify participants' preference distributions on a set of options. Best-worst choice is less cognitively demanding on participants than asking them to rank all options and far more efficient than pairwise forced choices on all combinations of options (Louviere et al., 2008). In many cases, analyzing best-worst data with the maxdiff model may be the best approach, especially if researchers have no reason to believe that options are strongly correlated, or if all pairs of options have equally strong correlations. It is an open question, left for future research, whether correlations between options in applied choice research can create similar dissociations in best-worst choice.

The current study only considered Case 3 best-worst choice (Marley & Pihlens, 2012), where the attributes of options (in this case, height/width, TDD, diagonal) are systematically manipulated. This study did not consider Case 1 best-worst choice, where researchers are interested in preference for each option as a whole (e.g., a consumer's preference for cars over bicycles) or Case 2 best-worst choice, where researchers ask participants to select their preferred attribute from a set (e.g., a consumer's preference for short waiting times over physician experience in an urgent care clinic). Future research should consider ways to generalize the current paradigm and results to the other best-worst choice types.

CHAPTER 4

CORRELATED VALUATIONS IN PREFERENTIAL CHOICE

4.1 Introduction

Thus far, the dissertation has focused on perceptual choice. This has allowed for the reconciliation of conflicting findings from other researchers (Spektor et al., 2018; Trueblood et al., 2013), using a Thurstonian choice model which was developed from the ground up in a simplified choice environment.

However, many decision theorists, in particular those who study context effects, are interested in a wide variety of choice environments. For example, the original demonstration of the attraction effect came from the marketing literature (Huber et al., 1982), where participants selected amongst hypothetical consumer products. This chapter generalizes the paradigm and model from Chapter 2 to preferential choice. Participants were presented with sets of consumer stimuli, which were developed by previous researchers and designed to elicit context effects (i.e., the attraction and repulsion effects). In one phase of the experiment, participants provided the selling prices for consumer goods, a measure analogous to the area judgments from Experiment 2. In a second phase of the experiment, they chose their preferred alternative from the same choice sets. The parameters of the Thurstonian choice model (e.g., means, variances, correlations) were estimated from the pricing data. Crucially, the target-decoy correlation ρ_{TD} was quite strong, a conceptual replication of the results of Experiment 2. The Thurstonian mode, conditional on the estimated parameters, was then used to make predictions for the choice data. The model was generally

successful in making predictions, albeit with some limitations which are discussed below.

4.1.1 Expanding the Paradigm to Preferential Choice

In Experiment 2, participants provided psychophysical ratings which were used to estimate the parameters of a Thurstonian choice model. This model, conditional on estimated parameter, was then used to make predictions for choices collected from the same set of participants.

The next step, in developing and testing both the experimental paradigm and the Thurstonian choice model, was to generalize the paradigm to a preferential choice environment. The goal of this research is to further the understanding of context effects, particularly the attraction and repulsion effect. Context effects have their empirical and theoretical origins in preferential (consumer) choice, so preferential choice provides a natural next step in this research program.

To test this approach in preferential choice, we collected continuous preference ratings from participants in the former of selling prices, a relatively analogous measure to the continuous area judgments collected in Experiment 2.

In most studies of consumer preference, researchers collect choice data rather than ratings. There are good reasons for this. The literature on willingness to pay (WTP; the largest amount a given consumer would be willing to pay for a particular product) has shown that, when responding to hypothetical survey questions, participants tend to over-estimate their WTP by a sizeable amount (Breidert et al., 2006; Schmidt & Bijmolt, 2020), c.f. Miller et al. (2011). Furthermore, WTP estimates may not simply be off by a constant; Jedidi and Zhang (2002) asked participants to state the price they would be willing to pay for a series of Compaq and Dell laptops, and, in a separate phase of the study, to indicate whether they would be willing to pay various actual listing prices for each laptop. Comparing the former stated WTP estimates to those

estimated from those estimated from the latter choice data, the results showed that the stated WTP values were sizeably higher, on average, than those estimated from choice data. The stated WTP and estimated WTP values were positively correlated, albeit fairly weakly (maximum $r = .43$). Furthermore, the authors fit two demand curves (one for stated WTP and the other for WTP estimated from choice data) to estimate the percentage of respondents willing to pay various prices for a laptop. The curve based on the stated WTP estimates tended to overestimate demand at low prices and simultaneously underestimate demand at high prices.

Bridges et al. (2012) conducted a study comparing WTP methods, asking hearing-loss patients to provide both Likert-scale (ordinal) ratings the importance of each attribute of hearing aids, as well as to complete a series of pairwise choices between hearing aids with varying attributes (a research technique known as conjoint analysis). The researchers then estimated WTP values for each attribute (e.g., how much would the average consumer be willing to pay for good battery life) using logistic regression. The mean estimated WTP values were ordinally related across methods, though the authors found that the Likert scale method tended to lead to floor and ceiling effects.

In a review of the WTP literature, Breidert et al. (2006) recommended strongly that researchers do not attempt to estimate WTP by directly asking consumers to provide price estimates. Other authors have made similar recommendations Jedidi and Jagpal (2009). Miller et al. (2011) compared the empirical value of both stated WTP and choice-based conjoint (CBC) analysis to two other approaches: the Becker, DeGroot, and Marschak auction (BDM, **becker<empty citation>**), where participants bid a price for a product and are required to purchase the product if a price drawn from a lottery is no larger than their bid, and the incentive-aligned choice-based conjoint (ICBC) analysis, a more complex method where the participant completes a hypothetical choice, the researcher infers their WTP based on these data, and this value is put through a BDM mechanism.

Using a cleaning product as the stimulus, the researchers found that all methods overestimated consumers' true WTP (using actual purchase data as the benchmark). BDM showed the smallest bias, followed by ICBC, stated WTP, and CBC. All methods are do reasonably well, however, in predicting actual purchase data (even given the aforementioned biases). The authors argued that when possible, researchers should use methods based on incentive alignment (i.e., BDM and ICBC) to estimate WTP. They do note that for many applications, however, stated WTP may work reasonably well, particularly when resources are limited and incentive-based methods would be difficult to implement.

In a meta-analysis, Schmidt and Bijmolt (2020) found that stated WTP methods actually showed less bias (i.e., overestimation) than indirect methods (e.g., BDM, ICBC, CBC). However, they also found that bias increased with actual prices of products, and that the bias was stronger in within compared to between-participant studies.

There is not a strong consensus on the best way to estimate pricing data from participants in a consumer choice study, nor do the measurement properties of WTP data appear to be well understood. These concerns, while crucial to applied researchers, are less pertinent to the current study, as the goal is to estimate prices on a relative, rather than absolute, scale. In other words, if participants over (or under) estimate their preferences by a constant, but generally rate higher valued options more highly than lower valued options, it may still be possible to obtain reasonable estimates on the ρ parameters required by the Thurstonian model. The lack of firm understanding on the measurement properties, however, may still limit the current approach.

Other researchers have studied context effects with ratings measures. Wedell and Pettibone (1996) collected Likert scale attractiveness ratings for attraction effect stimuli, generally finding that the presence of a decoy increased mean ratings for a target option. Windschitl and Chambers (2004) asked participants to judge the

likelihood of various events (also on a Likert scale). They found that the presence of a *dud* (highly unlikely) alternative increased participants' ratings of focal options. Cai and Pleskac (2023) and Fang et al. (2024) demonstrated similar effects with continuous probability judgments.

To the author's knowledge, however, there has been no research systematically connecting valuations and choices in a single experiment. This chapter seeks to fill this gap in the literature while also generalizing Chapter 2 to consumer choice. Continuous (price) data were collected to estimate the multivariate normal parameters μ and Σ for the choice model from Chapter 2, which was then used these to predict consumer choice data collected from the same group of participants.

4.1.2 Correlations in Preferential Choice

Chapter 2 demonstrated that the model can capture the repulsion effect in perceptual choice (Spektor et al., 2018), through the estimated target-decoy correlation ρ_{TD} . The current goal is to test whether 1) preferential stimuli also elicit these correlations and 2) the model can capture the repulsion effect in preferential choice, conditional on these estimated parameters.

The current experiment focuses on the attraction and repulsion effects. In the attraction effect, an asymmetrically dominated *decoy* option increases the choice share of a similar, but dominating *target* option at the expense of a dissimilar *competitor* option (Huber et al., 1982). The repulsion effect occurs when the competitor is chosen more often than the target (Simonson, 2014).

The literature on the repulsion effect in preferential choice is relatively sparse. Liao et al. (2021) varied TDD (target-decoy distance) in preferential choice and found a U-shaped relationship between TDD and the Relative Share of the Target (RST), with the attraction effect occurring at low and high TDD levels but the repulsion effect occurring at more intermediate TDD levels. Spektor et al. (2022) demonstrated

the repulsion effect in (risky) preferential choice, displaying stimuli graphically but in the same triangle display as Spektor et al. (2018). Participants chose the competitor more than the target at all levels of TDD, but the effect was strongest when TDD was low (similar to the results of Spektor et al. (2018), see Chapter 2).

Banerjee et al. (2024) demonstrated a binary-ternary form of the repulsion effect using the stimuli depicted in Figure ??, across multiple experiments. Participants saw either two or three options on each trial (i.e., binary or ternary choice sets), each varying on two dimensions. The options were consumer choice products from a number of categories (e.g., cameras, coffee makers, laptops), and the dimension names varied by product category (e.g., coffee makers' dimensions were brew speed and features). Attribute values were always displayed numerically using ratings of 1-100.

In each choice set of Banerjee et al. (2024)'s experiments, the target (t) was always the most extreme option - particularly high on one dimension and particularly low on the other dimension. The competitor (c) was a more intermediate option. For example, consider the blue-colored stimuli in Figure ???. t is very high on X and very low on Y . Compared to t , c is slightly worse on X but slightly better on Y . d , however, is as high as t on X but even worse on Y .

Using these stimuli, Banerjee et al. (2024) showed that the competitor's choice share increased from binary to ternary choice sets, $P(C|[T, C, D]) > P(C|[T, C])$, in violation of the regularity principle (Marley, 1989). They also showed that the repulsion effect decreased with TDD .

Banerjee et al. (2024)'s experiments compared binary to ternary choice rather than ternary to ternary choice, as in Spektor et al. (2018). To do a ternary-ternary comparison, one would "flip" the target and competitor labels, such that the target is the intermediate option, the competitor is the extreme option, and the decoy is nearby the new, intermediate target. Though Banerjee et al. (2024) were able to generate violations of regularity in this binary-ternary comparison, the results are

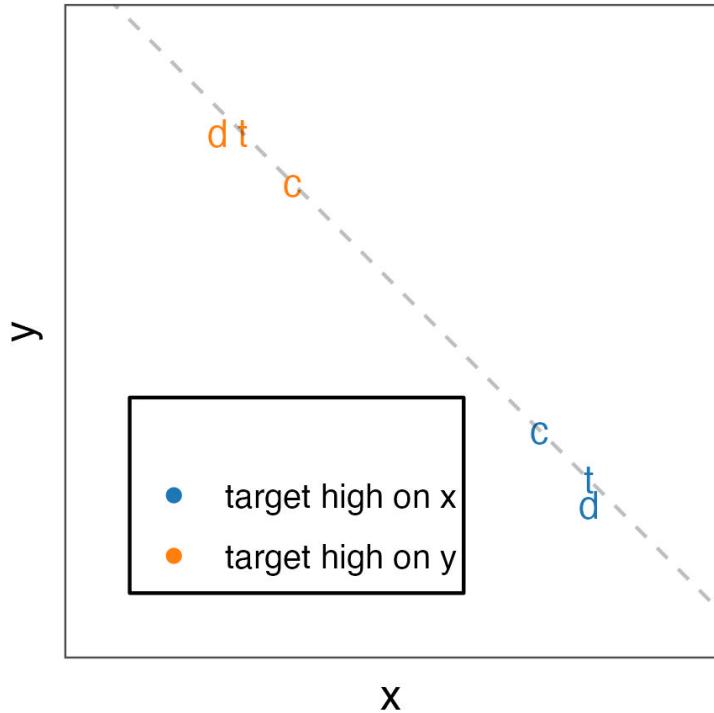


Figure 4.1. Graphical depiction of a subset of the stimuli used in Banerjee et al. (2024), Experiment 5. Target, competitor, and decoy are labeled t , c , and d , respectively. Dimensions are (generically) labeled X and Y. The choice sets vary based on whether the target is higher on the X or Y dimension. The dashed line is the diagonal line of indifference, assuming equal weighting of both the X and Y dimensions.

somewhat limited by the fact that the target was always more extreme than the competitor. In other words, though Banerjee et al. (2024) demonstrated that the choice share of the competitor option increased with the introduction of the decoy, this result may be due to extremeness aversion, decision-makers' tendency to not prefer options positioned more extremely in attribute space (Simonson & Tversky, 1992). The introduction of the decoy may highlight, to participants, the fact that the target is positioned particularly extremely compared to the target. For example, see their stimuli plotted in Figure ???. Consider the blue choice set, where the target is high on dimension X . Both T and C are relatively high on the X dimension and low on the Y dimension. C is, however, higher on Y while T is higher on X . In choosing T over C , consumers are forced to trade a small improvement in the X dimension for an option with a particularly dismal Y value. The introduction of the decoy may draw further attention to the Y dimension, leading to greater choice for C over T . This result is quite different than the results of Spekter et al. (2018), because the decoy was never positioned near the less extreme option.

Banerjee et al. (2024) argued that their results are consistent with the tainting hypothesis because the repulsion effect is strongest when the target and decoy are similar. . The tainting hypothesis is the idea that the decoy can sometimes diminish the perceived value of the nearby target (Simonson, 2014). They also argued that the decoy may have caused participants to focus more attention on the competitor's superior dimension. For example, in the blue choice set of Figure ???, the decoy is quite poor on Y while being equally good as the target on X , so participants may have focused more attention on Y , leading to a preference for the competitor.

Banerjee et al. (2024)'s results are worth exploring further. The current study uses their stimuli to measure participants' valuations of consumer products as well as collect choices from the same sets of products.

4.2 Experiment 4

The goal of Experiment 4 was to collect ratings and choice data in a preferential choice setting using (a subset of) Banerjee et al. (2024)'s Experiment 5 stimuli. These data were used to estimate the parameters of the choice model from Chapter 2.

For a ratings measure, participants were told assign selling prices to each option. Though people often overestimate prices (Breidert et al., 2006), pricing measures are approximately continuous¹ and monotonic with value (Miller et al., 2011) and are thus comparable to estimated area, the value measure in Experiment 2.

4.2.1 Methods

4.2.1.1 Participants

137 U.S. adults participated in the experiment. Participants were recruited from Prolific, an online platform for research studies, and they were paid \$5 for their participation. 24 participants were removed from all analyses for failing catch trials (see below), leaving a final sample size of $N = 113$.

4.2.1.2 Stimuli

The stimuli were borrowed from Banerjee et al. (2024)'s Experiment 1. The stimuli were hypothetical consumer choice products. All stimuli varied on two attributes, each of which ranged from 0-100. The products came from four different categories: televisions, washing machines, laptops, and microwave ovens.

In each phase, there were two types of trials: critical trials and catch trials. The critical trial stimuli are shown in Figure ??.

There were two types of critical trials: those designed to elicit the repulsion effect (a replication of Banerjee et al.), and those designed to elicit the attraction effect (because the stimuli are located in the center of the attribute space with a decoy

¹Here they only varied down to a single dollar. Thus, prices are approximately, but not perfectly, continuous.

option ● c ● d ● t

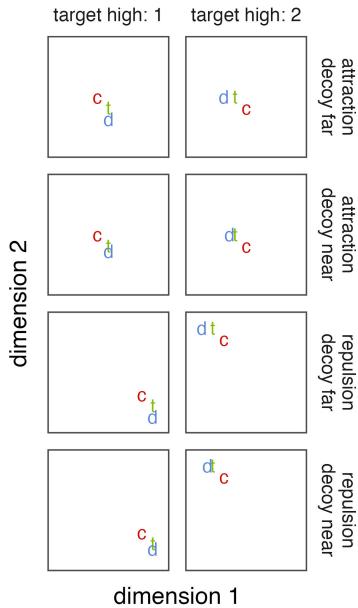


Figure 4.2. Graphical depiction of the critical stimuli from Experiment 4. Rows show the different choice sets designed to elicit the attraction/repulsion effect, with the label also specifying whether the decoy is near or far from the target in attribute space. The columns indicate which dimension the target is high on (1 or 2). Dimensions are labelled generically because their names vary with product category.

near one of two the focal options). These trials will be referred to as repulsion and attraction trials.

Within both the attraction and repulsion trials, the stimuli varied on which dimension the target was higher on (1 or 2), *TDD* (designated near or far from the target), and product category (microwaves, washing machines, laptops, and televisions). Note that to create the attraction trials, the target and competitor were shifted towards the center of the attribute space. That is, target and competitor are equally similar in both repulsion and attraction trials, but they are both more extreme in the repulsion trials.

The attribute names varied by category. Televisions varied on screen size and average lifespan. Washing machines varied on average lifespan and energy savings. Laptops varied on processing speed and memory (RAM). Microwave ovens varied on warranty and cooking power.

Within each category, one attribute was arbitrarily designated as dimension 1 and another as dimension 2 (see below).

The catch trials were designed such that one option was clearly superior to the other two. On each catch trial, the superior option's dimension values were each independently sampled from the vector [50, 55, 60, 65, 70, 75, 80, 85, 90, 95], while the two inferior options' dimension values were independently sampled from the vector [5, 10, 15, 20, 25, 30, 35, 40, 45, 50].

4.2.1.3 Design

The experiment took place in two phases: pricing and choice. The trial types were identical for both phases.

As discussed above, there were both critical trials and catch trials in each phase.

In both the rating phase and the choice phase, there were 32 critical trials (16 designed to elicit the repulsion effect and 16 designed to elicit the attraction effect) and 8 catch trials.

The experiment did not contain binary repulsion effect trials, as in Banerjee et al. (2024)'s experiments, so this chapter cannot assess the repulsion effect to the same degree as those authors. The goal of this experiment was to measure valuation correlations in consumer preference and relate them to choice.

4.2.1.4 Procedure

The experiment took place in two phases: a pricing phase and a choice phase.

Prior to the pricing phase, participants were provided with a cover story. According to the cover story, they were told to imagine that they run an online consumer

goods resale business. On each trial, they would see three products, and they needed to determine which price to sell each product for. Participants were told that the ratings varied from 0 to 100, where 0 was the lowest possible rating and 100 was the highest possible rating. Participants were also told that they should determine a price that maximizes both profit and the likelihood the product is purchased.

During the pricing trials, the three options were presented in a table, with the options in rows and the attributes in columns. All attributes were represented numerically. The options were labeled A, B, and C. The last column of the table contained three boxes, which participants used to type in their selling price for each option. Participants typed in their selling price, and then clicked a button on the screen to advance to the next trial. Both option order and dimension order was randomized on each trial. See Figure ?? (left panel) for an example trial. Participants were only allowed to enter in whole numbers (e.g., dollars not cents).

After completing all pricing trials, participants moved onto the choice phase. Prior to this phase, participants were told to imagine that they were purchasing consumer goods in bulk. On each trial, they were to select the option they wanted to purchase.

As in the pricing phase, options were presented in a table. See Figure ?? (bottom) for an example trial.

In both phases, trial order and option order within each trial were randomized.

After the choice phase, participants completed a short demographics form before ending the experiment.

4.2.2 Results

4.2.2.1 Data Processing

First, 24 participants were removed from the data because they did not pass at least 5/8 catch trials in both the pricing phase and the choice phase. To pass a pricing catch trial, the participant needed to price the superior option at least as high as the

Microwave ovens



Please enter the price you want to sell each product for.

Product	Cooking power (1=worst, 100=best)	Warranty (1=worst, 100=best)	Your Selling Price
Product A	60	75	\$ <input type="text" value="0"/>
Product B	5	30	\$ <input type="text" value="0"/>
Product C	45	25	\$ <input type="text" value="0"/>

Televisions



Please select one of the following products::

Product	Average lifespan (1=worst, 100=best)	Screen size (1=worst, 100=best)	
Product A	25	30	<input type="radio"/>
Product B	35	10	<input type="radio"/>
Product C	70	85	<input type="radio"/>

Figure 4.3. Sample trials from the pricing phase (top) and choice phase (bottom) in Experiment 4.

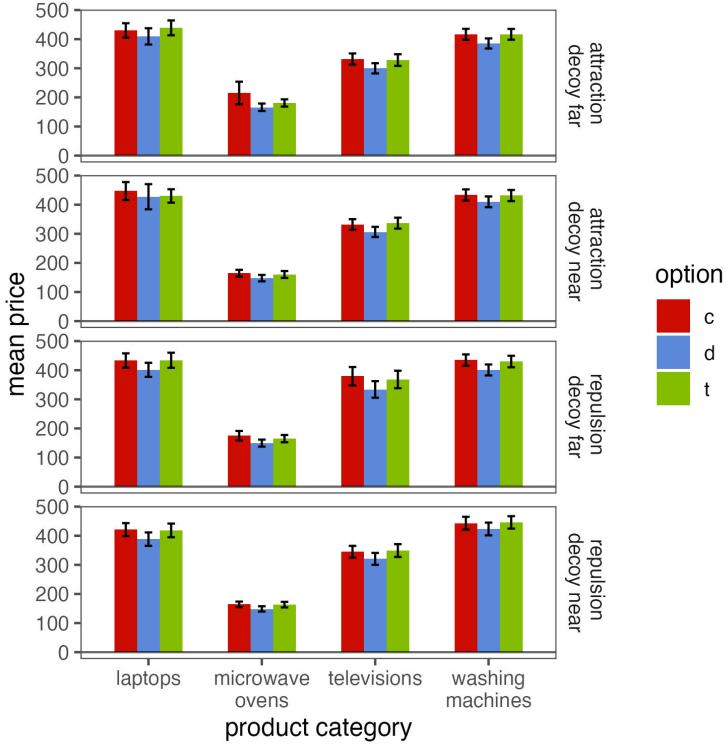


Figure 4.4. Experiment 4 mean prices by product category, option, and trial type. Error bars are ± 1 SEM.

other two inferior options. To pass a choice catch trial, the participant needed to select the superior option.

4.2.2.2 Pricing Trials

First, mean prices were computed for the target, competitor, and decoy options within each trial type and product category. These means are shown in Figure ??.

On average, participants priced the target and competitor higher than the decoy. They also assigned higher prices to products that are typically more expensive (e.g., washing machines are more expensive than microwave ovens). This suggests that participants were engaged with the task and, in a relative sense, performed the task well.

A Bayesian modeling analysis was performed to estimate the parameters of the Thurstonian choice model, comparable to that of Experiment 2. This analysis was

used to estimate the means, variances, and correlations for the pricing data and perform inference on these data. The details of the estimation and the results are presented in the Appendix, with the exceptions of the posterior distributions for several crucial parameters (i.e., means and correlations). The main text discusses descriptive statistics for these parameters, but whenever it is claimed that one parameter value is greater than another, the reader can see the Appendix for statistical inference which supports these conclusions.

To account for participant-level differences in pricing, all prices were normalized within each participant. To avoid the influence of outliers on correlation estimates, 33 trials in which at least one price z-score had an absolute value > 3 were also removed, leaving 3,583 trials remaining.

The mean prices were computed for target, competitor, and decoy options within each trial type, collapsing over product category and TDD, shown in Figure ???. In both repulsion and attraction effect trials, the target and competitor do not differ in mean price, while both are priced higher than the decoy option.

Correlations between the prices assigned to options were computed within each trial type. The normalized prices are plotted in a series of scatterplots, with the Pearson correlations included. See Figure ?? for repulsion effect scatterplots and Figure ?? for attraction effect scatterplots.

Note that in both Figure ?? and Figure ??, the decoy is occasionally priced higher than the target or the competitor (i.e., the points above the diagonal in the target-decoy and competitor-decoy scatterplots). This may be due to participant inattention or response error, as the decoy should never be priced higher than the target provided adequate attention.

Posterior distributions of the correlations are plotted in Figure ???. The repulsion trials, replicated the results of Experiment 2, in that $\rho_{TD} > \rho_{TC}$ and $\rho_{TD} > \rho_{CD}$. The results also showed that $\rho_{TC} > \rho_{CD}$, while in Experiment 2 $\rho_{TC} \approx \rho_{CD}$. In the

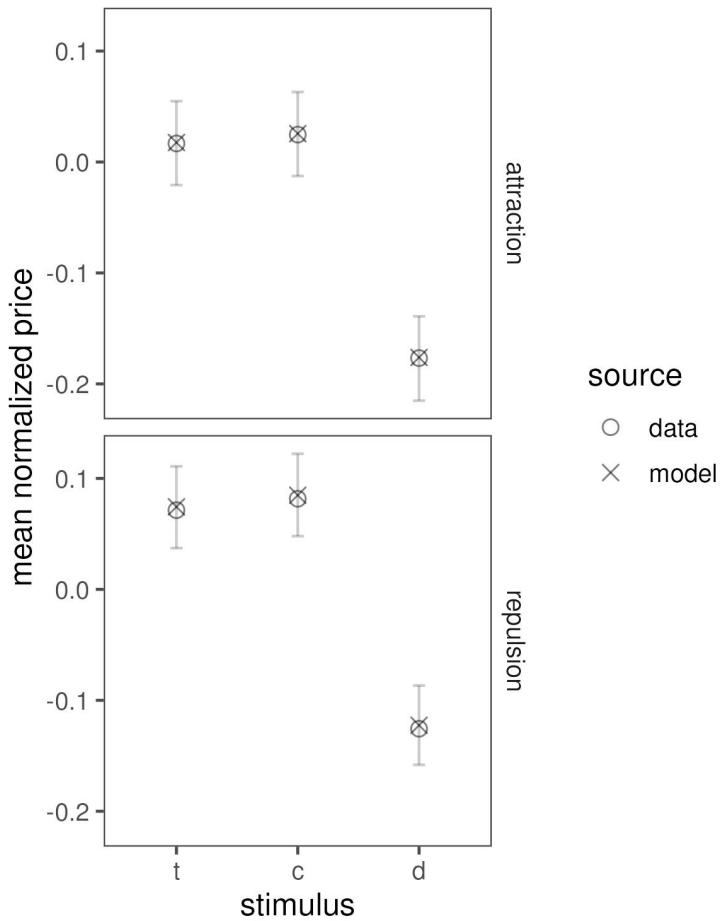


Figure 4.5. Experiment 4 mean prices for target, competitor, and decoy options in both repulsion and attraction trials. Model values are the means from the posterior distribution, and error bars are 95% HDIs.

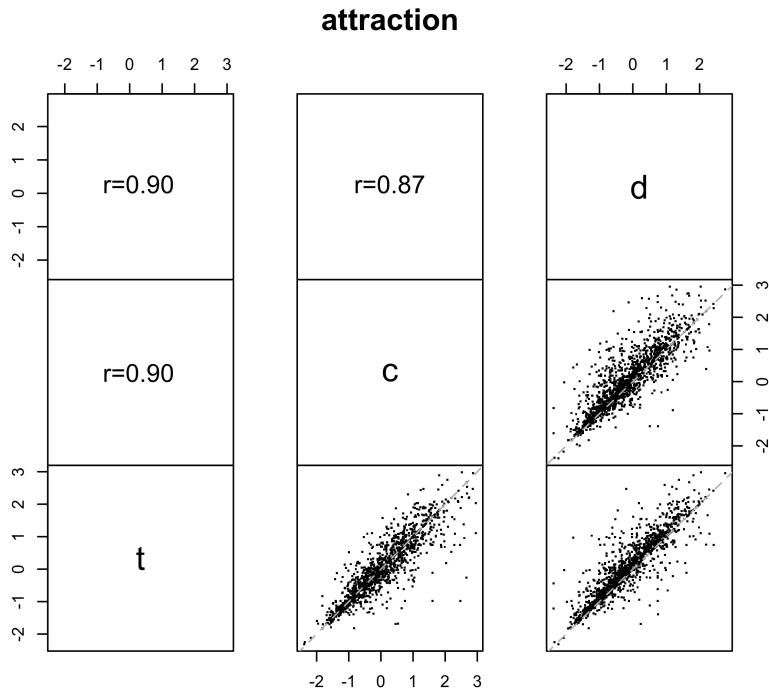


Figure 4.6. Experiment 4 correlation plots for all pairs of stimuli, in trials designed to elicit the attraction effect. t=target, c=competitor, and d=decoy.

attraction trials, the correlations showed a slightly different pattern, where $\rho_{TC} \approx \rho_{TD} > \rho_{CD}$. In other words, the target and competitor are approximately equally similar as target and decoy, which are in turn more similar than competitor and decoy.

4.2.2.3 Choice Trials

Next, the choice proportions were computed for the critical choice trials. These results are collapsed across participant (due to the small n per subject), as well as product category and the target's superior dimension.

Participants seldom chose the decoy, another indication that they were attentive to the task. This also provides evidence that decoy selection is far more common in perceptual choice than preferential choice.

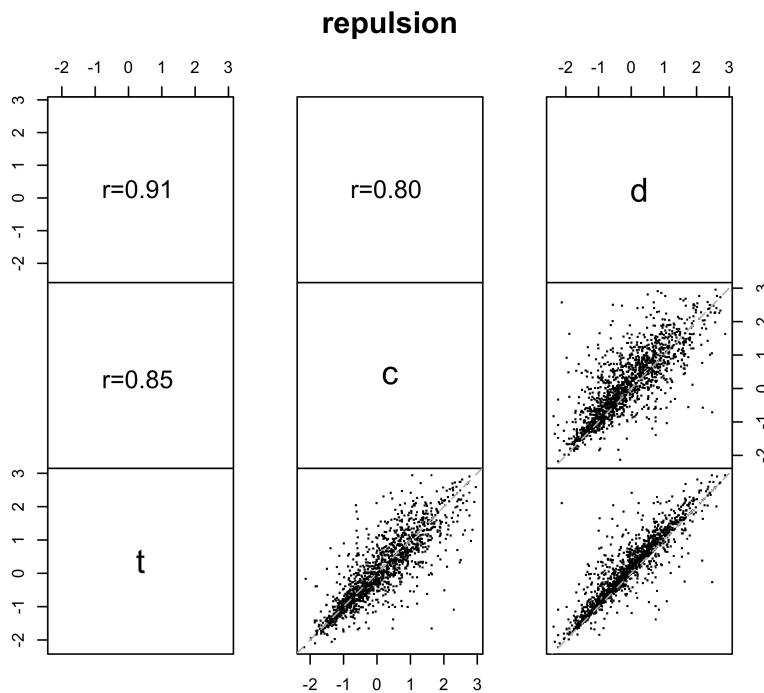


Figure 4.7. Experiment 4 correlation plots for all pairs of stimuli, in trials designed to elicit the repulsion effect. t=target, c=competitor, and d=decoy.

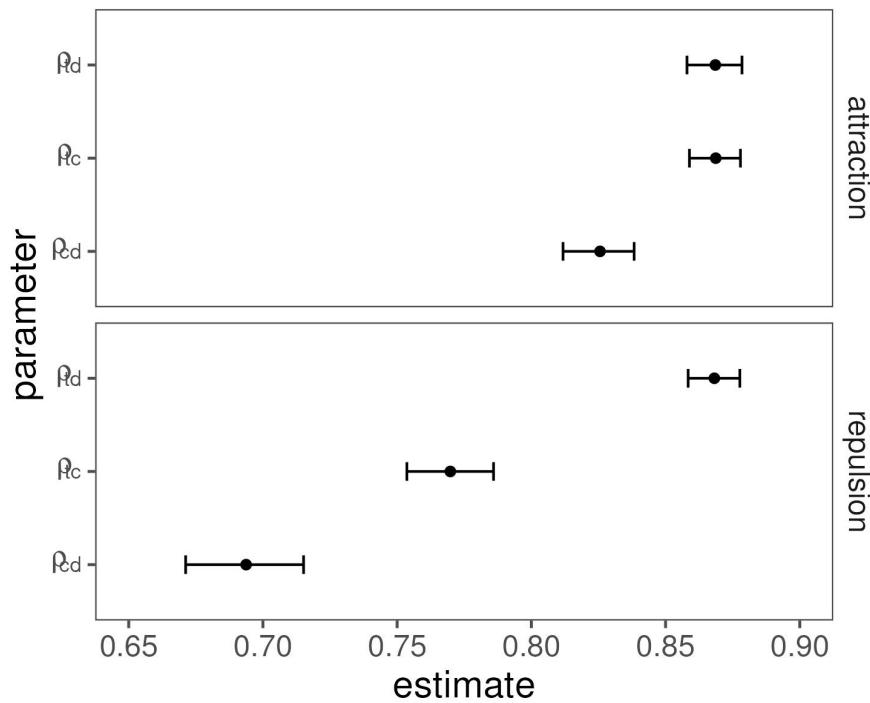


Figure 4.8. Experiment 4 posterior distributions on correlation parameters. Dots are means, and error bars are 95% HDIs.

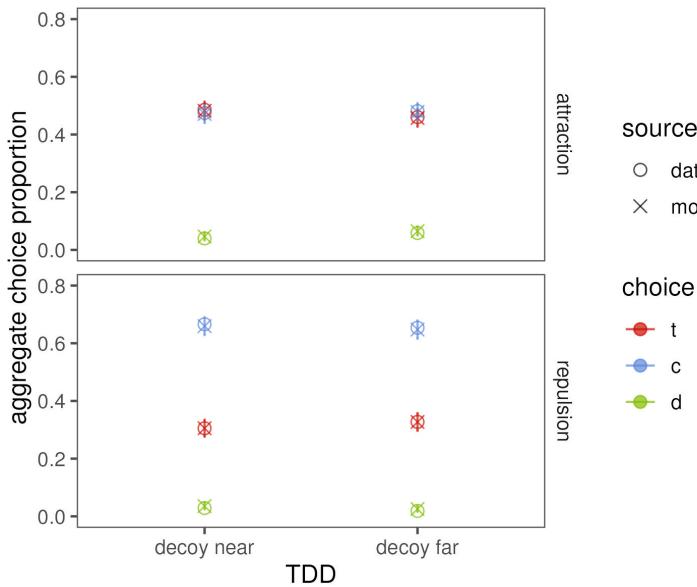


Figure 4.9. Experiment 4 aggregate choice proportions for each trial type, TDD, and option. Data points are aggregate choice proportions, while model points are posterior means computed from the Bayesian Dirichlet-multinomial model presented in the Appendix. Error bars are 95% HDIs.

These choice proportions are plotted in Figure ???. The results clearly show a null attraction effect, regardless of *TDD*. Participants chose the target and competitor options at equal rates. This is likely due to the strong similarity of target and competitor. The target and competitor were particularly close to one another, a design which is atypical of attraction effect studies.

The results show a strong repulsion effect, where the participants generally prefer the competitor option to the target option. These data replicate the results of Banerjee et al. (2024), albeit without the binary-ternary comparison included in their experiments. These results may be due to participants simply preferring the less extreme option, as discussed in the introduction to this chapter.

4.2.2.4 Model Simulations

As in Chapter 2, The parameter estimates for the Thurstonian choice model,i.e., μ and Σ , were used to simulate choice. Though the model was originally applied to

perceptual choice, it is a general purpose choice model where the primary dimension is value, and the model is agnostic about what this value refers to.

As in Chapter 2, the model assumes that value is stochastic while choice is deterministic². The model always chooses the option perceived as most valuable, regardless of the magnitude of the difference between the winner” and runners-up. That is, given a vector \mathbf{X}_i of perceived values on trial i with set K , the probability a participant selects stimulus j is:

$$P(j|i, K) = P(\mathbf{X}_{ij} > \mathbf{X}_{ik}), \forall k \in K, j \neq k \quad (4.1)$$

1,000,000 simulations of the model were run, with the results plotted against the data in Figure ??.

The model mispredicts the attraction trials. It predicts a slight repulsion effect when in fact the data suggest a null effect. This is similar to the results of Experiment 2 (horizontal condition), where the model predicted a repulsion effect even when the empirical data showed a repulsion effect, due to the influence of the target-decoy correlation.

The model does, however, successfully predict a qualitative repulsion effect, i.e., $P(C) > P(T)$. However, it strongly overpredicts the decoy choice proportions. It also underpredicts competitor choice proportions. The model relies on the correlation between target and decoy choice proportions to predict the repulsion effect. According to the model because the target and decoy are strongly correlated, it is more likely that the utility of the decoy exceeds the target than the competitor. The decoy then takes away choice shares from the competitor. This prediction makes sense in percep-

²This assumption also assumes ties are not possible, which is true if and only if value is truly continuous.

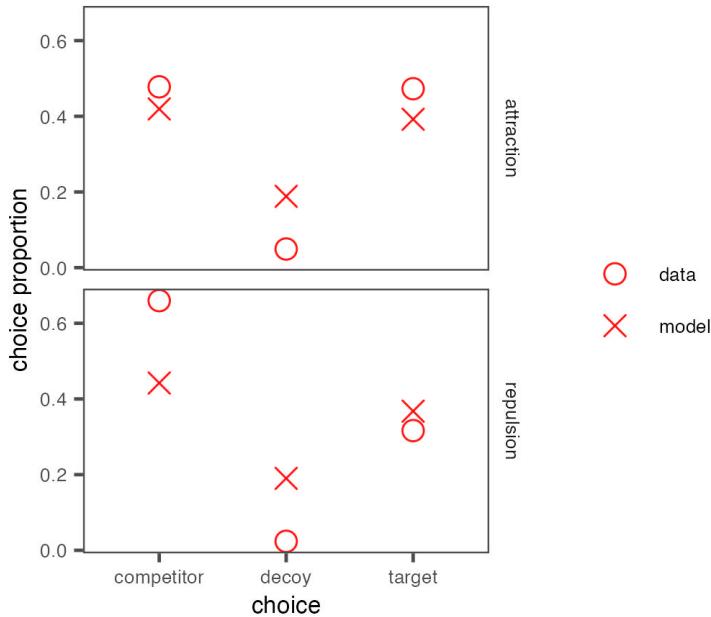


Figure 4.10. Experiment 4 data vs. Thurstonian model predictions.

tual choice, where stimulus discriminability is not a given and participants pick the decoy roughly 20-30% of all trials (see Experiment 2). In preferential choice, participants almost never pick the decoy, and researchers assume that any participant with sufficient attention can always discriminate the target and competitor from the decoy. Thus, though the model can qualitatively predict a repulsion effect, the mechanism by which it does so is implausible.

This model also does not account for a potential extremeness bias. That is, it is plausible that the competitor and target are indeed equally valuable on average, but that the competitor is chosen more often due to participants' unwillingness to choose the target, which is more extreme than the competitor. The current model does not account for this bias, and thus the conclusion that the repulsion effect cannot be predicted by the Thurstonian choice model may be premature.

4.3 Discussion

This experiment generalizes the paradigm of Chapter 2 to preferential choice. Participants completed two phases; in the first phase, they assigned a selling price to each of three options on each trial. In the second phase, they selected the option they would most prefer. Option sets were designed to either elicit the attraction effect or the repulsion effect. These prices were used to estimate the mean value of each option as well as the correlations between all pairs of options. In doing so, this work extends not only the experimental paradigm of Chapter 2, but also the modeling framework, to a preferential choice setting.

Crucially, when estimating the correlations, the data replicated the result of Experiment 2, that, in the repulsion effect $\rho_{TD} > \rho_{TC}$ and $\rho_{TD} > \rho_{CD}$. The inferential statistics also showed that $\rho_{TC} > \rho_{CD}$. This result was unexpected, but it may be due to the fact that, because both target and competitor are high on one dimension and low on another. The competitor may draw attention to the dimension on which it is best, a dimension in which the decoy is slightly worse on. It may be easier, or at least more likely, for participants to compare target and competitor to one another than it is to compare the competitor to the decoy. Participants also typically (but not always) priced the decoy as less than the target and competitor. There thus may have been an upper limit to the decoy pricing which could affect the correlation estimates.

In the trials designed to elicit the attraction effect, Experiment 4 showed that $\rho_{TC} \approx \rho_{TD} > \rho_{CD}$. This pattern is likely due to the similarity of target and competitor on both attributes (i.e., one option's dimension values were [50, 60] while the other's was [60, 50]). The target and competitor are easily comparable to one another, and the tradeoff on attributes is negligible. Furthermore, the target and competitor are both located in an intermediate region of attribute space rather than in an extreme region as in the repulsion effect trials.

The choice results replicated those of Banerjee et al. (2024), in that participants chose the competitor more than the target in each of the repulsion effect choice sets. However, given that the decoy location did not vary (i.e., the competitor was always less extreme than the target), nor did the experiment include a binary-ternary choice comparison, these results may be due to a bias for the less extreme option, which happens to be the competitor in this case. Future research should include binary-ternary and ternary-ternary trials to generalize these results.

The strong correlation between target and decoy valuations, compared to competitor-decoy valuations, appears to be a robust finding, holding across perceptual and preferential choice. It is worth exploring, in greater detail, what causes these correlations. One strong hypothesis, considered by other researchers, is that these correlations are measures of similarity.

In the attraction and repulsion effect, the target and decoy are designed such to be more similar to each other than either option is to the competitor. It may be that, by measuring the correlation in valuations, we are actually measuring the *similarity* between options. Indeed, the similarity of target and decoy was a primary motivation for the original demonstration of the attraction effect (Huber et al., 1982).

Other researchers have argued that, in models of choice, correlations between options measure similarity. Kamakura and Srivastava (1984) parameterized correlations in a choice model as an exponentially decreasing function of distance in attribute space, such that options located more closely in attribute space are more strongly correlated. They also showed that, when embedded in the multinomial probit model, a model based on this parameterization can successfully predict the similarity effect - the finding that the introduction of a similar option can sometimes decrease the choice share of a focal option Tversky (1972). Their model is nearly identical to the model of similarity developed by Shepard (1987), which also models similarity as an exponentially decreasing function of distance in psychological space and has success-

fully accounted for empirical data across multiple domains (Nosofsky, 1986; Roads & Love, 2024).

Natenzon (2019) implemented a model using the multinomial probit, allowing the correlations between options was also a decreasing function of distance in attribute space. They used cosine similarity, where similarity is the cosine of the angle formed by options in bivariate attribute space, to measure correlations and showed that not only can the model explain choice reversals (i.e., context effects).

Spektor et al. (2019) developed a model, known as the accentuation of differences (AOD) model, to account for context effects in choice. According to their model, the subjective value of each option can be either increased or decreased by the presence of similar options, where similarity is also an exponentially decreasing function of distance in attribute space. This similarity-based mechanism is governed by a free parameter; the model can account for either the similarity effect (if option value is decreased by similar options) or the attraction effect (if option value is increased by similar options), but not both effects simultaneously.

These correlations may also be measuring the ease of comparability between pairs of options. Comparability has previously been shown to drive the attraction effect (Cataldo & Cohen, 2019; Noguchi & Stewart, 2014), and several models of context effects rely on comparisons of options on single attributes to generate context effects (Roe et al., 2001; Trueblood et al., 2014). Supporting this hypothesis is the finding that $\rho_{TC} > \rho_{TD}$ in the trials designed to elicit the attraction effect, when the target and competitor were quite similar on each attribute and thus easier to compare.

Future work could test these hypotheses by systematically manipulating option comparability and assessing whether the correlations vary with comparability. Chapter 5 works towards this, by testing the effect of comparability on choice, though future work should measure inter-option correlations in choice environments of varying comparability.

CHAPTER 5

COMPARABILITY IN PERCEPTUAL CHOICE

5.1 Introduction

Thus far, the dissertation has explored perceptual and decisional processes in both perceptual and preferential choice. Experiment 2 showed that stimuli which are more similar to one another, and are thus more easily comparable, generate valuations with stronger correlations. This result holds across both perceptual choice (Chapter 2) and preferential choice (Chapter 4). The comparison process is defined as a cognitive operation where a participant attends to the relative difference between two options on a choice set, typically (though not necessarily) on a single dimension.

Embedded in a Thurstonian choice model (Thurstone, 1927), and conditional on parameters estimated from Experiment 2 data, these correlations can produce the repulsion effect (Simonson, 2014; Spektor et al., 2018) because the decoy option, whose value is tightly correlated with the target, occasionally exceeds the target in perceived value and thus takes choice shares away from the target. The model can also predict the attraction effect, but parameters estimated from actual empirical data could not predict the attraction effect.

In this chapter, I directly manipulate stimulus comparability in a perceptual choice task, to explicitly test the relationship between comparability and choice. I first review previous literature on comparability and then present the results of a perceptual choice experiment.

5.1.1 Previous Literature on Comparability

Other researchers have studied the comparison process in decision-making, particularly in high-level choice (e.g., preferential). Below, relevant preferential choice research is introduced before transitioning to relevant research on perceptual choice.

Chang and Liu (2008) tested the compromise effect by varying the presentation of options. In the compromise effect, a “middle” ground option decreases the choice share of two dissimilar, “extreme” options. Chang and Liu (2008) displayed the options either by-alternative format, where option names are listed as columns while attribute values are listed as rows, or by-attribute, where option attributes are columns while option names are rows. The former display makes it more difficult to compare options on a single attribute, while the latter makes it easier. Chang and Liu (2008) found that listing options by-attribute increased the choice share of the compromise option, relative to a by-alternative display.

Cataldo and Cohen (2019) replicated this result, also finding that a by-alternative format nullified the attraction effect. The authors attributed this result to a “flexible comparison process”, where the comparison strategy is influenced by display format. According to this account, the by-attribute format increases the ease of target-decoy comparisons relative to the by-alternative format.

Noguchi and Stewart (2014) studied context effects using eye-tracking, showing that people tend to compare pairs of options on a single attribute, and that this appears to drive the attraction, similarity, and compromise effect. In their study, participants’ eye movements showed that they were more likely to transition between options on a single dimension than they were to transition between dimensions within a single option. They also found that transitions between two options are negatively related to the choice share of a third option.

Hayes et al. (2024) manipulated attribute comparability, such that the dimensions of each option were either measured in the same unit (high comparability, e.g., 0-

10 ratings) or in different units (low comparability, e.g., CPU speed vs. RAM for laptops). They found that the attraction effect only occurred in the low comparability condition.

Hasan et al. (2025) conducted a large scale replication of the attraction effect, systematically varying option order, presentation mode (numerical or graphical), and presentation format (by-attribute or by-alternative). They found that the attraction effect was stronger when the target and decoy options were adjacent to one another, presumably because this allows for easier target-decoy comparison. The attraction effect was stronger when attributes were presented numerically compared to graphically, a result found by other researchers (Frederick et al., 2014; Yang & Lynn, 2014). They did, however, fail to replicate Cataldo and Cohen (2019)'s finding that the attraction effect varies with by-alternative vs. by-attribute format.

Hsee and colleagues (Hsee et al., 1999; Hsee, 1996, 1998; Hsee & Leclerc, 1998) have also shown that the comparison of options affects consumer behavior. For example, they repeatedly showed that participants' evaluation of a given option can change with the addition of a reference point (i.e., lower valued options improve with a high reference point and vice versa). That is, participants' judgments can reverse when options are evaluated jointly, compared to separately (Hsee et al., 1999).

Several computational models of decision-making also rely on the comparison process. Roe et al. (2001)'s Multialternative Decision Field Theory (MDFT) model also assumes that options accumulate evidence through comparison, and that comparisons between nearby options exhibit greater influence on preference. According to Trueblood et al. (2014)'s Multiattribute Linear Ballistic Accumulator Model (MLBA), each option accumulates evidence through pairwise comparisons to all other available options. These comparisons are modulated by several processes, such as distance in attribute space and extremeness aversion. Other decision models incorporate similar

mechanisms (Landry & Webb, 2021; Noguchi & Stewart, 2018; Usher & McClelland, 2004; Wollschläger & Diederich, 2012) (c.f. Bergner et al. (2019) and Bhatia (2013)).

Trueblood et al. (2022) argued that options that are more similar garner more attention in the comparison process. They presented a simple Markov model where pairwise comparisons on a single attribute determine the accumulation of preference, and the time spent on a comparison is an increasing function of the similarity of options on the attribute. Their model can successfully, and simply, account for the “big three” context effects (attraction, compromise, and similarity).

5.1.2 Comparability Effects in Perceptual Choice

There has been other research, albeit relatively limited, on the comparison process in perceptual decision-making. Much of this work has focused on the spatial layout of the options and its effect on perceptual context effects.

Trueblood et al. (2022) re-analyzed previous perceptual choice context effect data (Trueblood et al., 2015) by examining the order of the options on the screen. They found that the attraction effect was strongest when the target and decoy were next to each other, while the effect was weak (or even absent) when the options were separated spatially. Their conclusion, supported by a modeling analysis, was that people tend to compare pairs of options which are spatially closer to one another more often than pairs further away from one another.

Evans et al. (2021) found a similar result in perceptual choice, though in their experiment the options were separated both spatially and temporally. In their experiment, participants saw three rectangles, presented sequentially, and selected the largest rectangle after all stimuli were presented. They found that orders in which the target and decoy were presented in the latter two positions elicited an attraction effect, whereas orders in which the competitor and decoy were presented in the latter two positions tended to elicit a repulsion effect. They interpreted their results as

evidence that the comparison process can be altered through spatial and temporal properties of the stimuli.

Another interpretation of their results, and those of Trueblood et al. (2022), is that by altering the location and timing of the stimuli, the researchers are also altering the comparability. In the perceptual model of Chapter 2, increased comparability is represented by an increase in perceptual correlation. As shown previously, this perceptual correlation can create a repulsion effect by allowing the decoy to more easily take choice shares from the target.

The goal of this experiment was to isolate the effect of comparability from context effects. Below is presented a simple perceptual choice experiment where participants saw three rectangles at a time and selected the largest one. On critical trials, two of these rectangles were equally large but oriented differently (i.e., *focal* rectangles, as in Experiments 1, 2, and 3). A third *decoy* option was a symmetrically dominated decoy - equally similar to either option. One of the two focal options as the *target* based on its proximity and comparability to the decoy.

To manipulate comparability, the positioning of the options on screen was systematically manipulated. Options were displayed in one of four ways: all aligned in a horizontal line, as in Trueblood et al. (2013); two adjacent options aligned vertically, with a third option positioned in a different vertical location; and the triangle alignment from Spektor et al. (2018). See Figure ?? for example stimuli.

Proximity is defined as closeness in space, and comparability is defined as the ease of comparison between two stimuli. The critical display is the two-aligned condition, where the target and decoy are positioned such that they are easily compared, while the competitor is located where comparisons are more difficult. Based on the results of Chapter 2, ease of comparability should increase the correlation between the target and decoy and result in a *decrease* in the target's choice share in the two-aligned condition, relative to the none aligned and all aligned conditions. In the model and

experiment presented in Chapter 2, the similarity of the target and decoy caused the decoy to take choice shares away from the target. Here, both focal options are equally similar to the target, but the target is located closer to the decoy and is more comparable. These predictions are generally borne out in the data, albeit with limitations which will be discussed below.

5.2 Experiment 5

Experiment 5 addresses the effect of comparability in perceptual choice using *symmetrically dominated* decoys. A symmetrically dominated decoy is dominated by both focal options but is also equally similar to both options. Thus, the terms target and competitor, which have been used throughout this dissertation, take on a different meaning here. Here the target is defined as the option that is both adjacent to and easily comparable to the decoy. Based on the experimental and modeling results of Chapter 2, it was predicted that the choice share of the target will be reduced when it is particularly comparable to the decoy.

5.2.1 Methods

5.2.1.1 Participants

231 undergraduate students at the University of Massachusetts Amherst participated in the lab, in exchange for course credit. 17 participants' data were removed from all analyses because they failed to achieve at least 80% correct on catch trials (see below), leaving a final sample size of $N = 214$.

5.2.1.2 Stimuli

The stimuli were gray-scale rectangles and squares, varying systematically on height and width.

The critical stimuli are depicted in Figure ???. The focal stimuli (H and W) are equal in area and fell on two diagonals, the upper diagonal area being 25000 square

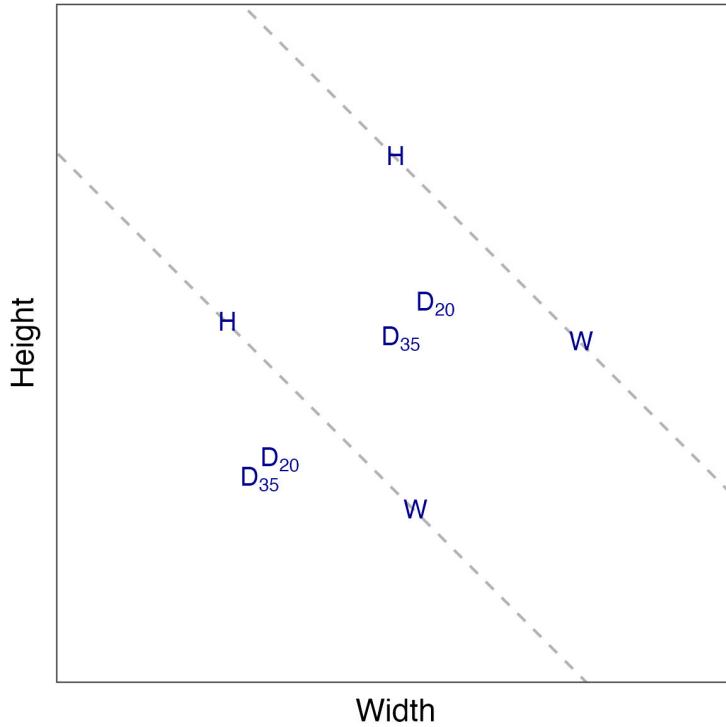


Figure 5.1. Graphical depiction of critical stimuli from Experiment 5. The stimuli fall on two diagonals, referred to as upper and lower. The H rectangles are taller than wide, while the W rectangles are wider than tall. The decoy (D) rectangles are equally wide and tall (i.e., squares). The decoy subscripts indicate the *TDD %*.

pixels and the lower diagonal being 7581px^2 . On the lower diagonal, the focal stimuli had dimension values of 57 and 133 pixels, while on the upper diagonal, the the focal stimuli had dimension values of 127 and 141 pixels. The decoy options were either 20% or 35% smaller than the focal options. This was determined based on the results of pilot data and with the goal of making the decoy somewhat difficult to discriminate from the focal options. For the manipulation to work, participants needed incentive to consider the decoy and thus to compare it to the two focal options.

The stimuli were arranged in one of four displays: all-aligned, two-aligned, none-aligned, or triangle. See Figure ?? for sample trials.

In the all-aligned display, all stimuli were arranged in a horizontal array, as in the experiments of Trueblood et al. (2013) and Spektor et al. (2018), Experiment 4.

In the two-aligned display, two options were aligned horizontally in the top-left and top-middle positions, while the third option was placed in the bottom-right position of the screen. This is a crucial condition and an instantiation of the comparability hypothesis, in which the comparison of the two aligned options is far easier than all other pairwise comparisons.

In the none-aligned display, all options are located in different vertical and horizontal positions, such that all comparisons should be more difficult, as determining the relative areas between rectangles is no longer straightforward.

The triangle display is identical to the triangle display of Experiments 1 and 2, with the exception that on half of all triangle display trials, the triangle was inverted. Note that this is distinct from the two aligned condition, as the options are located in distinct vertical and horizontal positions and it is difficult to determine the relative sizes between rectangles. The triangle display condition was collected for future analyses but is not germane to the current research question, and it will be excluded from critical analyses.

In all displays, the horizontal distances between all options was constant.

In addition to varying diagonal, *TDD*, and display, option order also varied, such that all six orders (*DHW*, *DWH*, *HDW*, *HWD*, *WDH*, and *WHD*) were equally common.

There were other types of stimuli on non-critical trials: filler-random, filler-square, and catch.

On filler-random trials, three options were randomly generated by sampling a height and width from the $U(57, 200)px$ distribution. Filler-random trials were included to avoid participants noticing the manipulation on the critical trials and to include enough challenging trials to keep participants engaged in the task.

On filler-square trials, a square was randomly generated by sampling a side length from the $U(57, 200)px$ distribution. Then, two non-square rectangles were generated

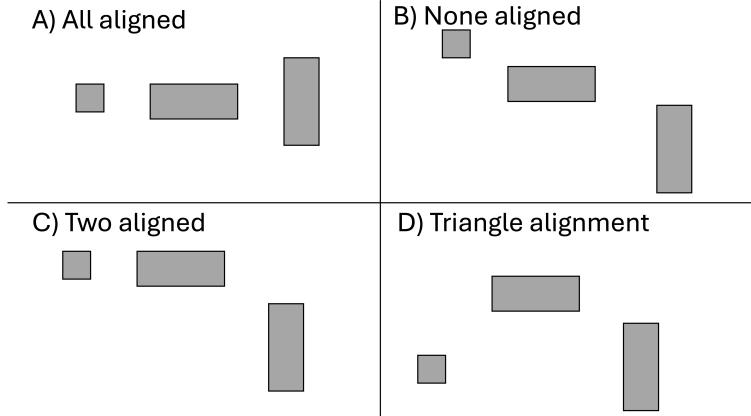


Figure 5.2. Sample critical trials from Experiment 5. A) all aligned. B) Two aligned. C) None aligned. D) Triangle alignment.

by sampling a height and width from a the $U(57, S)px$ distribution, where S is the side length for the square. This manipulation ensured that the square was always the largest option on these trials. These trials were included to ensure that participants did not learn to ignore the squares, as the critical trials rely on participants comparing the squares to the focal options.

On catch trials, one large option was randomly generated by randomly sampling a stimulus from the upper diagonal (see Figure ??). Two smaller options were randomly sampled from the lower diagonal.

5.2.1.3 Design

As discussed above, there were four types of trials: critical trials, filler-square trials, filler-random trials, and catch trials. The study took place in four blocks.

This was a 2 (diagonal: lower, upper) \times 2 (*TDD*: 20%, 35%) \times 4 display: (all-aligned, two-aligned, none-aligned, triangle) \times 6 (order: *DHW*, *DWH*, *HDW*, *HWD*, *WDH*, and *WHD*) within-participants study. Each participant completed 4 trials for all combinations of these factors (1 per each of the four blocks), except for

the two-aligned trials, for which they completed 8 trials (2 per each of the four blocks). Thus, there were a total of 480 critical trials ($(2 * 2 * 3 * 6 * 4) + (2 * 2 * 1 * 6 * 8) = 480$).

On each of the non-critical trials, stimulus order was randomized. Additionally, one of the four displays (all-aligned, two-aligned, none-aligned, triangle) was selected at random.

There were 40 filler-random trials per block for each of four blocks, leading to a total of 160 filler-random trials. There were 40 filler-square trials per block for each of four blocks, leading to a total of 160 filler-square trials. There were 10 catch trials per block for each of four blocks, leading to a total of 40 catch trials.

There were a total of 840 trials in the experiment (480 critical + 160 filler-random + 160 filler-square + 40 catch=840).

5.2.1.4 Procedure

On each trial, participants saw three rectangles, labeled ‘1’, ‘2’, and ‘3’. Participants were told to select the largest rectangle. They made their choice by pressing the corresponding key on the keyboard.

As mentioned above, the experiment was split into four blocks. There was a 15-second break between blocks.

5.2.2 Results

5.2.2.1 Data Processing

In addition to removing participants who failed to meet the 80% correct criterion for catch trials, 2,319 trials with RTs $< 100ms$ or $> 10,000ms$ were removed from all analyses.

5.2.2.2 Catch and Filler Trials

On average, participants performed well above chance on the catch, filler-random, and filler-square trials, including on all display types. See Figure ?? for data.

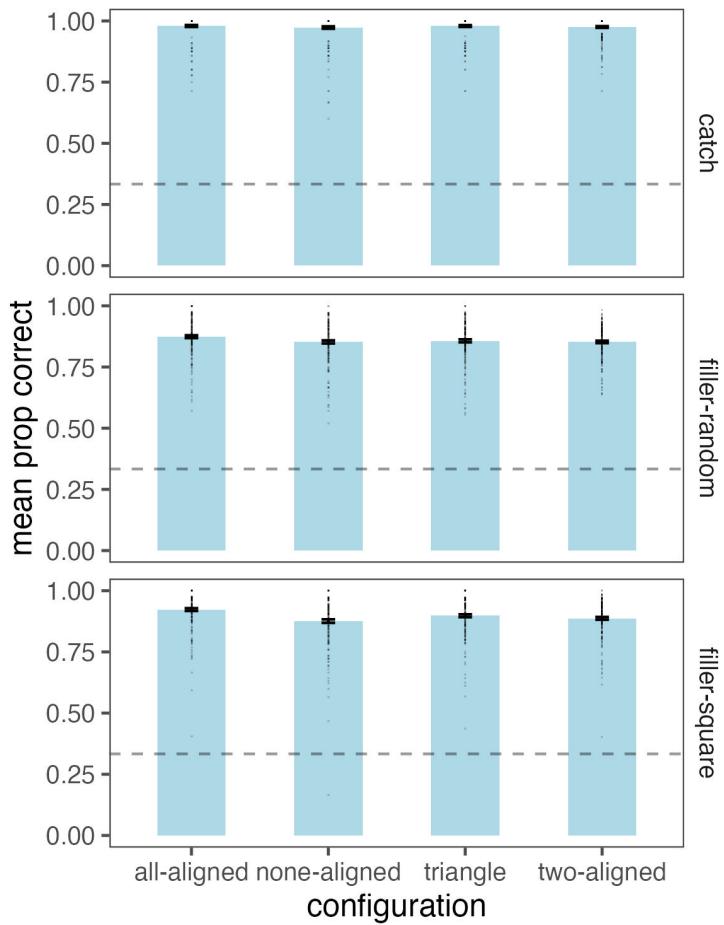


Figure 5.3. Results from non-critical trials in Experiment 5. Rows show trial types. Bars show mean proportion correct in a given condition, with the error bars showing ± 1 SEM. Dots show individual participant data. Dashed line is at 1/3 (chance performance).

5.2.2.3 Critical Trials

The goal of the critical trial analysis was to determine how alignment affected choice for a target option, defined as the rectangle located next to the decoy. The triangle condition was removed from all analyses.

Consider the order of options on screen. There were six possible orderings: *DHW*, *DWH*, *HDW*, *HWD*, *WDH*, and *WHD*. Given that the crucial configuration is the two-aligned display, where the first two options are aligned vertically and a third option is unaligned both vertically and horizontally, the crucial trials are those trials where the decoy is among the first two options.

The ordering was re-classified into a variable referred to as alignment. Because the two-aligned condition is the critical one, the alignment variable is labeled based on the order in the two-aligned condition. If the ordering is *DHW* or *HDW*, the alignment is "*H* aligned with *D*". If the ordering is *WDH* or *DWH*, the alignment is "*D* aligned with *W*". I removed the *WHD* and *HWD* trials from further analysis.

I computed mean choice proportion for the *H*, *W*, and *D* rectangles based on alignment, which are shown in Figure ???. The data show that, in the two-aligned condition, participants were less likely to choose the *W* option when it was aligned with *D* than when *H* was aligned with *D*. This effect also appears to occur in the none-aligned and all-aligned conditions, which suggests a position bias.

Next, I removed all trials in which participants chose the decoy. I refer to the option aligned with the decoy as the *target*. I next computed mean target choice proportions by configuration, results which are plotted in Figure ??.

On average, participants select the target option on less than 1/2 of trials (conditional on not having selected the decoy). This again may suggest a position bias. However, crucially, they select the target less when it is aligned with the decoy in the two-aligned condition than when it is adjacent to the decoy in the none-aligned condition. See the Appendix for inferential statistics which support these conclusions.

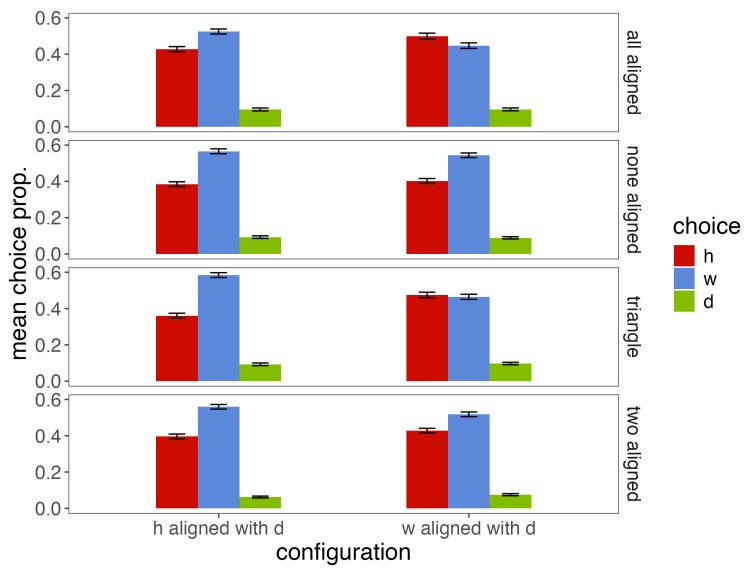


Figure 5.4. Results from critical trials in Experiment 5. Mean choice proportions for the H , W , and D rectangles conditioned on alignment and configuration.

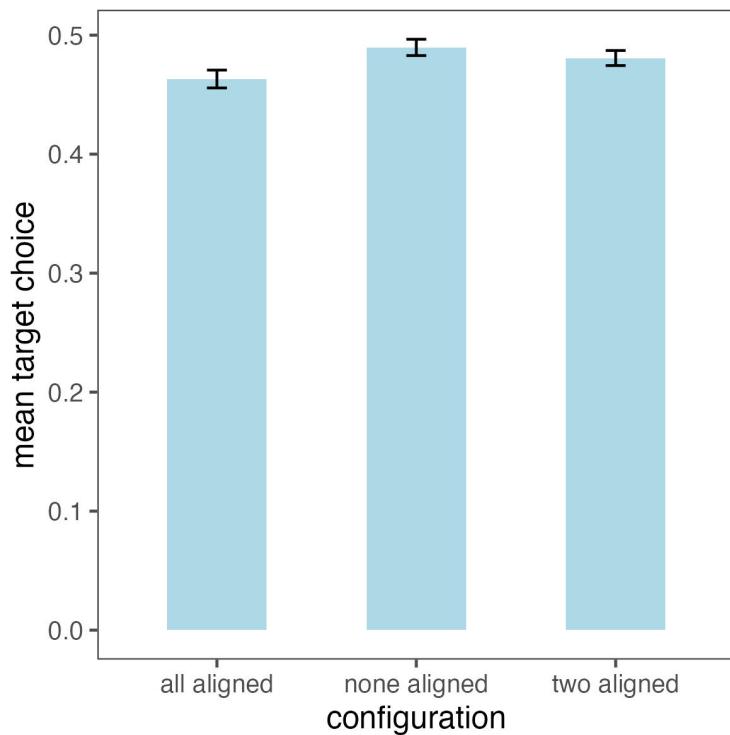


Figure 5.5. Experiment 5 mean target choice proportions by configuration.

5.3 Discussion

In Experiment 5, I showed that comparability can affect choice, in a form similar to the repulsion effect. Given two equally viable, but dissimilar options, when one of these options (i.e., the target) is more easily comparable to a symmetrically dominated decoy option, participants choices are "repulsed" away from the target option and towards the competitor option. This effect is small but nonetheless present even after accounting for participant effects and a position bias.

This result aligns with the predictions from the Thurstonian perceptual choice model from Chapter 2. Increasing the comparability of a focal option and a decoy option increases the perceptual correlations between the two, which in turn decreases the choice share of the comparable *target*, for the benefit of the non-comparable competitor option. This result is also similar to previous results presented by Trueblood et al. (2022) and Evans et al. (2021), who also manipulated the arrangement of options on screen in perceptual choice.

These results are, however, somewhat limited by the positioning of the target and decoy options. In the two-aligned condition, the target and decoy were always presented in the first and second position. The statistical model accounted for this through a position bias effect, though a more thorough design would include a variety of presentation formats to more effectively test this effect.

I assume that increasing comparability decreased target choice share through perceptual correlation; however, given that I did not measure correlations directly, this may not be the case. It would be interesting to use the paradigm from Experiment 2 to directly measure the correlations between options when the decoy is symmetrically dominated and the comparability is systematically manipulated.

Future research should generalize this paradigm to high-level preferential choice. For example, given three consumer products, does the comparability of two of them affect the choice for a third option? I leave this question for future research.

The effect demonstrated is another form of context dependence, the main focus of this dissertation. Here, the context is not the choice set (which remains constant), but rather the presentation of the options. In this sense, the repulsion effect in this experiment is qualitatively similar to the repulsion effect of Spektor et al. (2018) and Experiment 2 of this dissertation.

In the final chapter, I discuss the implications of all experiments, future directions, and limitations of the current research.

CHAPTER 6

GENERAL DISCUSSION AND CONCLUSIONS

6.1 General Discussion

Decisions, even simple ones, may be impacted by context. Context effects occur when the relative choice for a particular option varies with situational properties. In particular, the set of other available affects choice. The attraction effect occurs when a decoy option "boosts" the choice share of a similar, superior target option. The repulsion effect, a reversal of the attraction effect, occurs when the inclusion of the decoy causes people to select the dissimilar competitor more than the target.

This dissertation has explored context dependence in choice, largely by studying the attraction and repulsion effect (Chapters 2-4) but also through studying context dependence induced by the presentation format of options in simple perceptual choice (Chapter 5).

In Chapter 2, I used a Thurstonian perceptual choice model to measure the correlation between valuations in the attraction and repulsion effect. In Experiment 2, I collected valuations (area estimations for simple rectangles) and choices (where participants selected the largest rectangle from each ternary choice set). I connected valuations to choices using the Thurstonian model. I showed that, through the ρ_{TD} parameter, this model can parsimoniously account for the repulsion effect without invoking higher-level decision processes (Experiment 2). The model cannot, however, account for the attraction effect, suggesting that higher-level decision processes may be required to explain this effect. I also demonstrated systematic discriminability

issues in a 2AFC task, using the same experimental stimuli, in accordance with the Thurstonian model (Experiment 1).

In Chapter 3, Experiment 3, I showed that the model makes an interesting prediction for best-worst choice experiments. In best-worst choice, participants select their most and least preferred options from a given choice set. Given the stimuli from Experiment 2 (a set of target, competitor, and decoy rectangles in a perceptual choice experiment), the model predicts a non-monotonic relationship between best and worst choice probabilities. Specifically, the model predicts that the target is both less likely to be chosen as worst, compared to the competitor, and also less likely to be chosen as best. This effect is not predicted by the maxdiff model, a highly influential of best-worst choice. Thus, I have identified another form of context dependence: whether participants are selecting the best option or the worst option from a particular choice set.

In Chapter 4, Experiment 4, I generalized the paradigm and model from Chapter 2 to preferential choice. On each experimental trial, participants saw three consumer products (e.g., microwave ovens, laptops) and assigned each one a viable selling price. In later experimental trials, they saw the same three options and selected the option they most preferred. I showed that the similarity, and comparability, of the target and decoy options, appears to generalize across choice types and can be reliably measured using Pearson correlations. I also replicated previous researchers' choice results (Banerjee et al., 2024), albeit with limitations. For example, the experiment did not systematically decoy position nor did it include binary choices to combat this limitation.

The model from Experiment 4 is able to qualitatively account for the repulsion effect, there is one crucial limitation here; the model accounts for the effect through the correlation between target and decoy evaluations, which causes the decoy to take choice shares away from the target. In preferential choice, and unlike perceptual

choice, participants seldom if ever select the decoy. In the absence of these correlations, or if all correlations are equal (i.e., $\rho_{TD} = \rho_{TC} = \rho_{CD}$), the model will be unable to predict the effect¹. Thus, this form of the repulsion effect may be due to higher-level decision processes. Nonetheless, the demonstration of target-decoy correlations, and indeed target-competitor correlations, is a novel and interesting result.

Though other researchers have proposed correlations as a measure of the similarity between options in a choice set (Kamakura & Srivastava, 1984; Natenzon, 2019), these studies was the first (to my knowledge) to systematically measure these correlations using valuations, incorporate them into a Thurstonian choice model, and connect this model to choices obtained from the same experimental participants.

In Chapter 5, Experiment 5, I demonstrated a new form of context dependence, where choice systematically varies based on option comparability. Given a *symmetrically dominated decoy* option, placing a focal target option in a nearby position, such that participants can more easily compare it to the decoy, *decreases* the target's choice share. This is similar to the standard repulsion effect, with the important caveat that both focal options are equally perceptually similar to the decoy.

There were limitations to this experiment. In particular, given the critical "two-aligned" condition, the target and decoy were only ever in the first and second positions. Future work should fix this experimental design flaw, while also including different configurations.

The results of this dissertation also have important methodological considerations. In particular, I argue that researchers should carefully consider the assumptions made when designing and analyzing experiments. For example, the experiments of Spektor et al. (2018) contain a crucial assumption: that stimulus discriminability issues do not systematically affect target or competitor choice, and that the repulsion effect

¹See the diagonal line from Figure ?? for evidence of this result.

observed in these experiments is a qualitative reversal of the attraction effect rather than just an empirical one. I also showed, in Chapter 3, that the independence assumption of the maxdiff choice model is incorrect (at least in some cases) and a failure to consider whether the stimuli of a given experiment can cause these violations may lead to incorrect conclusions about participants' preferences. The results of Chapter 5 show that the comparability, and even order on screen, can systematically affect choice. Previous researchers have also argued in favor of this point (Evans et al., 2021; Hasan et al., 2025; Trueblood et al., 2022).

There are numerous directions that this work could take beyond this dissertation. I could generalize the experimental and modeling paradigm of Experiment 2 to other context effects (e.g., compromise, similarity). I am also interested in measuring correlations between option valuations at the individual participant level, which is currently limited by the quantity of data available.

Regarding best-worst choice, future work should explore models of best-worst choice that can be used when the independence assumption is violated. Exploration, or development is necessary, is beyond the scope of this dissertation. However, given the numerous applied uses for best-worst choice, this avenue of research would be important and fruitful.

In the future, I plan on continuing the line of research begun in Experiment 4. For example, I have already conducted a binary-ternary version of the choice phase from Experiment 4. I also plan on running an experiment collecting both prices and choices in binary and ternary choice sets. This work will significantly add to the preferential choice and context effects literature.

In addition to the experimental modifications discussed earlier, future work in comparability should generalize the paradigm to various choice types. Additionally, the effect observed in Experiment 5 was quite small; practically speaking, this have

limited impact on actual choices. Future work should address the limitations of comparability in affecting choice.

6.2 Conclusions

In this dissertation, I have identified various forms of context dependence, in both perceptual and preferential choice. I provided theoretical explanations for these results in the form of a mathematical model of choice. To ensure falsifiability, I tested the model's predictions on out-of-sample data, to considerable success. This work will further the study of context effects and decision-making in general.

APPENDIX

BAYESIAN LOGISTIC REGRESSION MODEL OF 2AFC DISCRIMINABILITY FROM EXPERIMENT 1

The 2AFC data from Experiment 1 was analyzed with Bayesian Hierarchical Logistic Regression.

Recall that in this experiment, participants were presented with three stimuli (target, competitor, and decoy rectangles). They were then asked to select the largest rectangle out of a pair of two of these options. There are three trial types: target/competitor (TC), target/decoy (TD), and competitor/decoy (CD). As discussed in the main text, all TC trials and all $TDD = 0\%$ trials were removed from the main analyses.

A.1 Model Details

The model predicts the probability of discriminating the target/competitor from the decoy option. According to the model, discrimination D for participant i on trial j is:

$$D_{ij} \sim Bernoulli(\theta_{ij}) \quad (\text{A.1})$$

To compute θ_{ij} , η_{ij} is first predicted from a linear combination of the relevant variables.

$$\eta_{ij} = (\beta_0 + S_{0_i}) + (\beta_{\text{or}} + S_{\text{or}_i}) \cdot \text{or}_{ij} \quad (\text{A.2})$$

$$+ (\beta_{\text{horiz}} + S_{\text{horiz}_i}) \cdot \text{horiz}_{ij} \quad (\text{A.3})$$

$$+ (\beta_{\text{TD}} + S_{\text{TD}_i}) \cdot \text{TD}_{ij} \quad (\text{A.4})$$

$$+ (\beta_{\text{TDD5}} + S_{\text{TDD5}_i}) \cdot \text{TDD5}_{ij} \quad (\text{A.5})$$

$$+ (\beta_{\text{TDD9}} + S_{\text{TDD9}_i}) \cdot \text{TDD9}_{ij} \quad (\text{A.6})$$

$$+ (\beta_{\text{TDD14}} + S_{\text{TDD14}_i}) \cdot \text{TDD14}_{ij} \quad (\text{A.7})$$

$$+ (\beta_{\text{TDD5xTD}} + S_{\text{TDD5xTD}_i}) \cdot \text{TDD5}_{ij} \cdot \text{TD}_{ij} \quad (\text{A.8})$$

$$+ (\beta_{\text{TDD9xTD}} + S_{\text{TDD9xTD}_i}) \cdot \text{TDD9}_{ij} \cdot \text{TD}_{ij} \quad (\text{A.9})$$

$$+ (\beta_{\text{TDD14xTD}} + S_{\text{TDD14xTD}_i}) \cdot \text{TDD14}_{ij} \cdot \text{TD}_{ij} \quad (\text{A.10})$$

All β terms are fixed effects, and all S terms are random (participant) effects. β_{or} is the fixed effect of orientation, where or_{ij} is a dummy variable which = 0 if the target and decoy are taller than wide and = 1 if the target and decoy are wider than tall. β_{horiz} is the fixed effect of the horizontal display, where horiz_{ij} is a dummy variable which = 0 for triangle display trials and = 1 for horizontal display trials. β_{TD} is the fixed effect of comparison, where $\text{TD}_{ij}=0$ for CD trials and $\text{TD}_{ij} = 1$ for TD trials. The TDD variable has 4 levels (2%, 5%, 9%, and 14%), so there are three dummy variables ($TDD5$, $TDD9$, and $TDD14$) with 2% being the reference level for TDD . The interaction captures the additional boost / decrement to TD over CD trials at each level of TDD .

η_{ij} is then transformed to the probability scale using the logit function:

$$\theta_{ij} = \frac{1}{1 + e^{-\eta_{ij}}}$$

A.2 Prior Distributions on Parameters

- $\beta_0 \sim \mathcal{N}(0, 5)$
- $\beta_{or} \sim \mathcal{N}(0, 5)$
- $\beta_{horiz} \sim \mathcal{N}(0, 5)$
- $\beta_{TD} \sim \mathcal{N}(0, 5)$
- $\beta_{TDD5} \sim \mathcal{N}(0, 5)$
- $\beta_{TDD9} \sim \mathcal{N}(0, 5)$
- $\beta_{TDD14} \sim \mathcal{N}(0, 5)$
- $\beta_{TDD5xTD} \sim \mathcal{N}(0, 2.5)$
- $\beta_{TDD9xTD} \sim \mathcal{N}(0, 2.5)$
- $\beta_{TDD14xTD} \sim \mathcal{N}(0, 2.5)$
- $S_{0_i} \sim \mathcal{N}(0, \sigma_{S_0})$
- $S_{or_i} \sim \mathcal{N}(0, \sigma_S)$
- $S_{horiz_i} \sim \mathcal{N}(0, \sigma_S)$
- $S_{TD_i} \sim \mathcal{N}(0, \sigma_S)$
- $S_{TDD5_i} \sim \mathcal{N}(0, \sigma_S)$
- $S_{TDD9_i} \sim \mathcal{N}(0, \sigma_S)$
- $S_{TDD14_i} \sim \mathcal{N}(0, \sigma_S)$
- $S_{TDD5xTD_i} \sim \mathcal{N}(0, \sigma_S)$
- $S_{TDD9xTD_i} \sim \mathcal{N}(0, \sigma_S)$

- $S_{TDD14xTD_i} \sim \mathcal{N}(0, \sigma_S)$
- $\sigma_{S_0} \sim \text{LogNormal}(0, 2.5)$
- $\sigma_S \sim \text{LogNormal}(0, 2.5)$

Note that the model assumes equal variance for all random effect distributions aside from the random intercepts.

A.3 Modeling Results

The model was coded using the Stan programming language (Carpenter et al., 2017) and implemented with the RStan package (Stan Development Team, n.d.). The sampler ran 5 chains, each for 2500 iterations. Posterior diagnostics indicated that the sampler converged.

A.3.1 Parameter estimates.

Table ?? shows parameter estimates, including means and 95% credible intervals.

Inference is made by examining the posterior distributions of the fixed effect parameters (i.e., all β values). First, consider the main effects. The intercept β_0 was above 0, $M = 0.44, 95\%CI[0.32, 0.57]$, indicating that participants could perform the discrimination task, even at the lowest TDD level. There was also a main effect of orientation, $M = -0.54, 95\%CI[-0.66, -0.43]$, indicating that participants performed worse when the target and decoy were oriented wide than when they were oriented tall. The main effect of horizontal, $M = 0.23, 95\%CI[0.12, 0.34]$, indicates that participants performed better in the horizontal display condition than in the triangle display condition. The main effect of TD comparison was above 0, $M = 0.17, 95\%CI[0.01, 0.33]$, indicating participants were performed better in target-decoy trials than in competitor decoy trials.

Parameter	M	SD	CI low	CI high
β_0	0.44	0.06	0.32	0.57
β_{or}	-0.54	0.06	-0.66	-0.43
β_{horiz}	0.23	0.06	0.12	0.34
β_{TD}	0.17	0.08	0.01	0.33
β_{TDD5}	0.40	0.08	0.23	0.56
β_{TDD9}	0.81	0.09	0.64	0.98
β_{TDD14}	1.45	0.10	1.25	1.64
$\beta_{TDD5xTD}$	0.14	0.12	-0.09	0.36
$\beta_{TDD9xTD}$	0.61	0.13	0.36	0.85
$\beta_{TDD14xTD}$	0.79	0.15	0.50	1.10
σ_{S_0}	0.20	0.04	0.12	0.29
σ_S	0.34	0.03	0.29	0.39

Table A.1. Parameter estimates for Bayesian Hierarchical Logistic Regression from Experiment 1 Data, including means, standard deviations, and 95% Credible Intervals.

Crucially, there was an interaction between comparison (TC vs TD) and TDD. The effect of TD at $TDD = 5\%$ was not reliably above 0, $M = 0.14, 95\%CI[-0.09, 0.36]$. However, the effect of TD at $TDD = 9\%$ was above 0, $M = 0.61, 95\%CI[0.36, 0.85]$, even after accounting for the main effect of TD comparison. The effect of TD at $TDD = 14\%$ was also above 0, $M = 0.79, 95\%CI[0.50, 1.10]$.

APPENDIX

BAYESIAN HIERARCHICAL MODELING OF CIRCLE JUDGMENT DATA FROM EXPERIMENT 2

The circle judgment data were analyzed with the multivariate Thurstonian perceptual model first presented in Chapter 2.

A.1 Model Details

The model assumes that, for participant i on trial j , the vector of perceived areas \mathbf{X}_{ij} is sampled from a multivariate normal distribution with parameters $\boldsymbol{\mu}_{ij}$ and $\boldsymbol{\Sigma}$. That is,

$$\mathbf{X}_{ij} \sim \mathcal{N}(\boldsymbol{\mu}_{ij}, \boldsymbol{\Sigma}) \quad (\text{B.1})$$

Using Bayesian statistical modeling, the parameters $\boldsymbol{\mu}$ and $\boldsymbol{\Sigma}$ were estimated for the model outlined in Chapter 2. Note $\boldsymbol{\mu}$ is allowed to vary systematically over trials and participants, but $\boldsymbol{\Sigma}$ remains constant. $\boldsymbol{\mu}$ is estimated via hierarchical regression while allowing the components of $\boldsymbol{\Sigma}$ (i.e., σ_T , σ_C , σ_D , ρ_{TD} , ρ_{TC} , ρ_{CD}) to vary freely.

The model was fit separately for the triangle and horizontal condition. First, the computation of $\boldsymbol{\mu}$ is described, followed by the computation $\boldsymbol{\Sigma}$. The prior distributions on each parameter separately for each of these components are shown, followed by an explanation of the modeling procedure and results. Note that the model predicts mean-centered log-transformed estimated area.

A.1.1 μ Parameterization

The model predicts the mean area μ_{ijk} for the i th participant on the j th trial for the k th stimulus. There were $k = 3$ stimuli on each trial. If $k = 1$, the stimulus is the target; If $k = 2$, the stimulus is the competitor; If $k = 3$, the stimulus is the decoy. Thus, μ can be broken down into μ_{ij1} (target), μ_{ij2} (competitor), and μ_{ij3} (decoy). Note that some parameters are common to all stimuli (e.g., the effects of diagonal or orientation), while others are common only to a particular option (e.g., the effect of competitor vs. decoy vs. target).

μ_{ij1} is computed as:

$$\begin{aligned} \mu_{ij1} = & (S_{0_i} + \beta_0) + \beta_{or} \cdot or_{ij1} + \beta_{diag2} \cdot diag2_{ij} + \\ & \beta_{diag3} \cdot diag3_{ij} + \beta_{TDD5} \cdot TDD5_{ij} + \\ & \beta_{TDD9} \cdot TDD9_{ij} + \beta_{TDD14} \cdot TDD14_{ij} \end{aligned} \quad (\text{B.2})$$

S_{0_i} is a random intercept for participant i . β_0 is the fixed intercept. β_{or} is the fixed effect of orientation, where or_{ij1} is a dummy variable which = 0 if the target is taller than wide and = 1 if the target is wider than tall. β_{diag2} is the fixed effect of the middle diagonal, which = 1 if the all stimuli on the trial fall on the middle diagonal and = 0 otherwise. β_{diag3} is the fixed effect of the upper diagonal, which = 1 if all stimuli on the trial fall on the upper diagonal and = 0 otherwise. β_{TDD5} is the fixed effect of TDD 5, and $TDD5_{ij}$ is a dummy variable which = 1 if $TDD = 5\%$ and = 0 otherwise. β_{TDD9} is the fixed effect of TDD 9, and $TDD9_{ij}$ is a dummy variable which = 1 if $TDD = 9\%$ and = 0 otherwise. β_{TDD14} is the fixed effect of TDD 14, and $TDD14_{ij}$ is a dummy variable which = 1 if $TDD = 14\%$ and = 0 otherwise.

μ_{ij2} is computed as:

$$\begin{aligned}
\mu_{ij2} = & (S_{0_i} + \beta_0) + \beta_{or} \cdot or_{ij2} + \beta_{diag2} \cdot diag2_{ij} + \\
& \beta_{diag3} \cdot diag3_{ij} + \beta_{TDD5} \cdot TDD5_{ij} + \\
& \beta_{TDD9} \cdot TDD9_{ij} + \beta_{TDD14} \cdot TDD14_{ij} + \beta_{comp}
\end{aligned} \tag{B.3}$$

S_{0_i} is a random intercept for participant i . β_0 is the fixed intercept. β_{or} is the fixed effect of orientation, where or_{ij2} is a dummy variable which = 0 if the competitor is taller than wide and = 1 if the competitor is wider than tall. β_{diag2} is the fixed effect of the middle diagonal, which = 1 if the all stimuli on the trial fall on the middle diagonal and = 0 otherwise. β_{diag3} is the fixed effect of the upper diagonal, which = 1 if all stimuli on the trial fall on the upper diagonal and = 0 otherwise. β_{TDD5} is the fixed effect of TDD 5, and $TDD5_{ij}$ is a dummy variable which = 1 if $TDD = 5\%$ and = 0 otherwise. β_{TDD9} is the fixed effect of TDD 9, and $TDD9_{ij}$ is a dummy variable which = 1 if $TDD = 9\%$ and = 0 otherwise. β_{TDD14} is the fixed effect of TDD 14, and $TDD14_{ij}$ is a dummy variable which = 1 if $TDD = 14\%$ and = 0 otherwise. β_{comp} is a parameter that reflects the possibility of estimation bias for the competitor.

μ_{ij3} is computed as:

$$\begin{aligned}
\mu_{ij3} = & (S_{0_i} + \beta_0) + \beta_{or} \cdot or_{ij3} + \beta_{diag2} \cdot diag2_{ij} + \\
& \beta_{diag3} \cdot diag3_{ij} + (\beta_{TDD5} + \beta_{TDD5D}) \cdot TDD5D_{ij} + (\beta_{TDD9} + \beta_{TDD9D}) \cdot TDD9D_{ij} + \\
& (\beta_{TDD14} + \\
& \beta_{TDD14D}) \cdot TDD14D_{ij}
\end{aligned} \tag{B.4}$$

S_{0_i} is a random intercept for participant i . β_0 is the fixed intercept. β_{or} is the fixed effect of orientation, where or_{ij3} is a dummy variable which = 0 if the decoy is taller than wide and = 1 if the decoy is wider than tall. β_{diag2} is the fixed effect of the middle diagonal, which = 1 if the all stimuli on the trial fall on the middle diagonal and = 0 otherwise. β_{diag3} is the fixed effect of the upper diagonal, which = 1 if all

stimuli on the trial fall on the upper diagonal and = 0 otherwise. β_{TDD2D} is the fixed effect of TDD=2, and $TDD2D_{ij}$ is a dummy variable which = 1 if $TDD = 2\%$ for the decoy and = 0 otherwise. β_{TDD5D} is the fixed effect of TDD=5, and $TDD5D_{ij}$ is a dummy variable which = 1 if $TDD = 5\%$ for the decoy and = 0 otherwise. β_{TDD9D} is the fixed effect of TDD 9 for the decoy, and $TDD9D_{ij}$ is a dummy variable which = 1 if $TDD = 9\%$ and = 0 otherwise. β_{TDD14D} is the fixed effect of TDD 14 for the decoy, and $TDD14D_{ij}$ is a dummy variable which = 1 if $TDD = 14\%$ and = 0 otherwise.

Note that there is a common set of parameters for each level of TDD and additional set of parameters for each level of TDD that only apply to the decoy. In the data, it was clear that participants often adjusted the target and competitor relative to the decoy. In other words, even though the physical size of both target and competitor remains constant across TDD, participants' *estimation* of their size varied with TDD. The inclusion of a separate set of parameters for TDD that only apply to the decoy allows for a "deflection" of the decoy size, relative to target and competitor size.

Note the following reference points for the variables:

- TDD: 2%
- Orientation: taller than wide
- Diagonal: lower
- Stimulus: target

The β_0 parameter captures the fixed of a tall target on the lower diagonal at 2% TDD, and all other parameters reflect deflections from this.

A.1.1.1 Prior Distributions on Parameters

Below are shown the following prior distributions on each parameter relevant to μ :

- $\beta_0 \sim \mathcal{N}(0, 5)$
- $\beta_{or} \sim \mathcal{N}(0, 5)$
- $\beta_{diag2} \sim \mathcal{N}(0, 5)$
- $\beta_{diag3} \sim \mathcal{N}(0, 5)$
- $\beta_{TDD5} \sim \mathcal{N}(0, 5)$
- $\beta_{TDD9} \sim \mathcal{N}(0, 5)$
- $\beta_{TDD14} \sim \mathcal{N}(0, 5)$
- $\beta_{TDD2D} \sim \mathcal{N}(0, 5)$
- $\beta_{TDD5D} \sim \mathcal{N}(0, 5)$
- $\beta_{TDD9D} \sim \mathcal{N}(0, 5)$
- $\beta_{TDD14D} \sim \mathcal{N}(0, 5)$
- $\beta_{comp} \sim \mathcal{N}(0, 5)$
- $S_{0_i} \sim \mathcal{N}(0, \sigma_{S_0})$
- $\sigma_{S_0} \sim \text{Half-Cauchy}(0, 2.5)$

A.2 Σ Parameterization

Σ is a positive semi-definite 3x3 covariance matrix computed as:

$$\Sigma = S\Omega S \quad (\text{B.5})$$

where S is a diagonal matrix consisting of:

$$\begin{pmatrix} \sigma_T & 0 & 0 \\ 0 & \sigma_C & 0 \\ 0 & 0 & \sigma_D \end{pmatrix} \quad (\text{B.6})$$

and Ω is a correlation matrix:

$$\begin{pmatrix} 1 & \rho_{TC} & \rho_{TD} \\ \rho_{TC} & 1 & \rho_{CD} \\ \rho_{TD} & \rho_{CD} & 1 \end{pmatrix} \quad (\text{B.7})$$

Estimation of S was straightforward. The three standard deviation parameters σ_T , σ_C , and σ_D were freely estimated.

When estimating Ω , the LKJ distribution (Lewandowski et al., 2009) was used to set priors on the Cholesky factorization of the correlation matrix Ω . This was done to ensure that the resulting variance-covariance matrix Σ is positive semi-definite, a requirement of the multivariate Gaussian distribution. The critical inferences, however, are performed on the off-diagonal elements ρ_{TC} , ρ_{TD} , ρ_{CD} in each display condition. Priors were set on the σ parameters using the Half-Cauchy distribution (Gelman, 2006).

A.2.1 Prior Distributions on Parameters

Below are shown the following prior distributions on each parameter relevant to Σ .

- $\sigma_T \sim \text{Half-Cauchy}(0, 2.5)$
- $\sigma_C \sim \text{Half-Cauchy}(0, 2.5)$

- $\sigma_D \sim \text{Half-Cauchy}(0, 2.5)$
- $\Omega \sim \text{LKJCorr}(\eta = 1)$

A.3 Modeling Results

The model was implemented using the Stan programming language (Carpenter et al., 2017) using the cmdstanr interface (Gabry et al., 2024) in R .

The model ran for 2500 iterations (not including warm-up) with 4 chains for each display condition. Posterior diagnostics indicated that the sampler converged in each condition.

Below are parameter estimates for each display condition and relevant parameter. The estimates of the participant effects S_{0_i} are excluded for brevity. Estimates are rounded to two or three decimal places, depending on the size of the parameter.

The posterior estimates indicate that $\rho_{TD} > \rho_{TC} \approx \rho_{CD}$ in each display condition, in accordance with the predictions. Furthermore, the absolute values of all ρ values are greater in the horizontal condition than in the triangle condition, suggesting that the horizontal condition better facilitates comparisons.

The β estimates are generally as expected. The β_{diag} estimates show that participants increased their area estimations with the absolute size of the stimuli. Participants also decreased the size of decoy estimations as TDD increased. They also, to some extent, decreased the size of target and competitor estimations as TDD increased (captured by the β_{TDD5} , β_{TDD9} , and β_{TDD14}) parameters, indicating that participants adjusted the target and competitor relative to the decoy.

Interestingly, the β_{or} estimates indicated that participants rated wider stimuli larger than tall stimuli in the horizontal condition, but they rated taller stimuli larger than wide stimuli in the horizontal condition. This effect is quite small, but is nonetheless present in the parameter estimates.

Participants also rated the competitor slightly larger than the target, particularly in the triangle condition, although this effect is quite small. This effect was indeed too small to show differences in any single TDD level (see Figure ??).

Display Condition	Parameter	<i>M</i>	<i>SD</i>	HDI lower	HDI upper
Horizontal	β_0	-0.41	0.02	-0.44	-0.38
	β_{or}	0.003	0.002	-0.001	0.007
	β_{diag2}	0.47	0.01	0.46	0.48
	β_{diag3}	0.80	0.01	0.79	0.81
	β_{TDD5}	-0.005	0.01	-0.017	0.007
	β_{TDD9}	-0.007	0.01	-0.019	0.005
	β_{TDD14}	-0.01	0.01	-0.02	-0.0005
	β_{TDD2D}	-0.006	0.004	-0.013	0.001
	β_{TDD5D}	-0.01	0.004	-0.016	-0.003
	β_{TDD9D}	-0.04	0.004	-0.05	-0.04
	β_{TDD14D}	-0.08	0.004	-0.09	-0.07
	β_{comp}	0.003	0.002	-0.002	0.007
	σ_{S_0}	0.19	0.01	0.17	0.21
	σ_T	0.337	0.002	0.334	0.340
	σ_C	0.341	0.002	0.338	0.345
	σ_D	0.337	0.002	0.333	0.340
	ρ_{TC}	0.575	0.005	0.565	0.584
	ρ_{TD}	0.710	0.004	0.703	0.716
	ρ_{CD}	0.575	0.005	0.565	0.584
Triangle	β_0	-0.40	0.01	-0.42	-0.38
	β_{or}	-0.006	0.002	-0.01	-0.002
	β_{diag2}	0.47	0.005	0.455	0.474
	β_{diag3}	0.81	0.005	0.80	0.82
	β_{TDD5}	-0.01	0.006	-0.03	0.0003
	β_{TDD9}	-0.02	0.006	-0.03	-0.008
	β_{TDD14}	-0.03	0.006	-0.04	-0.01
	β_{TDD2D}	-0.0172	0.004	-0.024	-0.01
	β_{TDD5D}	-0.0167	0.004	-0.0237	-0.01
	β_{TDD9D}	-0.03	0.004	-0.037	-0.02
	β_{TDD14D}	-0.05	0.004	-0.06	-0.05
	β_{comp}	0.005	0.002	0.0001	0.009
	σ_{S_0}	0.15	0.01	0.14	0.17
	σ_T	0.335	0.002	0.332	0.338
	σ_C	0.338	0.002	0.335	0.341
	σ_D	0.335	0.002	0.331	0.338
	ρ_{TC}	0.541	0.005	0.531	0.551
	ρ_{TD}	0.675	0.004	0.667	0.682
	ρ_{CD}	0.533	0.005	0.523	0.543

Table B.1. Parameter estimates for Bayesian Hierarchical Thurstonian Model from Experiment 2 Circle Phase Data, including means, standard deviations, and 95% Credible Intervals.

APPENDIX

INFERENTIAL STATISTICS FOR EXPERIMENT 2 CHOICE DATA

Following Katsimpokis et al. (2022), I performed inference on *Absolute Share of the Target*, a variant of RST that corrects for a bias in RST. AST is an unweighted average of the target choice proportion from each choice set. Here, AST is computed as:

$$AST = 0.5 \cdot \left(\frac{P(H|H, W, D_H)}{P(H|H, W, D_H) + P(W|H, W, D_H)} + \frac{P(W|H, W, D_W)}{P(W|H, W, D_W) + P(H|H, W, D_W)} \right) \quad (C.1)$$

AST was computed for each participant in each display condition at each level of TDD. First are the analyses from the triangle condition followed by those from the horizontal condition.

A.1 Triangle Condition Analysis

A one-way within-groups ANOVA testing the effect of TDD on AST in the triangle condition was significant, $F(3, 636) = 79.97, p < .001$.

I then performed a follow-up one-sample t-test on AST at each level of TDD, using the within-participants error correction from Cousineau and O'Brien (2014) and comparing the mean AST value to the null value .5. I compared each p-value to a Bonferroni-corrected α level of $\alpha = \frac{.05}{4} = .0125$.

The AST value was significantly different from .5 at TDD=2%, $t(212) = -18.4, p < .001, M = .34, 95\%CI[.33, .36]$, indicating a repulsion effect.

The AST value was significantly different from .5 at TDD=5%, $t(212) = -13.2, p < .001, M = .39, 95\%CI[.38, .41]$, indicating a repulsion effect.

The AST value was significantly different from .5 at TDD=9%, $t(212) = -7.45, p < .001, M = .43, 95\%CI[.42, .45]$, indicating a repulsion effect.

The AST value was significantly different from .5 at TDD=14%, $t(212) = -2.34, p = .002, M = .48, 95\%CI[.46, .49]$, indicating a slight repulsion effect. Note that the mean $P(T) > P(C)$ in Figure ??; however, those values are not equally weighted.

A.2 Horizontal Condition Analysis

IA one-way within-groups ANOVA testing the effect of TDD on AST in the horizontal condition was significant, $F(3, 618) = 176.10, p < .001$.

I then performed a follow-up one-sample t-test on AST at each level of TDD, using the within-participants error correction from Cousineau and O'Brien (2014) and comparing the mean AST value to the null value .5. Each p-value was compared to a Bonferroni-corrected α level of $\alpha = \frac{.05}{4} = .0125$.

The AST value was significantly different from .5 at TDD=2%, $t(206) = -15.6, p < .001, M = .34, 95\%CI[.33, .36]$, indicating a repulsion effect.

The AST value was significantly different from .5 at TDD=5%, $t(206) = -8.12, p < .001, M = .41, 95\%CI[.39, .43]$, indicating a repulsion effect.

The AST value was not significantly different from .5 at TDD=9%, $t(206) = -0.04, p = .10, M = .50, 95\%CI[.48, .52]$, indicating a null effect.

The AST value was significantly different from .5 at TDD=14%, $t(206) = 5.00, p < .001, M = .56, 95\%CI[.54, .58]$, indicating an attraction effect.

Mean AST values for each TDD level in each display condition are plotted in Figure ??.

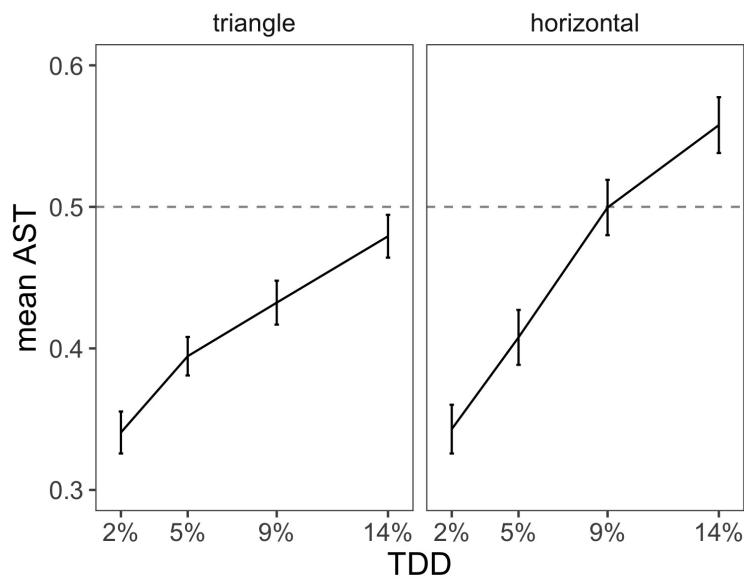


Figure C.1. Mean AST values for each display condition and TDD level from Experiment 2. Error bars are 95% CIs with the within-participants error correction from Cousineau and O'Brien (2014).

APPENDIX

MAXDIFF MODELING FROM EXPERIMENT 3

According to the maxdiff model of best-worst choice (Marley & Louviere, 2005), the probability $BW_K(x, y)$ of selecting option x as best and y as worst from choice set K is computed as:

$$BW_K(x, y) = \frac{e^{u_x - u_y}}{\sum_{\substack{p,q \in K \\ p \neq q}} e^{u_p - u_q}} \quad (\text{D.1})$$

where u_i is the utility of option i .

Below are the details of the maxdiff modeling, as applied to the data from Experiment 3.

A.1 Model Details

Following typical approaches in the choice modeling literature, the utility of each option in a choice set was estimated using linear regression. There was no intercept.

According to the model, the utility U_{ijk} for participant i on trial j and option k is computed as:

$$U_{ijk} = \beta_{or} \cdot or_{ijk} + \beta_{TDD5} \cdot TDD5_{ij} + \beta_{TDD9} \cdot TDD9_{ij} + \beta_{TDD14} \cdot TDD14_{ij} + \\ (\beta_{comp} + S_{comp_i}) \cdot comp_{ijk} + (\beta_{decoy} + S_{decoy_i}) \cdot decoy_{ijk} + \quad (\text{D.2})$$

As in the modeling of Experiment 2, there was an effect of option (i.e., target, competitor, decoy) where β_{comp} and S_{comp_i} are the fixed and random effects for the

competitor stimulus, respectively, and $comp_{ijk}$ is a dummy variable which equals 1 if the stimulus is a competitor and 0 otherwise. Similarly, β_{decoy} and S_{decoy_i} are the fixed and random effects for the decoy stimulus, respectively, and $comp_{ijk}$ is a dummy variable which equals 1 if the stimulus is a decoy and 0 otherwise. Note that the reference level is the target here. These analyses collapse over diagonal.

According to the model, the probability a participant i on trial j , given set K , selects option k as best and l as worst, $k \neq l$, is computed as:

$$BW_{ijk_K}(k, l) = \frac{e^{U_{ijk} - U_{ijl}}}{\sum_{\substack{p,q \in K \\ p \neq q}} e^{u_p - u_q}} \quad (\text{D.3})$$

The vector θ_{ij} is a vector of all possible best-worst choices for participant i and trial j , where $\sum \theta_{ij} = 1$.

The count vector of all possible BW choices C_{ij} is distributed:

$$C_{ij} \sim \text{Multinomial}(\theta_{ij}) \quad (\text{D.4})$$

Below are the prior distributions on all parameters.

A.2 Prior Distributions on Parameters

- $\beta_{or} \sim \mathcal{N}(0, 5)$
- $\beta_{TDD5} \sim \mathcal{N}(0, 5)$
- $\beta_{TDD9} \sim \mathcal{N}(0, 5)$
- $\beta_{TDD14} \sim \mathcal{N}(0, 5)$
- $\beta_{comp} \sim \mathcal{N}(0, 5)$

- $\beta_{decoy} \sim \mathcal{N}(0, 5)$
- $\beta_{S_{comp_i}} \sim \mathcal{N}(0, \sigma_{S_{comp}})$
- $\beta_{S_{decoy_i}} \sim \mathcal{N}(0, \sigma_{S_{decoy}})$
- $\sigma_{S_{comp}} \sim \text{Half-Cauchy}(0, 2.5)$
- $\sigma_{S_{decoy}} \sim \text{Half-Cauchy}(0, 2.5)$

A.3 Parameter Estimates

Table ?? shows parameter estimates, including means and 95% credible intervals.

Parameter	M	SD	CI low	CI high
β_{or}	0.27	0.01	0.26	0.28
β_{TDD5}	0.27	0.01	0.24	0.29
β_{TDD9}	0.64	0.01	0.61	0.67
β_{TDD14}	1.05	0.02	1.02	1.08
β_{comp}	-0.03	0.01	-0.05	-0.01
β_{decoy}	-0.25	0.02	-0.28	-0.21
σ_{comp}	0.14	0.01	0.12	0.16
σ_{decoy}	0.29	0.01	0.27	0.32

Table D.1. Parameter estimates for maxdiff modeling from Experiment 3, including means, SDs, and 95% Credible Intervals.

APPENDIX

BAYESIAN MODELING OF PRICE DATA FROM EXPERIMENT 4

The pricing data from Experiment 4 were modeled using the Thurstonian model from Experiment 2.

A.1 Thurstonian Price Model

The model assumed that on each trial i , a vector of prices \mathbf{X}_i is drawn of a multivariate normal distribution:

$$\mathbf{X}_i \sim \mathbf{N}(\boldsymbol{\mu}_{jk}, \boldsymbol{\Sigma}_k) \quad (\text{E.1})$$

where j is the product category (washing machines, laptops, televisions, microwave ovens) and k is the trial type (attraction, repulsion).

$\boldsymbol{\mu}_{jk}$ is the column vector:

$$\begin{pmatrix} \mu_{T_j k} \\ \mu_{C_j k} \\ \mu_{D_j k} \end{pmatrix} \quad (\text{E.2})$$

and $\boldsymbol{\Sigma}_k$ is a 3x3 positive semi-definite variance-covariance matrix:

$$\boldsymbol{\Sigma}_k = S \boldsymbol{\Omega}_k S \quad (\text{E.3})$$

where S is a diagonal matrix consisting of:

$$\begin{pmatrix} \sigma_T & 0 & 0 \\ 0 & \sigma_C & 0 \\ 0 & 0 & \sigma_D \end{pmatrix} \quad (\text{E.4})$$

with σ_T , σ_C , σ_D being the standard deviations for target, competitor, and decoy, respectively. $\boldsymbol{\Omega}_k$ is a correlation matrix:

$$\begin{pmatrix} 1 & \rho_{TC_k} & \rho_{TD_k} \\ \rho_{TC_k} & 1 & \rho_{CD_k} \\ \rho_{TD_k} & \rho_{CD_k} & 1 \end{pmatrix} \quad (\text{E.5})$$

with ρ_{TD_1} , for example, indicating the population-level correlation between target and decoy valuations in the attraction condition.

This model has relatively 24 free parameters, relatively few compared to the several hundred from Experiment 2.

There were no a priori predictions about the size or even direction of the price differences here. All $\boldsymbol{\mu}$ parameters were freely estimated rather than estimated through linear regression as in Experiment 2.

Prior to model estimation, all prices were normalized within participants.

A.2 Prior Distributions on all Parameters

- $\boldsymbol{\mu}_{jk} \sim \mathbf{N}(0, 1)$

- $\sigma_T \sim \text{Half-Cauchy}(0, 2.5)$
- $\sigma_C \sim \text{Half-Cauchy}(0, 2.5)$
- $\sigma_D \sim \text{Half-Cauchy}(0, 2.5)$
- $\Omega_k \sim \text{LKJCorr}(\eta = 0.5)$

A.3 Parameter Estimates

For brevity, the μ and σ estimates are omitted. ρ estimates are shown below.

Trial Type	Parameter	<i>M</i>	<i>SD</i>	HDI lower	HDI upper
Attraction	ρ_{TC}	.87	0.005	.86	.88
	ρ_{TD}	.87	0.005	.86	.88
	ρ_{CD}	.83	0.007	.81	.84
Repulsion	ρ_{TC}	.77	0.008	.75	.79
	ρ_{TD}	.87	0.005	.86	.88
	ρ_{CD}	.69	0.011	.67	.72

Table E.1. ρ Parameter estimates for ρ parameters from the Bayesian Hierarchical Thurstonian Model from Experiment 4 Pricing Data, including means, standard deviations, and 95% Credible Intervals.

APPENDIX

BAYESIAN MODELING OF CHOICE DATA FROM EXPERIMENT 4

The choice data of Experiment 4 were analyzed with a Dirichlet-Multinomial model. The Dirichlet distribution is a generalization of the Beta distribution to > 2 dimensions. Here the Dirichlet distribution is used to model the variability in ternary choice proportions for the attraction and repulsion trials from Experiment 4.

In this analysis collapsed over participants. This is a limitation, particularly given recent concerns about participant-level variability in context effects (Liew et al., 2016; Trueblood et al., 2015). However, given that the main goal of Experiment 4 was to measure correlations in pricing, and that participants made relatively few choices, this analysis was performed on aggregate choice data.

A.1 Dirichlet-Multinomial Choice Model

According to the model, the vector \mathbf{C}_{ijkl} of target, competitor, and decoy counts for trial type (attraction, repulsion) i , TDD (near, far) j , product category (laptops, microwave ovens, televisions, wachine machines) k , target high dimension (1,2) l is distributed:

$$C_{ijkl} \sim \text{Multinomial}(\boldsymbol{\theta}_{ijkl}) \quad (\text{F.1})$$

$\boldsymbol{\theta}_{ijkl}$ is a vector of choice probabilities which is turn distributed:

$$\boldsymbol{\theta}_{ijkl} \sim \text{Dirichlet}(\boldsymbol{\alpha}_{ijkl}) \quad (\text{F.2})$$

where all $\boldsymbol{\alpha}_{ijkl} > 0$.

For a prior distribution on $\boldsymbol{\alpha}$, it was assumed that:

$$\boldsymbol{\alpha}_{ijkl} \sim \text{LogNormal}(1, 1) \quad (\text{F.3})$$

Inference was performed using the mean target, competitor, and decoy choice probabilities, collapsed across product category and the target's high dimension. See Table ??.

Trial Type	TDD	Option	<i>M</i>	HDI lower	HDI upper
Attraction	Near	Target	.48	.45	.51
		Competitor	.47	.44	.50
		Decoy	.05	.03	.06
	Far	Target	.46	.43	.49
		Competitor	.48	.45	.51
		Decoy	.07	.05	.08
Repulsion	Near	Target	.31	.28	.34
		Competitor	.66	.63	.69
		Decoy	.04	.03	.05
	Far	Target	.33	.30	.36
		Competitor	.65	.62	.68
		Decoy	.03	.02	.04

Table F.1. Experiment 4 Mean Posterior Choice Proportions from the Bayesian Dirichlet-Multinomial Model.

On average, participants chose the competitor more than the target in both TDD levels, in the repulsion effect trials. In the attraction effect trials, participants chose the target and competitor at equal rates.

APPENDIX

BAYESIAN HIERARCHICAL LOGISTIC REGRESSION FOR EXPERIMENT 5 DATA

The comparability data from Experiment 5 were analyzed with a Bayesian hierarchical logistic regression model.

All trials where participants chose the decoy option were removed. Trials where the W and H rectangles were in the first two positions were also removed.

The target was classified as the option aligned with the decoy in the two-aligned option. The model predicted choice via a linear combination of an intercept, the configuration (none-aligned, two-aligned, all-aligned) and whether the target was in the middle position (1, 0). The reference level for configuration was none-aligned. There were no interactions included in the model. There was also a random effect of participant included in the model.

The model was fit as a Bayesian hierarchical logistic regression model using the rstanarm package (Goodrich et al., 2020), using default priors for all parameters. Posterior estimates for all fixed effects are shown in Table ??.

Parameter	M	SD	HDI lower	HDI upper
β_0	-0.18	0.03	-0.24	-0.13
$\beta_{\text{two-aligned}}$	-0.03	0.02	-0.08	0.01
$\beta_{\text{all-aligned}}$	-0.11	0.03	-0.16	-0.06
$\beta_{\text{target middle}}$	0.27	0.02	0.24	0.31

Table G.1. Experiment 5 Posterior Estimates for all Fixed Effects from the Bayesian Hierarchical Logistic Regression Model.

The main parameter of interest is $\beta_{\text{two-aligned}}$, which captures the change in target choice when comparing the none-aligned condition to the two-aligned condition. The posterior mean was below 0 ($M = -0.03$), and while the 95% HDI included 0 ($[-0.08, 0.01]$), 93.23% of all samples were < 0 , which is taken as moderate evidence for an effect.

Participants also chosen the target less in the all-aligned condition ($M = -0.11$), suggesting a bias away from the aligned option even when all options were aligned.

There was also a position effect, such that participants chose the target more when it was in the middle of the screen $M = -.27, 95\%CI[0.24, 0.41]$.

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