USING EX-GAUSSIAN MODELING TO REVEAL MECHANISMS OF THE FLANKER EFFECT

A Thesis

by

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ABSTRACT

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I replicated the experimental design conducted by Heiz and Engle (2007). A total of 180 participants were given a flanker task to complete. The task consists of three blocks of 80 trails with an increase in response deadlines after each block. Participants were asked to quickly and as accurately as possible identify the center letter in a five-letter string. There were two types of trials. First, the congruent trials, all the letters were identical for example five Ss were shown or five Hs. Whereas in the incongruent trials the central target letter was flanked by different letters. The flanker effect refers to the slowdown that occurs during the incongruent trials. This slowdown demonstrated the inability to ignore irrelevant information that flanks the target letter. The purpose of this study is to reveal the cognitive mechanisms behind the flanker effect and explore if the flanker effect occurs due to analytic processes such as thinking, decision making or due to nonanalytic processes such as stimulus driven automatic processes. We used the ex-Gaussian model to analyze the response times gathered from each participant. The ex-Gaussian model includes a normal component with mean (mu) and the exponential tail (tau). If the flanker effect is due to nonanalytic processes, the effect will appear in the normal component. If the flanker effect is due to analytic processes the effect will present in the tail component normal component. Results demonstrate that the effect occurs in the mu parameter therefore, the flanker effect is a nonanalytical process.

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CHAPTER I

INTRODUCTION TO THE FLANKER TASK

We have likely all experienced a similar phenomenon when we pull into our driveway or into the parking spot of our destination, and we wonder how we have made it safely, as we don't remember much about our drive. Somehow, we have successfully eliminated all the unnecessary stimuli such as cars, buildings, and other distractions occurring outside the car and in the car. The driving was done almost automatically, yet of course we still were able to react to important stimuli on the road appropriately. Thus, it is important to understand the cognitive processes involved in attention and visual processing. Historically, this has been studied in the lab via the flanker task.

The flanker task originates from Eriksen and Eriksen (1974), whose primary aim was to study visual processing. Participants were presented with a central target that was surrounded ("flanked") on both sides by distractors. The goal in the task was to identify the central target as quickly as possible, which required focusing on the target and ignoring the flankers around the target. Eriksen and Eriksen demonstrated that participants exhibited slower response times when the central target did not match with the flankers. They concluded that the flanked irrelevant stimuli were still processed to some degree by the participants and thus could not be completely ignored.

Since the original Eriksen and Eriksen (1974) study, the flanker task has been used many times in cognitive psychology to study the cognitive processes involved in visual processing and attention. For example, Heitz and Engle (2007) are one of many studies which have replicated the original flanker task and used the results to theorize about *why* the flanker effect occurs. In their study, Heitz and Engle asked participants to

identify the central letter of a five-letter string composed of S and H characters as quickly as possible. As with most flanker tasks, there were two types of trials: congruent and incongruent. In congruent trials all the letters on the five-letter string were the same; for example, SSSSS or HHHHH. On the other hand, incongruent trials were composed of the center target letter being flanked or surrounded by different letters; for example, SSHSS or HHSHH. To experimentally manipulate error rates, Heitz and Engle (2007) gave participants six blocks of 80 trials with an increase in response time deadlines after each block. In the first block, the response time deadline was 600 ms, with subsequent blocks decreasing this deadline by 100 ms each time (to a minimum deadline of 200 ms). The experiment demonstrated that responses are more accurate during congruent trials than in incongruent trials. In addition, the flanker effect decreased on longer reaction times which provided support for the spotlight model. The attentional spotlight model states that visual attention functions as a spotlight. When the participants have time, they can process and focus both on the targeted stimuli and the distractions. However, as the time the participants have to identify the targeted stimulus decreases so does their focus or spotlight. Participants' spotlight narrows to only the targeted stimuli.

Many other experiments have replicated the flanker task to further explore visual processing. Recently, Salagovic and Leonard (2020) used the flanker task to examine the impact of auditory stimuli on visual information processing. Participants were seated in front of the screen wearing headphones and an eye tracker. Three letters appeared on the screen, with the central letter as the target letter and with two letters surrounding the target on both sides. The flankers were either identical to the central target letter or different. There were two types of trials: sound-present trials and sound-absent trials. On

sound-present trials, a tone was played 100ms before the letter display. Respectively, sound-absent trials did not include the playing of a tone before the letters appeared on the screen. Salagovic and Leonard observed that the tone led to an increase in reaction times and a reduction of variability of responses, leading them to conclude that sound may alter the flow of information that is being processed with an increase in distraction when the letters presented were not identical. The findings of this study may help with work being conducted in the field of autism and ADHD.

In another study, Hsieh et al. (2012) used the flanker task to investigate the impact of age on information processing. In their experimental design, Hsieh et al. used arrows instead of letters as the targeted stimuli and the flankers. There were three types of trials: (1) congruent trials, where all the arrows were pointing in the same direction (← ← ← ← ←); (2) incongruent trials, where the central target letter was flanked by arrows going the opposite way (→ → ← → →); and (3) neutral trials, which contained only the central target arrow and neutral stimuli for the flankers (- - ← - -). In addition, this study incorporated a spatial compatibility manipulation. On compatible trials, which were signaled by green or red colored target arrow, participants pressed the "z" key in response to a target arrow pointing to the left (←) and the "/" key to a target arrow pointing to the right (→). On incompatible trials, which were signaled by a green or red colored center arrow, participants were instructed to respond the opposite way, pressing the "/" key to a target arrow pointing to the left and the "z" key to a target arrow pointing to the right. There were two groups of participants, first group with an age range of 18-24 and the second group were between 60 and 72 years old. The findings demonstrated

slight slower reaction times in the older participants, yet the flanker effect was evident in both groups and in both conditions.

Clearly, the flanker effect is widespread and easy to describe -- participants tend to have an increase in response times and error rates on incongruent trials compared to congruent trials. This flanker effect reflects the inability to ignore the unneeded information that surrounds the center letter during the flanker task. The purpose of this study is to further understand the flanker effect and ask "why" it occurs. To do this, I used mathematical modeling of response times to uncover the source of the flanker effect. More specifically, I employed the ex-Gaussian model (Hohle, 1965; Balota & Spieler, 1999) to identify if the flanker effect occurs due to analytic processes or nonanalytic processes.

Analytic and Nonanalytic Processes

The cognitive processes that contribute to decision-making when a stimulus is present can be divided into two types: analytic and nonanalytic processes (Balota, 1983; Hasher & Zacks, 1979; Jacoby, 1991). *Nonanalytic processes* are unconscious, automatic mental processes that occur outside of conscious awareness and control. These automatic processes were first identified by the psychologist Helmholtz who argued that perceptions are determined by unconscious processes from the stimulus in the environment (Reisberg, 2013). Compared to nonanalytic processes, which are typically stimulus driven and automatic, *analytic processes* are central attention-demanding processes. Together, nonanalytic and analytic processes are responsible for generating all the relevant information about a stimulus (Whittlesea & Price, 2001).

Analytic and nonanalytic processes are often discussed in the context of explicit and implicit learning and memory. Typically, memories are thought of as events that have occurred in the past which can be recalled (i.e., an analytic process). However, memories can also affect decision-making and behavior on a more unconscious level where there isn't an active and conscious recall (i.e., a nonanalytic process). A similar dichotomy holds for learning. For example, explicit learning is associated with conscious, intentional processes of knowledge acquisition (i.e., analytic processes), whereas implicit learning is a form of learning that involves unconscious, incidental, and procedural knowledge gain (i.e., nonanalytic processes). One example of this unconscious recall in memories occurs in people with amnesia. Though amnesiacs may not be able to recall a specific past event, yet they are still able to able to perform tasks by acquiring information. Yoon et al. (2017) measured if memory impairment (amnesia) had an impact on participants' ability to acquire knowledge during a communication task. The study consisted of healthy adult individuals, individuals who suffered from amnesia, and young healthy individuals. Participants had to describe tangram images to a partner. The descriptions of the participants were analyzed, and the results demonstrated that participants with amnesia (just like young healthy individuals and adult healthy participants) were able to adjust their descriptions based on what the partners knew. This study demonstrate that even in the absence of episodic memory, information can still be acquired and processed (i.e., nonanalytic processing).

Ex-Gaussian Models of Response Times

In the field of cognitive psychology, the most often used dependent variable is reaction time. However, the distribution of reaction times is usually positively skewed.

One way to account for this positive skew is to use a mathematical model to separate the distribution into distinct components. One such model is the ex-Gaussian model (Hohle, 1965), which combines a normal distribution with mean μ and standard deviation σ and an exponential distribution with mean τ (Rieger & Miller, 2019). This ex-Gaussian model is a three-parameter model with mean $E(x) = \mu + \tau$ and variance $Var(x)=\sigma^2 + \tau^2$. This decomposition is remarkable, because it allows the analyst the ability represent an overall mean observed response time as the sum of two specific components: the normal component mean μ and the exponential component mean τ.

This mathematical fact leads to one of the primary benefits of using the ex-Gaussian model; namely, that we can go beyond estimates of central tendency to reveal a more comprehensive view of the effect observed. To illustrate, let's suppose that we carry out a flanker experiment in which the mean response time for congruent trials is 550 ms, and the mean response time for incongruent trials is 600 ms; thus, we have observed a flanker effect of 50 ms. Let's further suppose that we performed ex-Gaussian decompositions of the distributions of congruent and incongruent trials. There are two scenarios that reflect the boundary conditions from which this 50-millisecond effect could have occurred. In Scenario 1, suppose the congruent trial mean (550 ms) is decomposed as $\mu + \tau = 400 + 150$ ms, whereas the incongruent trial mean (600 ms) is decomposed as $\mu + \tau = 400 + 200$ ms. In this scenario, the effect lies completely in the exponential parameter τ. In Scenario 2, let's again suppose that the congruent trial mean (550 ms) is decomposed as $\mu + \tau = 400 + 150$ ms, but this time let's suppose that the incongruent trial mean (600 ms) is decomposed as $\mu + \tau = 450 + 150$ ms. In Scenario

2, the effect lies completely in the normal parameter μ. Importantly, both scenarios say something completely different about the nature of the flanker effect.

In this way, ex-Gaussian modeling may lead us to a better understanding of the locus of flanker effect. Particularly, the different components of the ex-Gaussian model (μ and τ) may directly index the different cognitive processes involved. To this end, Matzke and Wagenmakers (2009) compiled a list of different possible cognitive interpretations attributed to the ex-Gaussian parameters. The normal component mean μ may represent nonanalytic processes (Balota & Spieler, 1999), stimulus variables (Blough, 1988), attentional cognitive processes (Kieffaber et al, 2006), and memory retrieval processes (Penner-Wilger et al., 2002). On the other hand, the exponential component mean τ may represent analytic processes (Balota & Spieler, 1999), attentional lapses (Epstein et al., 2006), intentional cognitive processes (Kieffaber et al, 2006), recall latency (Rohrer & Wixted, 1994), central processing (Spieler, Balota, & Faust, 1996), and higher cognitive functioning, such as working memory and reasoning (Schmiedek et al., 2007). Therefore, when decomposing experimental condition means using the ex-Gaussian model, the resulting parameters can be directly linked to different cognitive interpretations. As a result, the ex-Gaussian model is becoming increasingly popular for use in research to study ADHD, Alzheimer's disease, memory retrieval processes, and central decision processes.

In one such study, Kóbor et al. (2015) used the ex-Gaussian model to analyze data from an animal Stroop task that was performed by children with ADHD. In a Stroop task, participants are asked to identify the ink color in which a color word is printed. Participants generally take longer to respond when the ink color isn't the same as the

color implied by the word. For example, if the word GREEN appears on the screen in red ink, participants have to respond to the print color (red). This is generally effortful, as participants must first inhibit the response "green" that is implied by the text of the word. One variant of this task is an animal Stroop task, in which children were presented with a colored picture of two animals that differ in size. The image of one animal was larger than the other and the task was to identify which animal is larger in real-life, not which animal is larger on the screen. There were two types of trials: congruent and incongruent. In congruent trial, the larger image was in fact the larger animal in real life. For example, a giraffe was shown on the screen as the larger image next to a bird which was smaller in the image (and is smaller in size in real life as well). In incongruent trials, the larger in real-life animal was physically smaller on the screen than the smaller in real-life animal. As expected, Kóbor et al. (2015) showed that children with ADHD responded significantly slower than the control group. When the observed response times were further analyzed using the ex-Gaussian model, Kóbor et al. found that the normal component mean μ was significantly larger for incongruent trials than for congruent trials. However, when comparing the ADHD children vs. neurotypical children there was a significant increase in the exponential component mean τ. A similar result was obtained in a working memory task (Buzy et al., 2009), who also found a significant difference in the τ parameter between the two groups, with the ADHD group demonstrating more variability and slower reaction times than the control group.

The ex-Gaussian model has also been applied in research on Alzheimer's disease. Grady and Anderson (2012) examined the relationship between white matter volume on cognitive intra-individual variability and reaction times using the ex-Gaussian model. A

decrease in white matter is linked to a decrease in cognitive performance. The study consisted of 133 cognitively normal individuals and 33 individuals with early-stage Alzheimer's disease. Participants completed the Stroop task, Simon task, and consonant-vowel odd-even switching task. fMRI imagining and regional brain volumes were also collected by the examiners. For response times across all tasks, older adults had larger values for both μ and τ. In addition, the early-stage Alzheimer's disease group had a larger value of τ than cognitively normal individuals.

Lastly, Andriuta et al. (2020) analyzed the attentional problems in Alzheimer's disease and Lewy body dementia (LBD) using an ex-Gaussian analysis. There were 103 participants all over the age of 60. However, 48 participants were diagnosed with LBD and 33 participants with probable Alzheimer's disease, and 22 participants were the healthy control group. Participants were given an attention network test which is a combination of the flanker task and Posner cueing paradigm and a flanker task to perform. Structural images of grey matter, white matter, and cerebrospinal fluid were also obtained from the participants. The response time from each participant were then fit with an ex-Gaussian distribution. The μ and τ parameters showed an increase in the LBD group compared to the control, however there was no significant difference in either for the Alzheimer's disease group. Notably, researchers did find a relationship between Gaussian parameters and grey and white matter volume. For example, μ was negatively correlated to bilateral occipital, frontal, and temporal cortices for the Alzheimer's disease group. The normal standard deviation σ was negatively correlated with grey matter volume in some areas of the brain like the right frontal pole and positively correlated in other parts like the bilateral temporal gyri and cerebellum. This study demonstrates the

ex-Gaussian's model ability to provide more detailed and narrowed analyses instead of describing the distribution only using the central tendency measures.

The Proposed Study

The purpose of the current study is to understand the cause of the flanker effect which is evident in incongruent trials during a flanker task. Participants tend to have an increase in response times and error rates during incongruent trials vs. congruent trials. The flanker effect occurs due to the inability to ignore the unneeded information that surrounds the center letter during the flanker task. We will use mathematical models to uncover the source of the flanker effect. That is, the ex-Gaussian model will help to identify if the flanker effects occur due to analytic processes or non-analytic processes. If the flanker effect is due to nonanalytic processes, the effect will appear in the normal component. If the flanker effect is due to analytic processes, the effect will be evident in the tail component.

CHAPTER II

METHOD

Participants

A total of 180 participants completed a flanker task as part of a class assignment in PSYC 5316: Advanced Quantitative Methods and Experimental Design at Tarleton State University. The data are anonymous and available for download at https://github.com/tomfaulkenberry/courses/tree/master/canvas/5316/flankerData.

Materials and Design

The design of the flanker task was created to roughly mirror that of Heitz and Engle (2007). The task was created and administered via the open source software package OpenSesame (Mathôt, Schreij, & Theeuwes, 2012). The stimuli presented to the participants were five letters consisting of S and H. There were in total four different stimuli that were randomly presented to participants throughout the experiment. Congruent trials consisted of strings comprised of identical letters; either SSSSS or HHHHH. Incongruent trials consisted of strings where the target H was flanked by four S characters (i.e., SSHSS) or the target S was flanked by four H characters (i.e., HHSHH). The participants were presented with a total of 240 trials, which were divided into three blocks of 80 trials each. Each block was paired with an increasingly stringent response deadline. For block 1, the deadline was 1500ms; for block 2, the deadline was 600 ms. For block 3, the deadline was set at 300 ms.

Procedure

Data were collected individually with the participants seated comfortably at a laptop computer. The participants read the directions for the experiment, and once they

were ready, they were instructed to begin. In each block, participants were instructed to identify the center letter from a five-letter string as quickly as possible. Participants were instructed to press the S or H key as quickly as possible with each key corresponding to the center letter they identified. Participants placed their left and right index fingers on the S and H keys respectively. Once the participants finished the first block, a new set of instructions appeared on the screen explaining the 600-millisecond deadline to respond. After the 80 trials in block 2, the instructions for block 3 appeared with the response deadline of 300 milliseconds. Once block 3 was finished, the participants received a thank you for participating message on the screen and notify the administrator. Participants were able to take as much time as needed between blocks. The entire experiment took around six minutes to complete.

Analysis Plan

Since all data are already collected, the primary goal of this thesis is to submit the gathered response times to a mathematical model that is well-suited to represent the pronounced positive skew inherent in response time distributions. As described above, I used the ex-Gaussian model.

The analytic workflow is as follows. The dataset consists of a total of 43,200 trials that have already been collected. The first step is to clean the data (i.e., removing error trials and any trial with response time greater than 1500. Typically, these trials only comprise a small portion of the dataset. The next step is to separate the remaining response times into 360 experiment design cells, obtained from N =180 participants each completing N =2 conditions (congruent trials and incongruent trials).

Once the response times are separated into the design cells, the third step is to collapse the distributions of response times in each cell. The typical approach is to compute the mean or median, but in this thesis, I instead extracted ex-Gaussian parameter estimates using classical maximum likelihood estimation. The result will be three parameters for each design cell: μ, σ, τ . This allows me to directly compare the values of each parameter between congruent trials and incongruent trials (across all participants). To do this, the parameters from each participant is gathered and submitted to both a Bayesian paired samples *t*-test and a classical paired samples *t*-test. These statistical tests compare the values of each parameter between congruent trials and incongruent trials. If there is a reliable difference in the μ parameter, we can conclude that the flanker effect is driven by nonanalytic processes. That is, the slowdown that occurs in the incongruent trials will be due to stimulus-driven, automatic processes. If there is a reliable difference in the τ parameter, we can conclude that the flanker effect is driven by analytic processes. In this case, the inability to ignore irrelevant information would be due to the central, attention demanding processes.

CHAPTER III

RESULTS

A total of 43,200 trials were collected from participants. We then removed 7,021 error trials (16.3% error rate) and an additional 6 trials for which the response time was greater than 1500 milliseconds. After data cleaning 36,173 trials remained for analysis (83.7% of the original dataset). The response times were organized into 360 experiment design cells, obtained by crossing participants (N = 180) with congruity condition (N = 2: congruent, incongruent). All subsequent analyses were performed on these design cells.

Bayesian Hypothesis Testing

In addition to the traditional frequentist paired samples *t*-tests, I conducted Bayesian paired samples *t*-tests for each set of parameter estimates (Rouder, Speckman, Sun, Morey, & Iverson, 2009; Faulkenberry, Ly, & Wagenmakers, 2020). The primary output of the Bayesian paired samples *t*-test is a Bayes factor (BF), which is defined as the relative likelihood of the observed data under one model (i.e., the null or alternative hypothesis) compared to the other (Kass & Raftery, 1995). For example, a Bayes factor of $BF_{10} = 88$ would indicate that the observed data are 88 times more likely under the alternative hypothesis H_1 than under the null hypothesis H_0. On the other hand, a Bayes factor of $BF_{01} = 88$ would signify that the observed data are 88 times more likely under the null hypothesis H_0 than the alternative hypothesis H_1. Compared to traditional frequentist tests, there are several benefits to conducting Bayesian tests when analyzing data (Wagenmakers, 2007). One benefit is that the Bayes factor provides a direct index of evidence. A second benefit concerns interpretability; whereas a *p*-value simply represents how surprising the observed data would be *if* the null hypothesis were true, the

Bayes factor tells us directly how much more likely the data is under one model compared to the other. Finally, in a Bayesian analysis, both the null and the alternative hypothesis are considered as a potential model for the data. Therefore, our analysis can demonstrate support for either the null or the alternative hypothesis, which is particularly important in light of the goals of this thesis.

In the following response time analyses, I followed the recommendations of Dienes and Mclatchie (2018), who recommend combining both frequentist and Bayesian procedures in statistical reporting (see also Faulkenberry, Bowman, & Vick, 2018). By doing this, one is able to combine the familiarity of the traditional frequentist approach with a Bayesian measure of model evidence that is provided by the observed data.

Response Time Analysis

I performed two different analyses on the design cells that were defined above. First, I collapsed each design cell's distribution of response times into a single mean response time. These mean response times were then submitted to frequentist and Bayesian paired samples *t*-tests. As expected, there was a large, significant effect of congruity condition on mean response time, $t(179) = 27.10$, $p < 0.001$, Cohen's $d = 2.02$. Response times were larger on incongruent trials (M = 510 ms) than on congruent trials (M = 460 ms), representing a mean flanker effect of 50 ms (95% CI = [46.6 ms, 53.9 ms]). A Bayesian paired samples *t*-test revealed a Bayes factor of $BF_{10} = 4.68 \times 10^{61}$, indicating that the data were overwhelmingly more likely under the alternative hypothesis than under the null hypothesis.

Now that the traditional flanker effect has been observed in these data, I am able to carry out the next analysis, which attempts to uncover the source of this flanker effect.

For each design cell, the ex-Gaussian parameters μ, σ, τ were derived from that design cell's distribution of response times using classical maximum likelihood estimation (Myung, 2003). Next, I conducted both a traditional and Bayesian paired sample *t*-test on the collection of means for the μ and τ estimates.

First, I considered the analysis of the normal component means μ. Similar to the analysis of the mean response times conducted above, there was a large, significant effect of congruity on the normal component means μ, $t(179) = 16.4$, $p < 0.001$. The normal component mean μ was larger for incongruent trials ($M = 439.95$) than for congruent trials ($M = 388.99$). This can be seen clearly in Figure 1, which depicts a general increase in the μ estimates from congruent trials to incongruent trials.

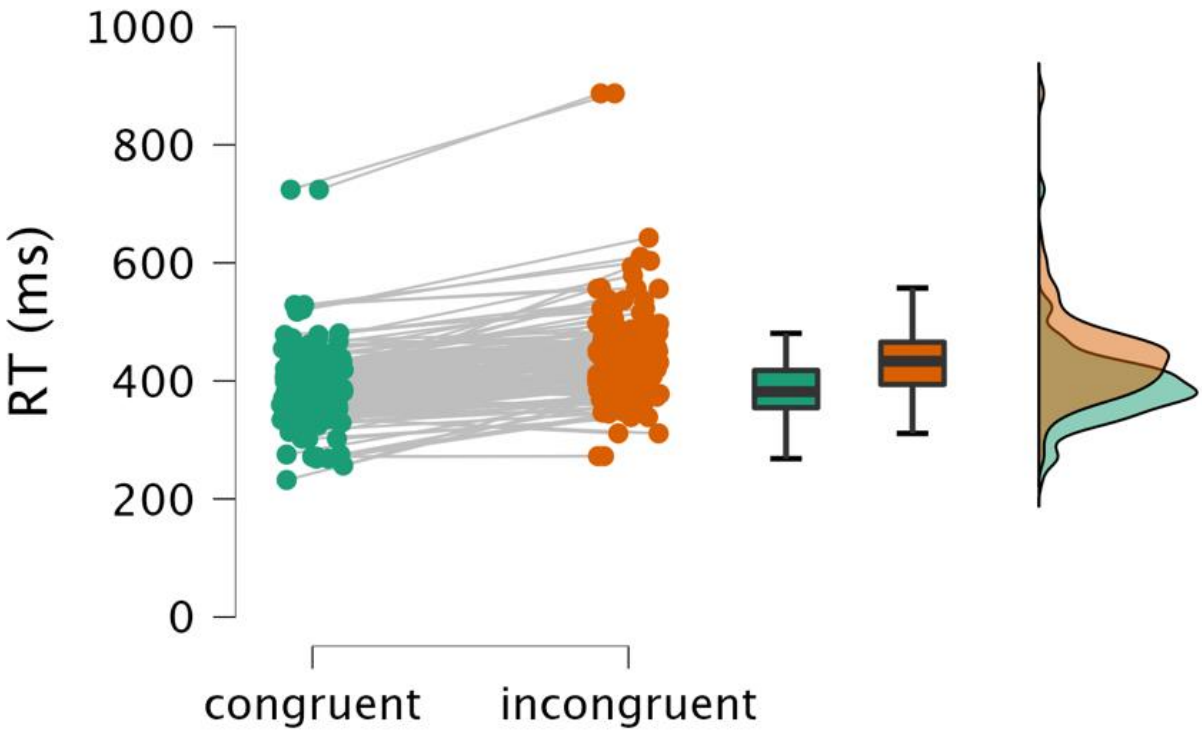

Figure 1. Raincloud plot demonstrating the increase in the estimates of the normal component mean μ in incongruent trials vs. congruent trials.

The raincloud difference plot in Figure 2 shows that most individuals exhibited a positive flanker effect in the normal component mean μ. Overall, the mean difference in normal component means μ between incongruent trials and congruent trials was 51 milliseconds, 95% CI = (44.8 ms, 57.1 ms). The Bayesian paired samples *t*-test on the normal component means μ resulted in a Bayes factor of $BF_{10} = 1.3 \times 10^{34}$, indicating that the observed data was 1.3 x 10^{34} times more likely under the alternative hypothesis than the null hypothesis. These data provide extreme evidence in favor of the alternative hypothesis, which allows us to conclude that the flanker effect exists in the normal component mean μ. That is, the flanker effect involves nonanalytic processes.

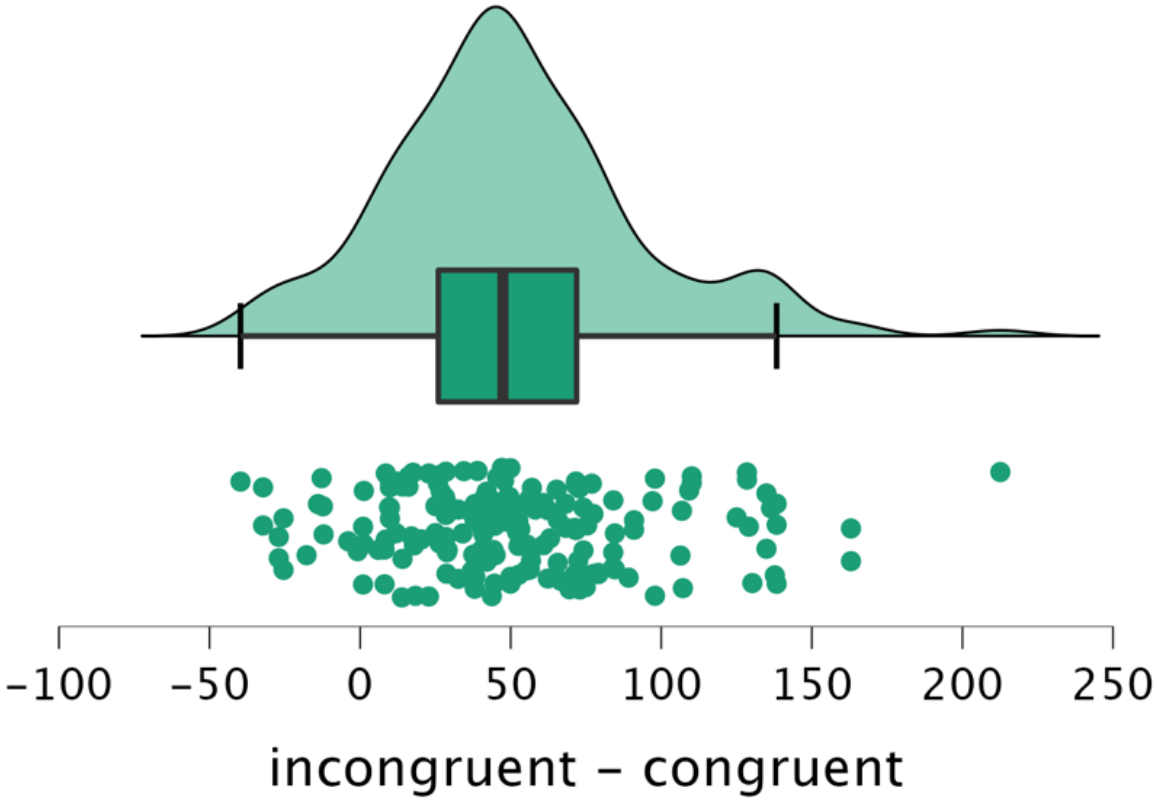

Figure 2. Raincloud plot showing the distribution of difference scores for the normal component mean μ between congruent trials and incongruent trials.

The same analysis was conducted for the tail component means τ. A paired samples *t*-test did not demonstrate a significant difference between congruent trials and incongruent trials, $t(179) = -0.182$, $p = 0.855$. Accordingly, the mean value of the tail component means τ for congruent trials was $M = 71.00$, whereas the mean value of the tail component means τ for incongruent trials was $M = 70.43$, a mean difference of -0.6 milliseconds, 95% CI = (-6.7, 5.6). This can be seen clearly in Figure 3, which shows that there was no discernible increase or decrease in tail component means between congruent and incongruent trials.

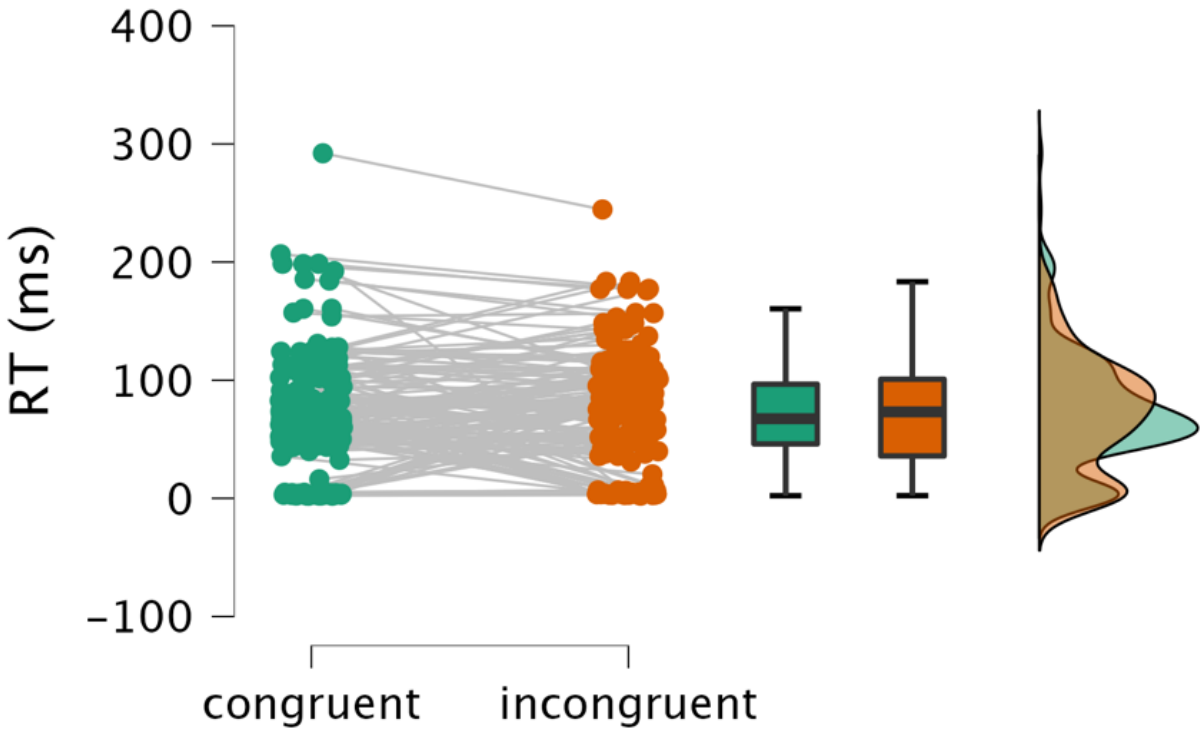

Figure 3. Raincloud plot demonstrating estimates of the exponential component mean τ for incongruent trials vs. congruent trials.

The distribution of difference scores for the tail component means τ is illustrated using the raincloud difference plot in Figure 4. A Bayesian paired samples *t*-test revealed a Bayes factor of BF_{01} =11.8, which indicates that the observed data were 11.8 times more likely under the null hypothesis than the alternative hypothesis. These data provide strong evidence in favor of the null hypothesis. Therefore, the analysis suggests that there is no flanker effect in the tail component mean τ . Overall, the ex-Gaussian analysis demonstrated that the flanker effect occurs in the μ parameter, not the τ parameter. Thus, the flanker effect appears to be primarily driven by nonanalytic processes.

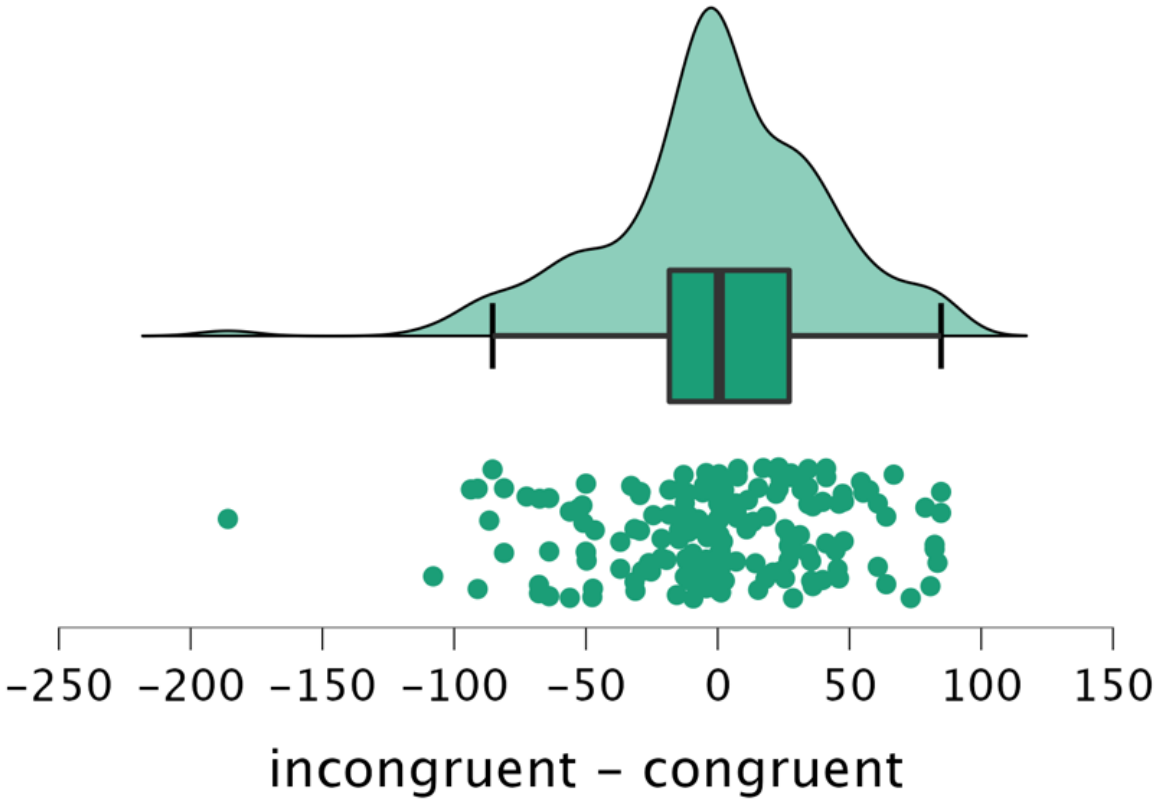

Figure 4. Distribution of difference scores for τ between congruent trials and incongruent trials.

CHAPTER IV

DISCUSSION

The purpose of this study was to identify the locus of the flanker effect using ex-Gaussian modeling. In a flanker task, participants are asked to identify the central character which is flanked or surrounded by distractor characters as quickly and as accurately as possible. Two types of trials were administered: congruent trials, where the central character was identical to the irrelevant stimuli surrounding it, and incongruent trials, where the central character was different than the irrelevant stimuli around it. The flanker effect refers to the slowdown of response times that occurs on incongruent trials. In this thesis, I replicated the flanker effect, but took the analysis one step further in an attempt to identify *why* the flanker effect occurs.

In my analyses, I used ex-Gaussian modeling as a tool to reveal the cognitive mechanisms implicated in the flanker effect. Two types of cognitive processes were identified in the prior literature: analytic and nonanalytic processes. Analytic processes refer to central attention demanding processes and are often associated with attentional lapses, intentional cognitive processes, recall latency, and higher cognitive functioning such as working memory and reasoning. Nonanalytic processes are automatic, stimulus driven processes that occur unconsciously. Both cognitive mechanisms attribute to the decision making when a stimulus is present.

As previously mentioned, I used ex-Gaussian modeling to separate observed response times into analytic and nonanalytic processes. The ex-Gaussian model decomposes the typically positive skew of a response time distribution into two components; a normal (Gaussian) component with mean μ, which is thought to reflect

nonanalytic processes, and an exponential tail component with mean τ, thought to reflect analytic processes. If the flanker effect is due to nonanalytic processes, the effect should appear mostly in the normal component. On the other hand, if the flanker effect is due to analytic processes, the effect should appear primarily in the tail component.

Perhaps surprisingly, a large effect was evident in the μ parameter from the ex-Gaussian model. There was a significant increase in the μ estimate from congruent trials to incongruent trials. A large Bayes factor indicated a large amount of evidence for this increase. However, there was no difference in tail component mean τ between congruent trials and incongruent trials. This null effect was confirmed by a Bayesian analysis indicating that the observed data were almost 12 times more likely under a null model where no such flanker effect occurred in the tail component means. Thus, these results indicate that the locus of the flanker effect is found in nonanalytic processes. Therefore, the slowdown that occurs in the incongruent trials are due to stimulus-driven, automatic processes.

Limitations

The primary limitation to this research is that it only looks at one mathematical model, the ex-Gaussian model. It would be beneficial and interesting to apply other models to the data to see the results obtained and if they are describing the same cause for the flanker effect. The diffusion model is one possible mathematical model which can be added. Recently, Matzke and Wagenmakers (2009) questioned whether the parameters of the ex-Gaussian model can truly represent different cognitive processes. To argue this, they first cited Hohle's (1965) conclusions that the μ parameter represents the residual time it takes to respond and the τ parameter indicates the decision time when responding.

Then, they pointed out that Hohle's interpretation is completely opposite from earlier studies conducted by McGill (1963) and McGill and Gibbon (1965), where the μ parameter instead was interpreted to indicate the decision making portion and the τ parameter represents the residual motor latency. Further, Luce (1986) criticized Hohle's findings on the grounds that they can be attributed to decompositions of reaction times which affects both parameters. In all, Matzke and Wagenmakers (2009) concluded that the ex-Gaussian model and the cognitive interpretation of its parameters doesn't have support from a theoretical standpoint. As the ex-Gaussian distribution gives a positive probability to negative reaction times, one can easily argue that the distribution cannot coincide with a credible cognitive process model. As a result, the ex-Gaussian model should be used cautiously.

Extensions of the Present Research

This study has provided the locus of effect of the flanker effect. Using the ex-Gaussian model showed that the inability to ignore irrelevant information occurs in the μ parameter, possibly indicating that nonanalytic processes are at play. The analysis demonstrated the importance of going beyond the central tendency and instead modeling the entire distribution of response times. Therefore, this type of analysis may be applied to other studies to examine not only if an effect occurs, but what is responsible for that effect.

A future interesting study would be to analyze the interplay of nonanalytic automatic, stimulus driven processes and analytic processes that are central demanding processes and how those processes can change and improve with practice. For example, one could administer the flanker task to participants to complete every day for six weeks

and see how the results are different in the ex-Gaussian parameters. I presume participant's performance will improve in identifying that central target, yet I am unsure the changes in the parameters. The ex-Gaussian modeling can also be used to further analyze performance in clinical populations. Applying the ex-Gaussian model to response times in common clinical tasks could better identify the mechanisms behind observable behaviors, which may help aide in providing more appropriate and tailored treatment plans.

In summary, ex-Gaussian modeling was used to reveal the cognitive mechanisms behind the flanker effect. The two cognitive mechanisms were analytical processes and non-analytic processes. If the flanker effect occurs in the normal component of the ex-Gaussian model then the it is due to nonanalytic process. If the flanker effect is evident in the tail component of the ex-Gaussian model the effect is a analytic process. The results demonstrated that the flanker effect resides in the mean of the normal component. Therefore, the flanker effect is due to nonanalytic, automatic processes. Example of possible nonanalytic processes at play are stimulus variable, attentional cognitive processes, and memory retrieval processes. The flanker effect occurs automatically, therefore even if participants are aware of this effect and the slowdown that happens in the incongruent trials they wouldn't be able to stop the flanker effect from occurring.

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