RELIABILITY OF DUAL-TASK PROCESSING EFFECTS

INVESTIGATING THE EXPERIMENTAL AND CORRELATIONAL RELIABILITY OF DUAL-TASK MEASURES IN THE PSYCHOLOGICAL REFRACTORY PERIOD PARADIGM

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A Thesis Submitted to the School of Graduate Studies in Partial Fulfilment of the Requirements for the Degree Master of Science

McMaster University MASTER OF SCIENCE (2022) Hamilton, Ontario (Psychology)

TITLE: Investigating the Experimental and Correlational Reliability of Dual-Task Measures in the Psychological Refractory Period Paradigm

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NUMBER OF PAGES: xii, 41

Lay Abstract

The purpose of this thesis is to explore the experimental and correlational reliability of the Backward Compatibility Effect (BCE) and Psychological Refractory Period (PRP) Effect produced in the PRP paradigm that is used to investigate dual-task processing. Using a multi-day experimental design and three PRP dual-task sessions, both experimental and correlational reliability were established for both effects. This thesis is the first research to establish correlational reliability for the BCE and PRP Effect, which indicates that these measures are valid and reliable to compare with other measures used to assess individual differences in cognitive processing and executive control, especially in regards to measures assessing parallel processing (multitasking), task switching, and task interference.

Abstract

The Psychological Refractory Period (PRP) paradigm is frequently used to explore human cognition, executive control, and parallel processing in individuals. However, it is also important to explore the individual differences between people. Before this dual-task paradigm can be used to explore individual differences and be compared to different measures of executive control, it must be established that the effects produced are both experimentally and correlationally reliable, meaning they replicate both across sessions and within individuals. This experiment had 85 McMaster University students participate in a two day experiment that collected multiple measures of executive control and included three PRP dual-task sessions. Data from participants were analyzed to investigate the two effects found in this paradigm: the Backward Compatibility Effect (BCE) in Task 1 (T1) and the PRP Effect in Task 2 (T2). Both effects were found to be individually reliable both experimentally and correlationally. The two effects were then correlated to explore the relationship between them, and a significant positive correlation was discovered. Subsequent analyses separated by response compatibility revealed that incompatible response trials were driving the positive correlation between the PRP Effect and BCE, and that the BCE is related to T1 reaction time on incompatible trials only. These findings suggest the BCE in T1 is driven by response interference between the two tasks on incompatible trials, and this effect then propagates to T2 performance. The reliability of these measures has not previously been explored in this way and this thesis is the first to establish these findings. The results of this thesis support using the BCE and PRP Effect for exploring individual differences between people, as reliable measures that can be explored with other tasks of cognitive

control and attention to investigate the presence of similar underlying cognitive processes.

Key Words: Psychological Refractory Period (PRP), dual-task processing, backward compatibility effect (BCE), PRP Effect, experimental reliability, correlational reliability, executive control, task interference

Acknowledgments

There are countless people I would like to acknowledge and thank for their support in my journey to complete my Masters degree. My family, friends, collegues, mentors, and staff in many departments of McMaster University have all contributed to supporting me throughout this complex process. To my Masters supervisors: Dr. Sandra Thomson, Dr. Bruce Milliken, and Dr. Scott Watter your wisdom, knowledge and patience has been invaluable and I have learned so much from all of you over the years. Scott, thank you for the insight to create this experiment to explore this area of research in such a detailed and specific way. I also appreciated your support and encouragement to care for myself and health when things got too complicated, your normalization of selfcare is something I will take with me forever. Bruce, I am forever grateful for your stepping in to be my McMaster supervisor at a time that was already so busy for you; thank you for your encouragement, thought provoking questions, and feedback. Sandra, I don't know where to begin in my thanks to you; without you I don't know how this thesis would have been completed. Thank you for all of our conversations, your insight and patience were a vital support in this process. Thank you for always having time to talk things out, on top of your other jobs, at-home schooling, and pandemic level stress. You are an amazing human, and I hope you know this. To those that were members of my committee over the years; Dr. Karin Humphreys, Dr. Ellen MacLellan, and Dr. Bruce Miliken: thank you all for your time and energy during these years. Your input and questions challenged me to explore deeper and your insights were always valuable. Karin, thank you for supporting me and going above and beyond, especially during 2014-

2015 when I was spending a lot of time in Hamilton, your kindness and compassion is something I hope to carry further into this world with my own actions. To Esther Manoian, thank you for all of your energy related to this journey. I am so grateful to you for your running of subjects, full day of intense scanning, and all your kindness and friendship over the years; you are one of the most wonderful people I have ever met.

I would also like to express my gratitude to my wonderful parents, Bill and Jocelyn, who were always there to offer support, even when they didn't fully understand my thesis topic, your love and encouragement were appreciated more than you know. To my partner, Ash Conn, thank you for your compassion and support during this intense time. From encouraging me to take breaks and making meals, your kindness was present throughout this process. Thank you. I love you, AConn. To my best friends, Sarah Forest and Lea Diskin, thank you for the laughter, memes, chats, voice notes, and ability to hold space over the years. Your friendship has been an invaluable component to my success in completing this thesis.

To all members of CogSci and the PNB department over the years, thank you for your support and contributions to my undergraduate and graduate experiences, your energy and our time together is forever imprinted in my memory. To members of my various meditation groups and communities, thank you for your time and opportunity to practice together. These moments of stillness have been invaluable to supporting my mental and physical wellbeing during this transformational point in my life.

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LIST OF ABBREVIATIONS AND SYMBOLS

AB: Attentional Blink

ANOVA: Analysis of Variance

BCE: Backward Compatibility Effect

BCSS: Bottleneck with Central Stage Shortening

BSS: Bottleneck Stage Shortening

FCE: Forward Compatibility Effect

GPA: Grade Point Average

MS: Milliseconds

MUQ: Multimedia Usage Questionnaire

OSPAN: Operation Span

PANAS-X:

PRP: Psychological Refractory Period

PRP1: PRP Session One

PRP2: PRP Session Two

PRP3: PRP Session Three

R1: Response One

R2: Response Two

RC+: Response Compatible

RC-: Response Incompatible

RSB: Response Selection Bottleneck

RS: Response Selection

RT: Reaction Time

S1: Stimulus One/First Stimulus

S2: Stimulus Two/Second Stimulus

SOA: Stimulus Onset Asynchrony

T1: Task One

T2: Task Two

Declaration of Academic Achievement

The inspiration for this thesis was conceptualized with Dr. Scott Watter, Dr. Sandra Thomson, and Lila Danis after a question was posed to Dr. Thomson by Dr. Karen Arnell during Dr. Thomson's PhD defence. The experimental design used for this thesis was a collaboration between Dr. Watter, Dr. Thomson, and Lila Danis, with experiment coding done by Dr. Watter. Data collection and the running of participants was completed by the McMaster University's Cognitive Sciences Laboratory Research Assistant, Ms. Esther Manoian. Coding of data was done my Ms. Manoian and Lila Danis. Statistical analysis of this experiment was completed by co-supervisor, Dr. Thomson and Lila Danis. The written thesis, tables and figures were conceptualized and executed by Lila Danis, with input from Dr. Thomson. Edits to this thesis were provided by co-supervisor, Dr. Thomson, co-supervisor, Dr. Bruce Miliken, and committee member, Dr. Ellen MacLellan.

INTRODUCTION

While researching the human brain, attention, and cognitive resources, it is valuable to consider findings beyond that of the individual or group, to also include individual differences found between people. Comprehending human cognitive capacities, abilities, and limitations, in relation to individual differences, is crucial to furthering our understanding of the human mind, cognitions, and resulting behaviour beyond the individual level. However, before investigating individual differences between people, it is critical to explore the reliability of the measures being used to assess and analyze these differences, primarily to explore if the effects found are statistically valid (in the context of individual differences) and the measurement tools being used are effective in capturing what researchers intend to investigate. If researchers assume the reliability of a measure or effect due to its ability to replicate in experimental research, they may be completely missing the nuance that correlational and individual differences research use a different definition of reliability (Hedge, Powell, & Summer, 2018).

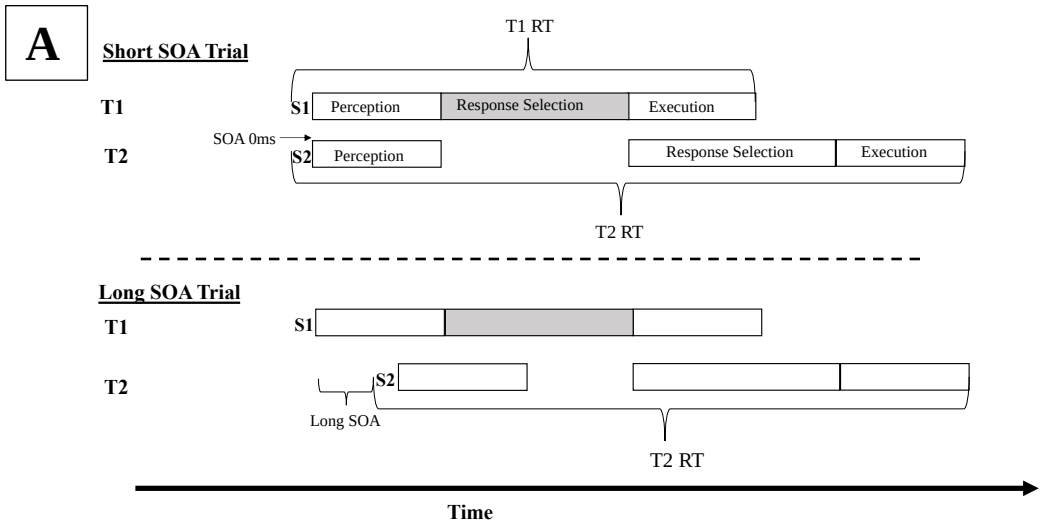
For the purpose of this thesis, we will be exploring a dual task method known as the Psychological Refractory Period (PRP) paradigm. This method was used to measure the PRP Effect and Backward Compatibility Effect (BCE) across multiple sessions and days, with the goal of determining whether the magnitudes of these effects are reliable across individuals. This is an important step before determining whether performance on this task is related to performance on other cognitive measures, and thus useful for application in correlational and individual differences research.

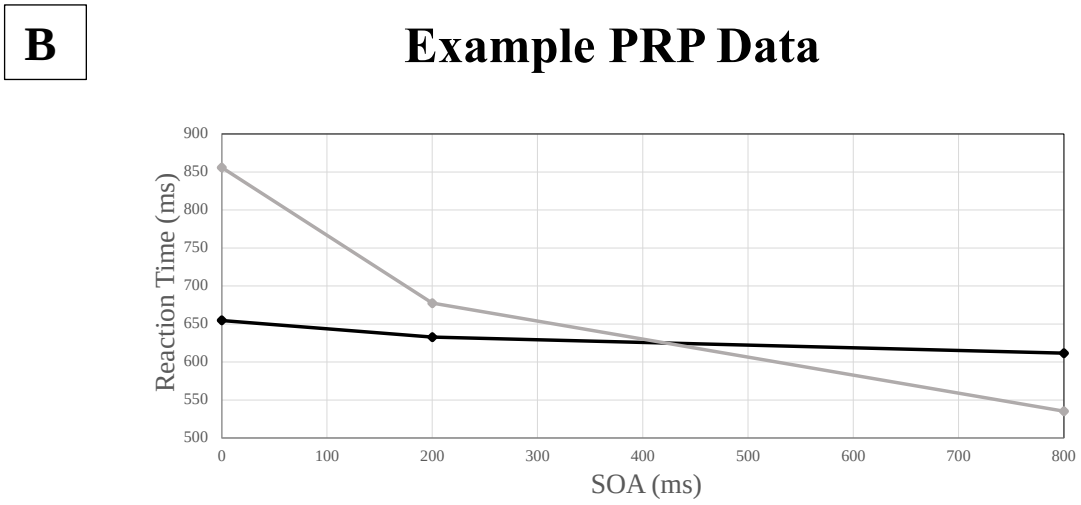
When individuals attempt to carry out more than one task at a time, it is generally accepted that as the number of tasks increase, the ability to respond rapidly and accurately decreases quickly. This phenomenon, first described by Telford (1931), likened an attentional mental refractory period to that observed in the skeletal muscles; and the conceptualization of a psychological refractory period has persisted.

The Psychological Refractory Period (PRP) paradigm has been used for decades to investigate the human ability, or inability, to perform two tasks simultaneously (Telford, 1931; Welford, 1952; Welford, 1959; Pashler, 1994). In a typical PRP experimental design, participants are exposed to two stimuli in close temporal succession and are required to make a speeded response to each, according to a set of task instructions. The typical result observed with this method is that the reaction time (RT) for the second stimulus (S2) increases as the stimulus onset asynchrony (SOA) between it and the first stimulus (S1) decreases, while the RT to S1 remains relatively unchanged across SOAs (Figure 1) (Pashler, 1984; Pashler & Johnston, 1998). This performance impairment for S2 at short SOAs has been observed in incredibly simple tasks (e.g., colour, letter, or number identification). This effect has been noted when the same task is used for Task 1 (T1) and Task 2 (T2), when different tasks are used as T1 and T2, and even when the required response executions involve different sensory modalities, meaning the tasks do not overlap at all (e.g., manual and verbal required response modalities; for reviews, see: Pashler, 1994; Pashler & Johnston, 1998).

Figure 1.

Example Timing of the Dual-Task Process





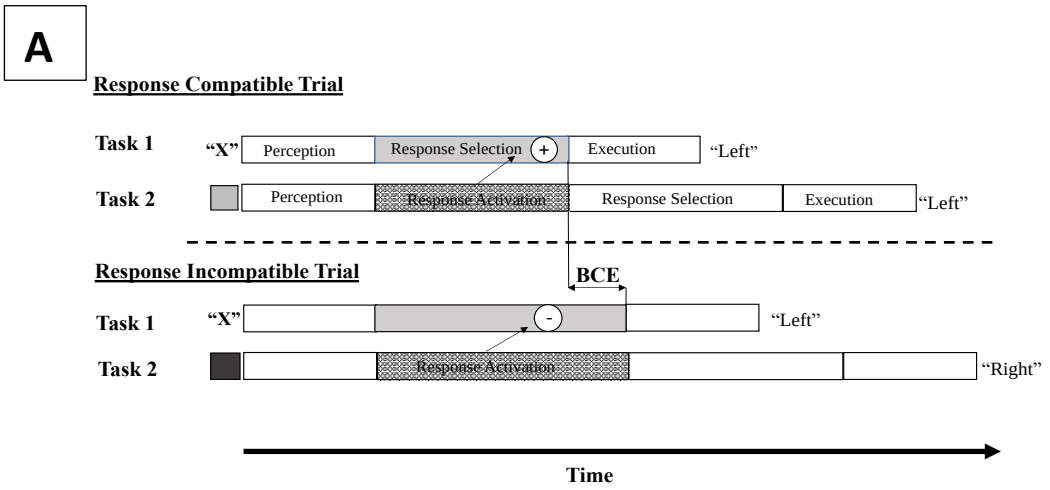
Note. (A) The timing of a dual-task experiment and the discrete processing stages involved for each task: Perception, Response Selection, and Response Execution. The first stimulus (S1) is presented, followed by a second stimulus (S2). Separating S1 and S2 is a time delay or stimulus onset asynchrony (SOA). Slower reaction times in the second task (T2 RT) are observed at short SOAs than at long SOAs. (B) PRP dual-task data. Here the T1 reaction time (RT) is thought to be relatively unchanged by SOA variations (the black line), whereas the T2 RT becomes faster as the SOA increases (the grey line), reflecting less response selection overlap and therefore less of an informational processing bottleneck to T2 processing and task completion. The PRP Effect is calculated by subtracting the T2 RT at the longest SOA (800ms) from the T2 RT at the shortest SOA (0ms).

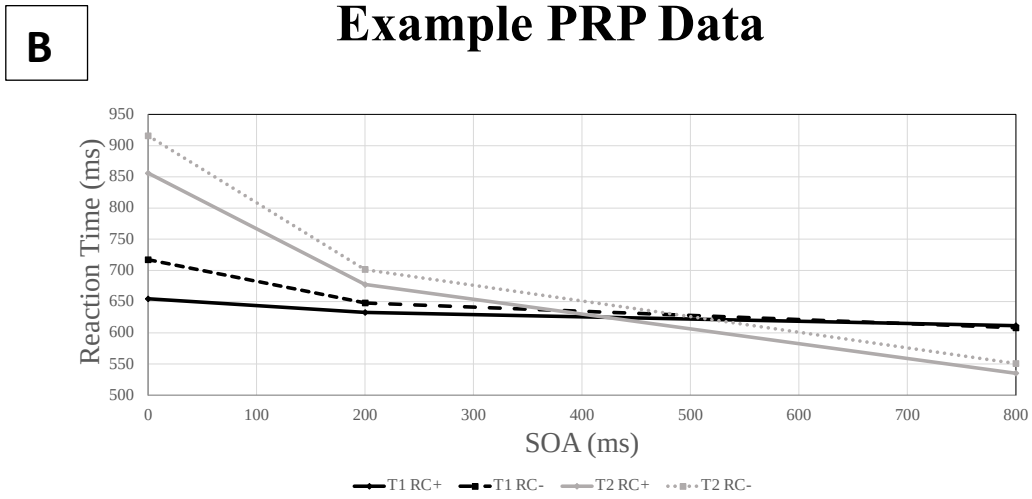
The reliable experimental observation of an inability to perform more than one task at a time was assumed to reflect a structural limitation in the human information processing system; specifically, an inability to perform the required central operations for T2 at the same time as the central operations for T1 (Welford, 1952; Welford, 1959). Welford (1952) proposed the concept of a cognitive bottleneck that occurs when selecting the correct response for each task. Pashler formalized the idea of a cognitive bottleneck in dual-task processing as The Response Selection Bottleneck (RSB) Theory (Pashler, 1984; Pashler & Johnston, 1989; Pashler, 1992; Pashler, 1994; Pashler & Johnston, 1998).

The RSB Theory relies on the locus-of-slack logic, and assumes that tasks can be divided into processing stages that are discrete and serial (for reviews see: Pashler, 1994; Pashler & Johnston, 1998). As shown in Figures 1A and 2A, the early stages of pre-bottleneck processing are often associated with perception and categorization of the stimulus. The central bottleneck stage of response selection (RS) involves decision making, regarding how to respond to the stimulus according to the task instructions and response mapping rules. The final, post-bottleneck, stage of processing is the execution of the response decision (for review, see: Pashler & Johnston, 1998). The limitation in performing multiple tasks simultaneously was commonly thought to be due to the inability to carry out the RS stage for more than one task in parallel, although both the pre- and post-bottleneck stages can overlap. This theory explains the PRP Effect simply, such that with short SOAs between S1 and S2 the T1 RS stage must be complete before the T2 RS stage can commence, resulting in a delay in T2 performance (Figure 1).

Figure 2.

Example PRP Data Based on Response Compatibility





Note. 2A This figure depicts the difference in T1 and T2 trials based on response compatibility. Here, T1 is a letter identification task and T2 is a colour identification task (see Figure 3 for more detail). The RT for each task starts once the stimulus has been presented and is stopped once a manual response has been executed (e.g., pressing the "left" or "right" key on the keyboard). The Backward Compatibility Effect (BCE) is the difference in T1 RT between response compatible (RC+) and incompatible (RC-) trials. This figure also depicts response activation occuring for T2 in parallel with the T1 response selection stage of processing, whereby information from T2 influences the duration of T1 response selection. Figure 2B presents typical PRP dual-task data that includes RC+ and RC- trials for both T1 and T2. Here we see the difference in RT for RC+ and RC- trials in T1 (black) and T2 (grey) performance. In both tasks, RC+ trials are faster, reflected by the solid lines, and RC- trials are slower, represented by the dashed lines. The BCE is calculated at the shortest SOA (0ms) by the difference in RT between RC+ and RC- trials.

This classic stage model has been supported by numerous studies using simple to complex stimuli (e.g., auditory tones, letters, numbers, colours, and words) and response modalities (e.g., vocal and manual; for review, see Pashler & Johnston, 1998). Dual-task costs have also been observed in a wide range of paradigms, including simple choice and go/no-go response designs, and for decisions requiring various types of judgements such as stimulus identification and categorization (for reviews, see Pashler & Johnston, 1998; Van Selst, Ruthruff, & Johnston, 1999). The PRP Effect is a robust experimental finding, such that it nearly always replicates, it is found in most participants, and it produces consistent effect sizes (Pashler & Johnson, 1998; Thomson, Watter, & Finkelshtein, 2010; for reliability review, see Hedge, Powell, & Summer, 2018).

Challenges to the obligatory discrete-stage-processing assumption of the RSB Theory have been made in informational crosstalk accounts of dual-task interference. While examining crosstalk effects in dual-task processing, Hommel (1998) observed a critical finding of backward response priming of T2 on T1 RT. In a series of five dual-task experiments, evidence was presented that is inconsistent with the central RSB Theory assumption that T1 RS must be complete prior to the start of T2 RS. Specifically, faster RTs were observed for T1 when both S1 and S2 required compatible responses (RC+). For example, on RC+ trials the T1 response (R1) might require manually pressing the left button and the T2 response (R2) might require saying ‘left’, whereas incompatible response (RC-) trials might require pressing the left button for R1 but saying ‘right’ for R2. This response-related priming from T2 to T1 suggests that RS stages must overlap to some extent, or there is some T2 response activation occurring prior to the start of the T2 RS stage that influences T1 response selection (Figure 2). If

the computation of response information occurred as serially as originally proposed, the second task response would not impact the RT for the primary task, as T1 RS is complete before T2 RS begins. This crosstalk of the R2 on T1 performance is referred to as the Backward Compatibility Effect (BCE; Figure 2). Hommel's (1998) BCE finding has been replicated in numerous other PRP studies since then using various stimuli and tasks (Ellenbogen & Meiran, 2008; Hommel & Eglau, 2002; Janczyk, Pfister, Hommel & Kunde, 2014; Janczyk, Renas & Durst, 2018; Logan & Delheimer, 2001; Logan & Gordon, 2001; Logan & Schulkind, 2000; Thomson, Danis & Watter, 2015; Thomson, Watter, & Finkelshtein, 2010; Watter & Logan, 2006).

The BCE and PRP Effect have not only been explored in single session dual-task response compatibility studies, they have also been investigated using PRP dual-task training studies. In these experimental designs, subjects become extremely practiced in a specific PRP paradigm across multiple training sessions (Thomson et al., 2015; Van Selst, Ruthruff, & Johnston, 1999). Training studies generally find a decrease in dual-task costs with practice, despite the use of varying stimulus input, required response output, and the amount of practice sessions implemented, across different experimental designs (Hazeltine, Teague, & Ivry, 2002; Schumacher, Seymour, Glass, Kieras, & Meyer, 2001; Van Selst et al. 1999). When experimental design allows the response for both tasks to occur in unison (e.g., different response modalities), dual-task costs have been eliminated, reflecting parallel processing of the two tasks after extensive practice (Schumacher et al. 2001; Van Selst et al. 1999). Although there is no consensus about whether parallel processing is possible in all circumstances, most researchers agree that with extensive practice the RT difference between short and long SOAs decreases, and

this may be interpreted as a challenge to the strict serial stages of processing assumed by the RSB Theory.

Van Selst et al. (1999) conducted an extensive PRP training study where subjects completed 36 sessions implementing mixed response modalities. They observed significant declines in dual-task cost with practice; however, a small remaining PRP Effect was observed. This led researchers to propose a Bottleneck Stage Shortening (BSS) hypothesis, that argues that practice does not eliminate the bottleneck, but it does shorten the T1 stages that create the observed interference (Van Selst et al. 1999). In a follow-up study by Ruthruff, Johnston, and Van Selst (2001) similar findings of dramatic declines in the PRP Effect were found when the required responses were of different modalities; however, when using a manual-manual response design, the declines were less drastic. Ruthruff et al. (2001) expanded on the BSS model by suggesting a Bottleneck with Central Stage Shortening (BCSS) model after extensive practice. These findings support an intact bottleneck in processing, although stages may shorten with practice to account for the decline in the observed PRP Effect.

In a dual-task PRP training experiment conducted by Thomson and colleagues (2015), the effects of practice on the BCE in relation to the PRP Effect were studied to determine the locus of the response priming effect on T1 performance. A decrease in T1 RT with dual-task practice primarily reflects shortening of the RS stage of processing (Ruthruff, Van Selst, Johnston, & Remington, 2006; Strobach, Liepelt, Pashler, Frensch & Schubert, 2013). Thomson and colleagues (2015) showed that practice also produces a reduction in the BCE, which is closely correlated with the decline in T1 RT. Here, converging evidence for a T1 RS locus of the BCE is provided, thus challenging a

response execution locus for this effect. These findings suggest the BCE reflects parallel generation of response information for both tasks in a PRP paradigm. This and other studies demonstrating parallel response activation in dual-task performance highlight the question of what function a substantial (and apparently stubborn) serial response selection stage may serve, if correct task responses are generated substantially independently of this processing stage (Thomson et al. 2015).

As outlined above, both the PRP Effect and the BCE have been explored in single session and multi-session experimental designs. From the perspective of experimental researchers, these effects are considered robust and reliable measures of cognitive performance and functioning. These experimentally reliable findings may be tempting to correlate and explore with other measures of attention and executive control; however, it is vital to be cautious and keep in mind that just because these effects replicate, does not mean that they are consistent within an individual. These effects are robust and easily replicate across PRP paradigms, in part due to their low between-participant variability; these findings are considered reliable and desirable from the perspective of experimental research (Hedge et al., 2018). However, this may not be the case when exploring these results from the standpoint of correlational or individual differences research. The focus of previous training studies was to examine the effects of practice over time and whether achieving perfect time sharing was possible, rather than assessing correlations in the PRP Effect within an individual across time. Therefore, it is important to explore the PRP Effect over time through the lens of reliability, as defined by individual differences and correlational research.

In the context of individual differences research, reliability refers to the extent to which a measure consistently ranks individuals, thus providing a fundamentally different definition of reliability from experimental designs (Hedge et al., 2018). It is crucial to take these differing definitions of reliability into consideration when doing individual differences research, because the individual reliability of the two measures limits the correlation that can be observed between them (Hedge et al., 2018; Nunnally, 1970; Spearman 1904). When conducting individual differences and correlational research one aims to explore factors that distinguish between individuals within a subject population (i.e., between-subject variance) whereas the experimental approach aims to explore the cognitive mechanisms based on the typical or average response to an experimental manipulation of variables (i.e., within-subject variance; Hedge et al., 2018). Hedge and colleagues (2018) explored the test-retest reliability of seven classic tasks of attention and executive control (e.g., Eriksen Flanker, Stroop, and go/no-go tasks) and found the observed reliabilities were much lower than expected, especially considering how experimentally robust the tasks are and how frequently they are used in experimental design. Attention and consideration are required when exploring the statistical findings of these experimental results in the context of individual differences.

The purpose of this thesis is to explore the reliability of the PRP paradigm and its observable effects (PRP Effect and BCE) for use in individual differences research. These dual-task findings are considered reliable and robust from the standpoint of experimental investigation. However, it is crucial to explore the reliability of these effects from the lens of correlational and individual differences research – particularly because these comparison measures are using difference scores. When using a measure

considered reliable for experimental research, it is likely to have low between-subject variance. The use of a subtraction methodology to find the effect of interest further decreases the amount of between-subject variance. However, this form of variance is ideally maximized when doing correlational and differential research (Draheim, Mashburn, Martin & Engle 2019; Hedge et al., 2018). Recall that simply because an observed effect can be replicated, does not mean that it is reliable when exploring individual differences (Hedge et al., 2018). This is especially true for effects that are measured using difference scores, such as the PRP Effect and the BCE.

This thesis will explore the experimental reliability of both the BCE and PRP Effect separately, by comparing the effects across three experimental dual-task sessions. If reliability can be established in both the BCE and PRP Effect individually, I will explore the association between the BCE and PRP Effect by correlating them with each other to assess how these effects relate to each other. Both of these effects are measures of parallel processing and executive control and it is worthwhile to explore if and how they correlate with each other, before considering the comparison of these effects to different measures of cognitive performance and multitasking found in other experimental paradigms.

As stated above, the BCE is measured in the T1 portion of the PRP paradigm and is calculated by comparing the RT difference in RC+ and RC- trials at short SOAs, with faster RTs frequently noted on RC+ trials compared to RC- trials. Recall, the PRP Effect is also observed in this dual-task paradigm, however it is measured in T2, as the difference in RTs at short versus long SOAs. The size of the PRP Effect is typically

calculated without regard to response compatibility (i.e. collapsed across RC+ and RC- trials).

There is reason to expect a relationship between the magnitude of the BCE and the magnitude of the PRP Effect. On the one hand, both effects measure the ability to respond to two tasks at the same time. A large BCE effect suggests that response information in T2 is computed before T1 RS has finished, essentially demonstrating parallel response selection. If participants have indeed determined the response to T2 early on these trials, it seems plausible to expect a smaller PRP Effect – perhaps the T2 RS stage is shorter following strong crosstalk between tasks. This would result in a negative correlation between BCE and PRP magnitude.

On the other hand, a large BCE may be associated with a large PRP Effect. For example, there is a known propagation effect from T1 onto T2, such that a longer RS stage for T1 (e.g., for incompatible relative to compatible trials, indicative of a larger BCE) can delay the RS stage of T2 processing. This would result in longer T2 RTs at short SOAs, and therefore produce a larger PRP Effect relative to that observed on RC+ trials. When the BCE is smaller (a smaller difference between RC+ and RC- trials in T1), these propagation effects may be less apparent and the PRP Effect less exaggerated. In this case, a positive relationship between the size of the two effects would be observed. Examining the correlation of these effects will be useful in understanding how these different measures of parallel processing relate to each other.

To further understand the relationship between the two effects, I examined the PRP Effect separately on compatible and incompatible trials, and assess the relationship

of each PRP Effect to the BCE. This approach could shed light on whether the BCE is driven by response interference on incompatible trials, facilitation on compatible trials, or both. If the BCE is related to the PRP Effect on compatible trials but not incompatible trials, it would suggest the BCE primarily reflects speeding of T1 on compatible trials. In contrast, a much stronger relationship with the PRP Effect on incompatible trials relative to compatibile trials would suggest the effect is driven by reponse interference on T1 processing when the T2 response is incompatible. Alternatively, the crosstalk producing the BCE may come from a combination of priming and interference, in which case we may observe similar relationships between the BCE and the PRP Effect when it is calculated for both compatible and incompatible trials.

Participants in this study completed a variety of experimental paradigms, exploring various cognitive measures in addition to indicating their affect and multimedia usage in two experimental sessions occurring over the span of two days. The focus of this thesis will be data obtained in the three PRP sessions from both the first and second day of study. I will assess the presence of a typical PRP Effect and BCE and then determine if the size of each effect correlates across sessions. If correlational reliability is established, I will examine the correlation between the two effects in order to better understand the relationship between them. If reliability is found within these dual-task effects, there will be a basis for comparing them to other cognitive measures exploring executive control and attention.

METHOD

Participants

Eighty-five McMaster University students (73 females; mean age = 21.92 years) participated in this experiment. The data from two participants were removed from the PRP data analysis; one due to experimental coding error and the other for not returning to complete the second day of the study. Participants were recruited from a subject pool that had expressed interest in participating in future experiments during previous participation in McMaster University's Cognitive Science Laboratory, or from the University's online experiment scheduling system. In exchange for partial course credit, each participant completed two sessions (one per day) within a 5-day span. The average span was 1.87 days, with 42 participants (51%) completing the experiment on consecutive days, 21 (25%) completing it within 2 days, 12 (13%) within 3 days, 5 (6%) within 4 days, and 3 (4%) within 5 days. All participants had normal or corrected-to-normal vision. Seventy-six of the participants were right-handed.

Apparatus

For the PRP, Operation Span (OSPAN), Task Switching, Flanker, and Attentional Blink (AB) tasks, all stimuli were presented using Presentation® software (Version 14.6 Build 08.31.10). Participants completed these tasks on a Dell Dimension 4600 computer with a 19-inch ViewSonic Professional Series P95f+ monitor, and they made manual responses using the computer keyboard for all tasks except the OSPAN task, where participants wrote their responses on the answer sheet provided. The Positive and Negative Affect Schedule - Expanded (PANAS-X) and Multimedia Usage Questionnaire

(MUQ) were administered in a paper and pencil format and responses were manually scored by the experimenter at the end of the experiment.

Stimuli and Procedure

Participants completed two experimental sessions (one per day) on consecutive days whenever possible, but in all cases within five days. All of the participants performed the tasks within each session in the following sequential order: Session 1: (1) the demographic and PANAS-X questionnaire, (2) the first PRP session (PRP1), (3) the OSPAN task, (4) the Task Switching task, (5) the Flanker task, (6) the second PRP session (PRP2). Task order in the second session was: (1) the PANAS-X form, (2) the third PRP session (PRP3), (3) the AB task, (4) the MUQ. Only the PRP task is described below, as the other tasks are not the focus of this thesis. Participants were tested individually and seated at a viewing distance of approximately 50 cm in a room with ambient lighting conditions.

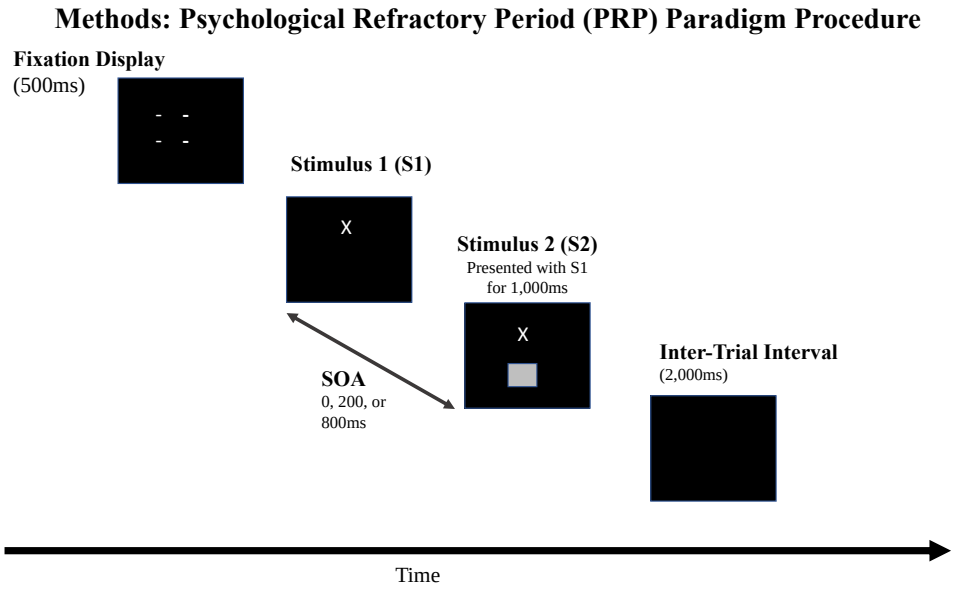
Questionnaire: At the beginning of the first session, after providing informed consent, participants completed a background questionnaire regarding their age, handedness, high school graduating GPA, and languages spoken.

PRP Task: At the start of each trial a fixation screen appeared for 500 ms, made up of two rows of two white dashes centred on the screen, separated laterally by approximately 1.1°, flanking the locations where the upcoming stimuli would appear (Figure 3). Participants were then presented with two successive stimuli, positioned one above the other, at the center of the screen on a black background. The first stimulus (S1) was a single capitalized letter (either ‘X’ or ‘Z’) displayed in white Helvetica 30-point

font, subtending 1° in height and 0.8° in width. The second stimulus (S2) was a coloured square presented in either yellow, orange, purple, or blue, subtending 0.9° in height and width. The vertical separation between stimuli was approximately 0.4° (Figure 4). S1 appeared alone for the duration of the SOA (0, 200, or 800 ms), and then S1 and S2 were displayed together for 1,000 ms, followed by a blank black screen for 2,000 ms before the next trial began (Figure 3).

Figure 3.

Example PRP Paradigm Procedure

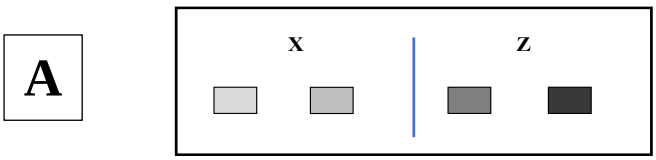


Note. An example of an experimental trial used in this study. Each trial began with a fixation point shown for 500ms, followed by onset of S1. S2 appeared after a predetermined SOA (0-, 200-, or 800ms). Both stimuli remained on the screen together for 1,000ms, followed by a blank screen for 2,000ms before the next trial began.

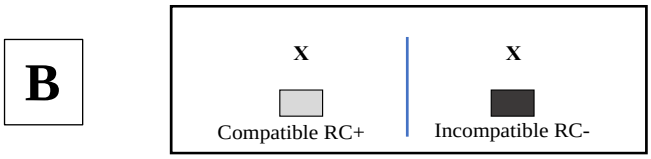
Figure 4.

Example Response Conditions in PRP Procedure

Example Response Mapping Condition:



Example Compatible and Incompatible Stimulus Pairs:



Note. Figure 4A demonstrates a response mapping condition that a participant may be assigned to. Here T1 is a letter identification task, where participants are asked to respond to an "X" with the left key and a "Z" with the right key. T2 is a colour identification task where warm colours (yellow and orange [denoted here with two light grey colours]) require a response with the left key and cool colours (purple and blue [denoted here with dark grey and black]) require a response with the right key. Figure 4B shows an example of stimuli that are response compatible (RC+) and incompatible (RC-) under this response mapping condition. In general, if the subject is required to press the same button twice for T1 and T2 it is considered a response compatible trial (RC+). However, if a participant is required to press two different buttons to complete T1 and T2, this is considered a response incompatible trial (RC-).

Participants were required to perform a separate task for each stimulus. For T1, participants indicated whether S1 was an 'X' or 'Z' (letter task); for T2 they indicated if S2 was 'warm' (yellow/orange) or 'cool' (purple/blue) (colour task). Participants responded to S1 and S2 using the 'A' and ';' keys on a standard keyboard, with one of the two letters in T1 and two of the four colours in T2 mapped to the same response key. Thus, responses could be either compatible (same response keys) or incompatible (different response keys) across tasks. Response mapping for both tasks was counterbalanced across participants. The experimenter explained the procedure verbally

using a visual diagram to ensure clarity and understanding, and a response mapping card was taped to the participant's computer monitor as a visual reminder (as in Figure 4A). Participants were instructed to respond quickly and accurately to each stimulus, but to prioritize T1.

Participants completed three identical PRP tasks across two experimental sessions (two in the first session and one in the second session). All PRP tasks used the same stimuli and task instructions, with participants remaining in their assigned response-mapping condition throughout the experiment. Each PRP task consisted of six blocks of 24 experimental trials. PRP1 commenced with two practice blocks of 24 trials, while the subsequent PRP sessions (PRP2 and PRP3) began with only one practice block. These practice blocks were not included in analysis. At the end of the practice block, and following each experimental block, participants received feedback regarding their mean RT and accuracy for T1 for the previous block. They were also given the opportunity to rest before initiating the start of the next block. Stimulus items were counterbalanced such that participants were exposed to an equal number of each letter-colour and SOA combination, although presentation order was randomized across the six blocks.

RESULTS

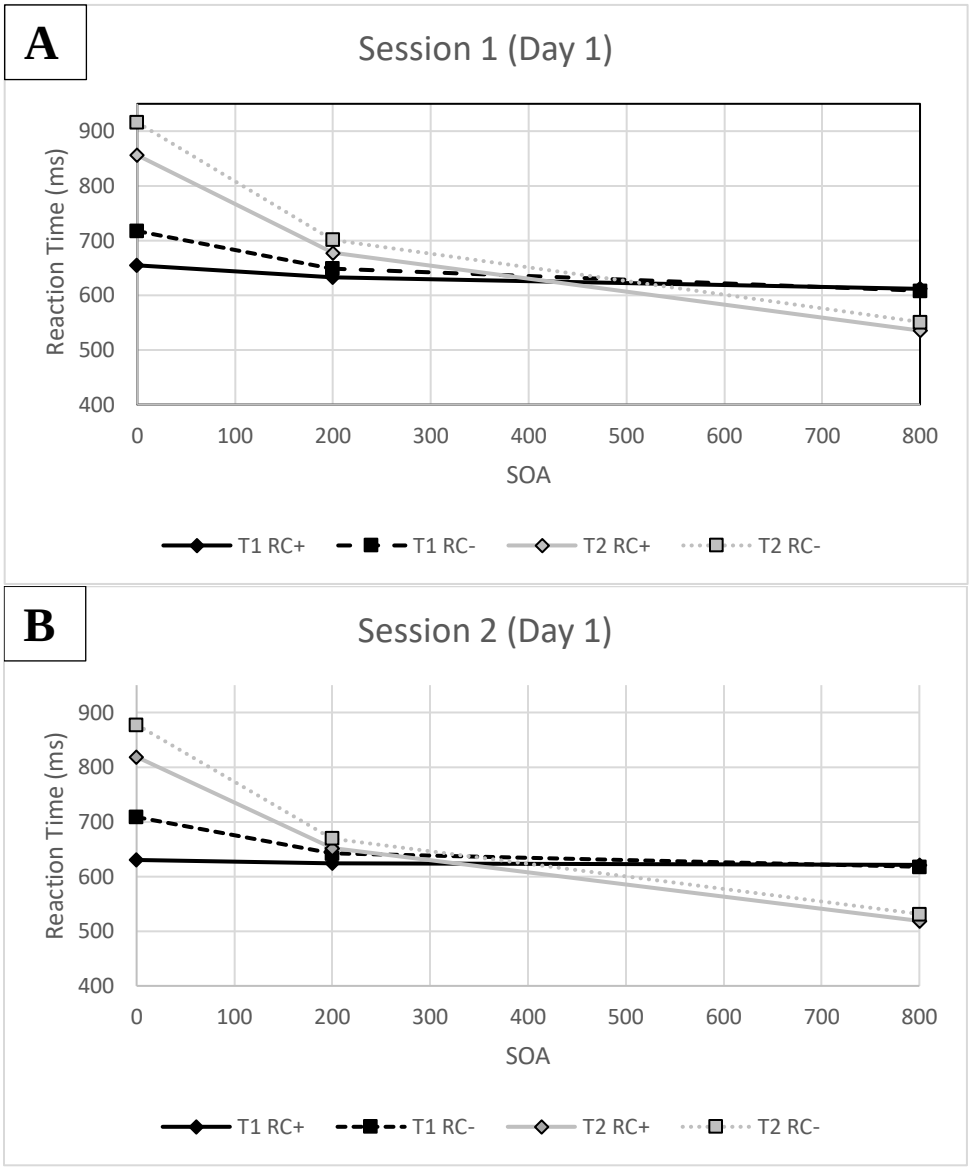
The mean RTs were calculated for trials where both T1 and T2 responses were correct. T1 RTs that were less than 300ms or greater than 1,500ms were removed from analysis and T2 RTs less than 300ms or greater than 2,000ms were also discarded. Implementation of these cut-off criteria removed approximately 1.5% of all trials from the three experimental PRP sessions.

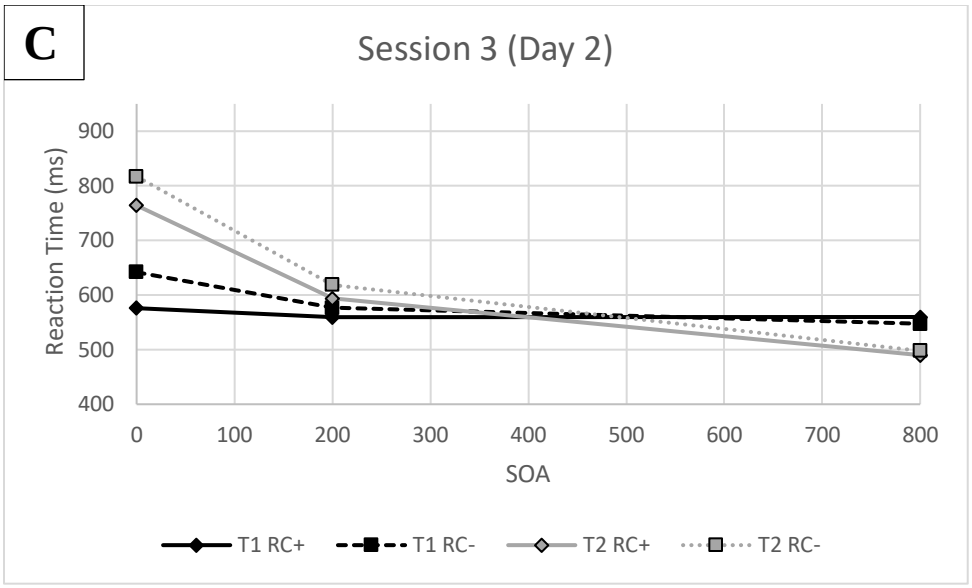
Reaction Time

The mean RTs for T1 and T2 RC+ and RC- trials at each SOA are plotted in Figures 5A through 5C for the first session on day 1 (PRP1; Figure 5A), the second session on day 1 (PRP2; Figure 5B), and the third session on day 2 (PRP3; Figure 5C).

Figure 5

Task 1 and Task 2 Reaction Time Data for PRP Sessions





Note. Figure 5A reflects the first PRP session (PRP1) mean RTs for T1 (black) and T2 (grey) for both RC+ (solid line) and RC- (dashed line) stimuli at each SOA. The BCE in T1 is the difference between black solid and black dashed lines, and the PRP Effect is reflected in T2 RTs that decrease from the shorter to longer SOAs (grey lines). Figure 5B demonstrates the corresponding findings for the second PRP session (PRP2) and Figure 5C displays the corresponding findings for the third PRP session (PRP3).

Two separate 3 (Session: PRP1, PRP2, PRP3) x 3 (SOA: 0, 200, 800 ms) x 2 (Response Compatibility: RC+, RC-) repeated-measures analyses of variance (ANOVAs) were conducted on the T1 and T2 RTs of the PRP task, with all variables considered within-subject factors. Significant main effects and two-way interactions were observed for both T1 and T2 RT data.

In the RT analysis for T1, significant main effects were noted for Session, $F(2, 164) = 48.54$, $p < .001$, $\eta_p^2 = .372$, SOA, $F(2, 164) = 16.27$, $p < .001$, $\eta_p^2 = .166$, and Response Compatibility, $F(1, 82) = 83.48$, $p < .001$, $\eta_p^2 = .504$. The significant main effect of Session indicates that mean RTs decreased across sessions, an expected practice effect in performance. The main effect of SOA indicates that participants were slowest on the shortest SOA trials and became faster as the SOA increased. The main effect of

Response Compatibility indicates that there was a significant BCE; participants were faster on RC+ trials than RC- trials.

A significant interaction was found between Session and SOA, F (4, 328) = 2.53, p = .040, η_p^2 = .030; the effect of SOA was largest in Session 1, and then decreased across sessions. More important, there was a significant interaction between SOA and Compatibility, F (2, 164) = 96.34, p < .001, η_p^2 = .540, indicating that the BCE was largest at the shortest SOA where there was the most temporal overlap between tasks. The Session x Compatibility interaction was not significant, F (2, 164) = 1.66, p = .193, indicating that the magnitude of the BCE did not change appreciably across sessions. The 3-way interaction was also not significant (F < 1).

In the RT analysis for T2, there were significant main effects of Session, F (2, 164) = 112.31, p < .001, η_p^2 = .578, SOA, F (2, 164) = 997.84, p < .001, η_p^2 = .924, and Response Compatibility, F (1, 82) = 58.13, p < .001, η_p^2 = .415. Similar to the T1 RT analysis, the significant main effect of Session reflects that mean RTs decreased as participants became more practiced in the dual-task experiment. The main effect of SOA indicates that a PRP effect was observed; T2 RTs decreased as the SOA increased. The main effect of Response Compatibility indicates that RTs for RC+ trials were lower than for RC- trials.

Significant interactions between Session and SOA, F (4, 328) = 18.21, p < .001, η_p^2 = .182, and SOA and Compatibility, F (2, 164) = 36.37, p < .001, η_p^2 = .307, were also observed. The significant Session x SOA interaction demonstrates that the size of the PRP Effect decreased across sessions, as expected based on previous PRP training

studies. The interaction between SOA and Compatibility indicates that the response compatibility effect was strongest at the shortest SOA.

Errors

Mean combined T1 and T2 error rates were examined using a 3 (Session) x 3 (SOA) x 2 (Response Compatibility) repeated measures ANOVA. Error data (% error) are summarized in Table 1. Results were in line with the T1 and T2 RT data and provide no evidence of speed-accuracy trade-offs. Once again, significant main effects were observed for all factors: Session, F (2, 164) = 9.58, $p < .001$, $\eta_p^2 = .105$, SOA, F (2, 164) = 11.37, $p < .001$, $\eta_p^2 = .122$, and Response Compatibility, F (1, 82) = 10.29, $p = .002$, $\eta_p^2 = .112$. The main effect of Session reveals that error rates were highest in the first experimental dual-task session. The significant main effect of SOA indicates that error rates were highest on the shortest SOA trials, with accuracy improving as the SOA increased. The main effect of Response Compatibility indicates that participants made more errors on RC- trials than on RC+ trials. A significant SOA x Compatibility interaction, F (2, 164) = 15.71, $p < .001$, $\eta_p^2 = .161$, indicates that the response compatibility effect was most pronounced on short SOA trials where task overlap was greatest.

Table 1

Mean Dual-Task Error Rates

	SOA 0ms		SOA 200ms		SOA 800ms	
	RC+	**RC-**	**RC+**	**RC-**	**RC+**	**RC-**
Session 1	5.97%	9.79%	7.28%	7.93%	7.58%	5.77%
Session 2	5.22%	9.39%	5.27%	6.82%	5.07%	4.62%
Session 3	5.32%	10.09%	4.97%	7.63%	6.07%	5.27%

Note. Mean dual-task error rates for each experimental session, explored across SOA (ms) and response compatibility (RC+ and RC- trials). Error rates reflect errors on either Task 1 or Task 2 of a particular trial (or in both tasks).

BCE Analysis

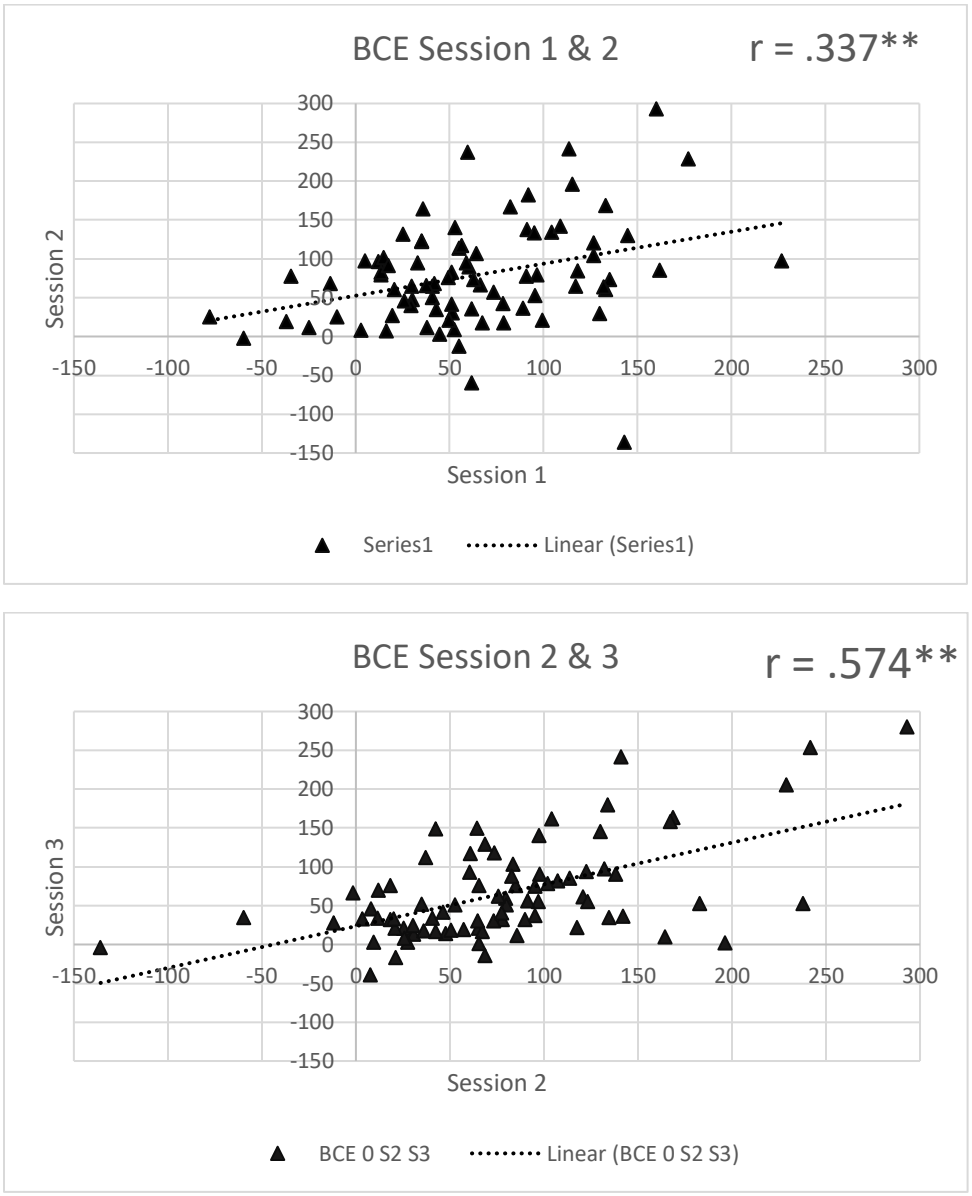
To more closely investigate the BCE across sessions I focused on the 0-ms SOA trials, where there is maximal temporal overlap between tasks and where the BCE is most pronounced. Mean T1 RT data were submitted to a 3 (Session) x 2 (Response Compatibility) repeated measures ANOVA. Significant main effects of Session, F (2, 164) = 61.71, $p < .001$, $\eta_p^2 = .429$, and Response Compatibility, F (1, 82) = 172.23, $p < .001$, $\eta_p^2 = .677$, were observed. As in the omnibus ANOVA, T1 RT decreased across sessions and response compatible trials were faster than response incompatible trials, demonstrating a BCE in T1 performance. Table 2 summarizes the BCE magnitude across sessions.

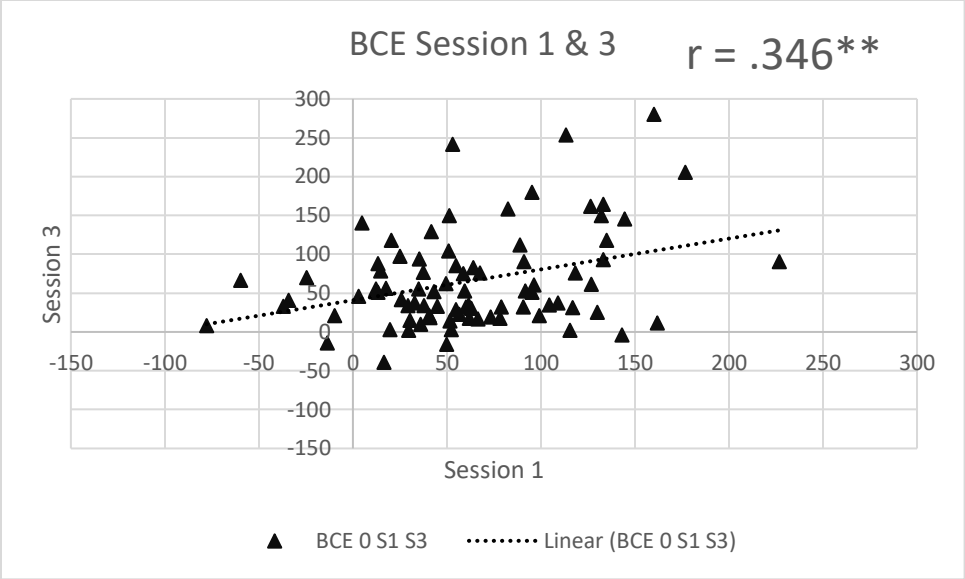
To further explore the reliability and consistency of participant's BCEs observed in Sessions 1, 2, and 3, I correlated the BCE for each possible pair of sessions (1-2, 2-3, 1-3). Figure 6A shows the BCE correlation between Sessions 1 and 2. Here we see a positive relationship, $r(81) = .337$, $p = .002$, in the scatterplot, indicating that the size of

the BCE in Session 1 was associated with the size of the BCE in Session 2. This finding was replicated when comparing Sessions 2 and 3, and when comparing Sessions 1 and Session 3. Figure 6B shows the strong positive association between Sessions 2 and 3, $r(81) = .574$, $p < .001$. The positive correlation between Session 1 and 3 is displayed in Figure 6C, $r(81) = .346$, $p = .001$.

Figure 6

BCE Correlations Between PRP Sessions





**Correlation is significant at the .01 level (2-tailed)

Note. Figure 6A displays a scatterplot reflecting the positive relationship between the BCE (ms) across Sessions 1 and 2. Figures 6B and 6C demonstrate this same relationship for Sessions 2 and 3, and for Sessions 1 and 3, respectively. The dashed line of all graphs represents the linear trendline.

Table 2

Magnitude of the BCE and PRP Effect Across Sessions 1 – 3

	T1 BCE (ms)	**T2 PRP Effect (ms)**
Session 1	63	343
Session 2	78	323
Session 3	66	297

Note. Size of the BCE and PRP Effects across Sessions 1-3 in ms.

PRP Effect Analysis

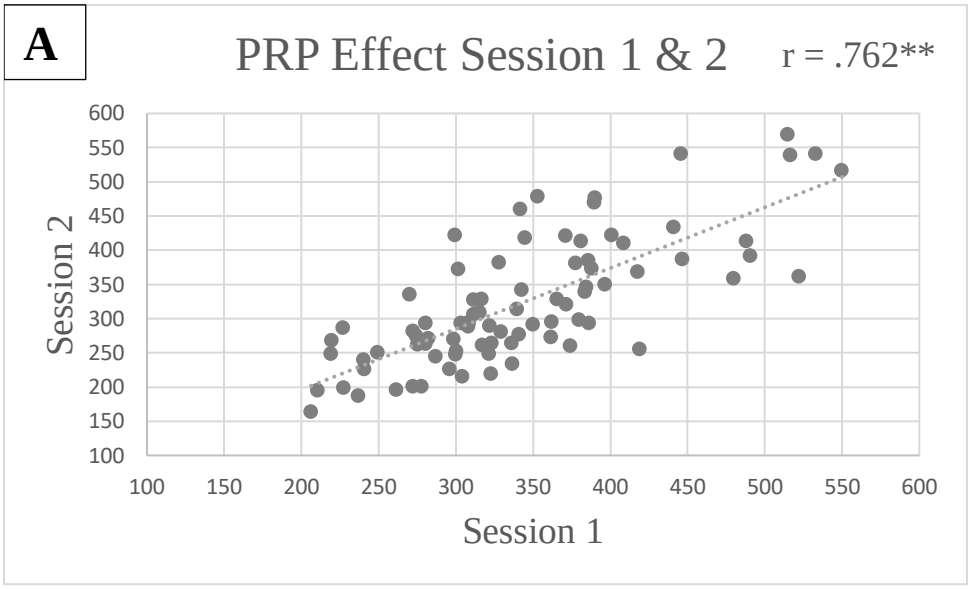
To determine the size of the PRP Effect, the T2 RT for each participant was collapsed across response compatibility, and then the RTs at the longest SOA (800 ms) were subtracted from the RTs at the shortest SOA (0 ms). Analysis of the PRP Effect across sessions was computed using a repeated measures ANOVA with three levels of

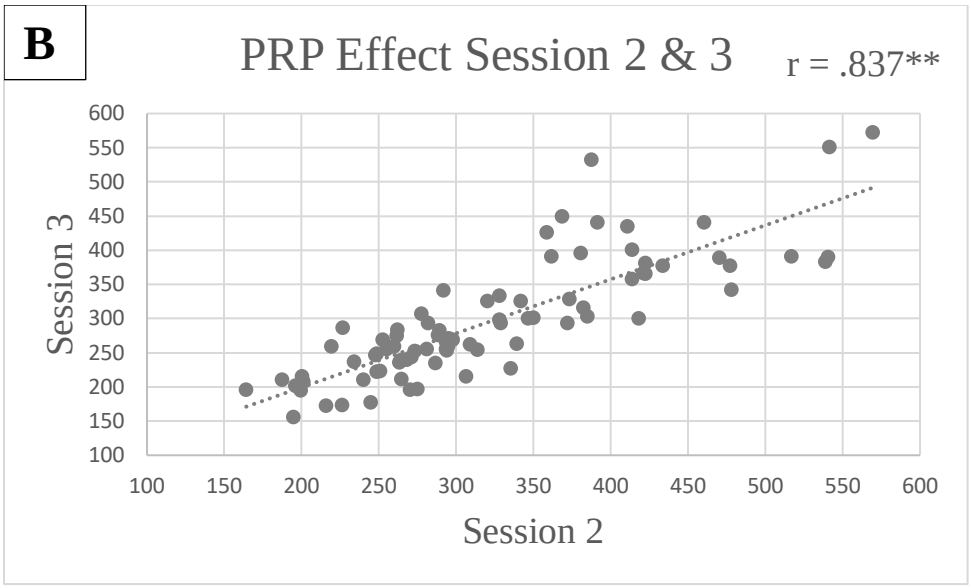
Session. A significant main effect was observed, $F(2, 164) = 27.79$, $p < .001$, $\eta_p^2 = .253$, reflecting a decrease in PRP Effect across sessions. Table 2 summarizes the PRP Effect across sessions.

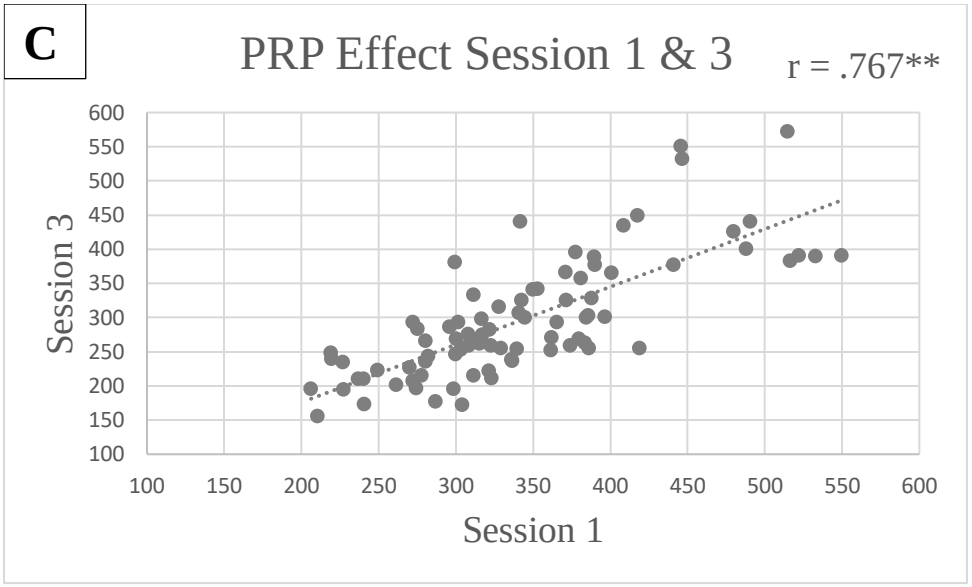
To further explore the reliability of the PRP Effect found in Sessions 1, 2, and 3, I correlated the PRP Effect for each possible pair of sessions (1-2, 2-3, 1-3). Figure 7A shows the correlation between Sessions 1 and 2, where we see a positive relationship across sessions $r(81) = .762$, $p < .001$. Figure 7B depicts this positive association for Sessions 2 and 3, $r(81) = .837$, $p < .001$, and Figure 7C depicts this positive association for Sessions 1 and 3, $r(81) = .767$, $p < .001$.

Figure 7.

Correlations Between PRP Effect Across Sessions







** Correlation is significant at the .01 level (2-tailed)

Note. Figure 7A shows the positive association between the PRP Effect measured in Sessions 1 and Session 2. Figures 7B and 7C demonstrate this same positive association for Sessions 2 and 3, and for Sessions 1 and 3, respectively. The dashed line on all scatterplots represents the linear trendline.

Relationship Between the BCE and PRP Effect

Having established that the BCE and PRP Effect are reliable individually, I was then able to examine their correlation to each other. I examined the correlation between

the BCE, and the PRP Effect averaged across RC+ and RC- trials for each session (Figure 8). Significant positive correlations between the T1 BCE and T2 PRP Effect were noted in all sessions: Session 1, $r(81) = .321$, $p = .003$, Session 2, $r(81) = .424$, $p < .001$, and Session 3 $r(81) = .486$, $p < .001$.

To investigate these significant correlations between the BCE and PRP Effect in more detail, I calculated the PRP Effect separately on RC+ and RC- trials, and examined the correlation of each these measures separately with the BCE. No correlations of significance were noted between the BCE and RC+ PRP effect across the three sessions; (all *p*s > .1). However, there were significant positive correlations, found in all sessions between the BCE and the PRP Effect on RC- trials (see Figures 9A, 9B, and 9C): Session 1, $r(81) = .507$, $p < .001$; Session 2, $r(81) = .584$, $p < .001$; and Session 3, $r(81) = .643$, $p < .001$. The correlations between the BCE and the PRP Effect averaged across compatibility, the PRP effect for RC+ trials alone, and the PRP effect for RC- trials alone are shown for each session in Table 3.

Table 3

Detailed Correlations Between the BCE and PRP Effect

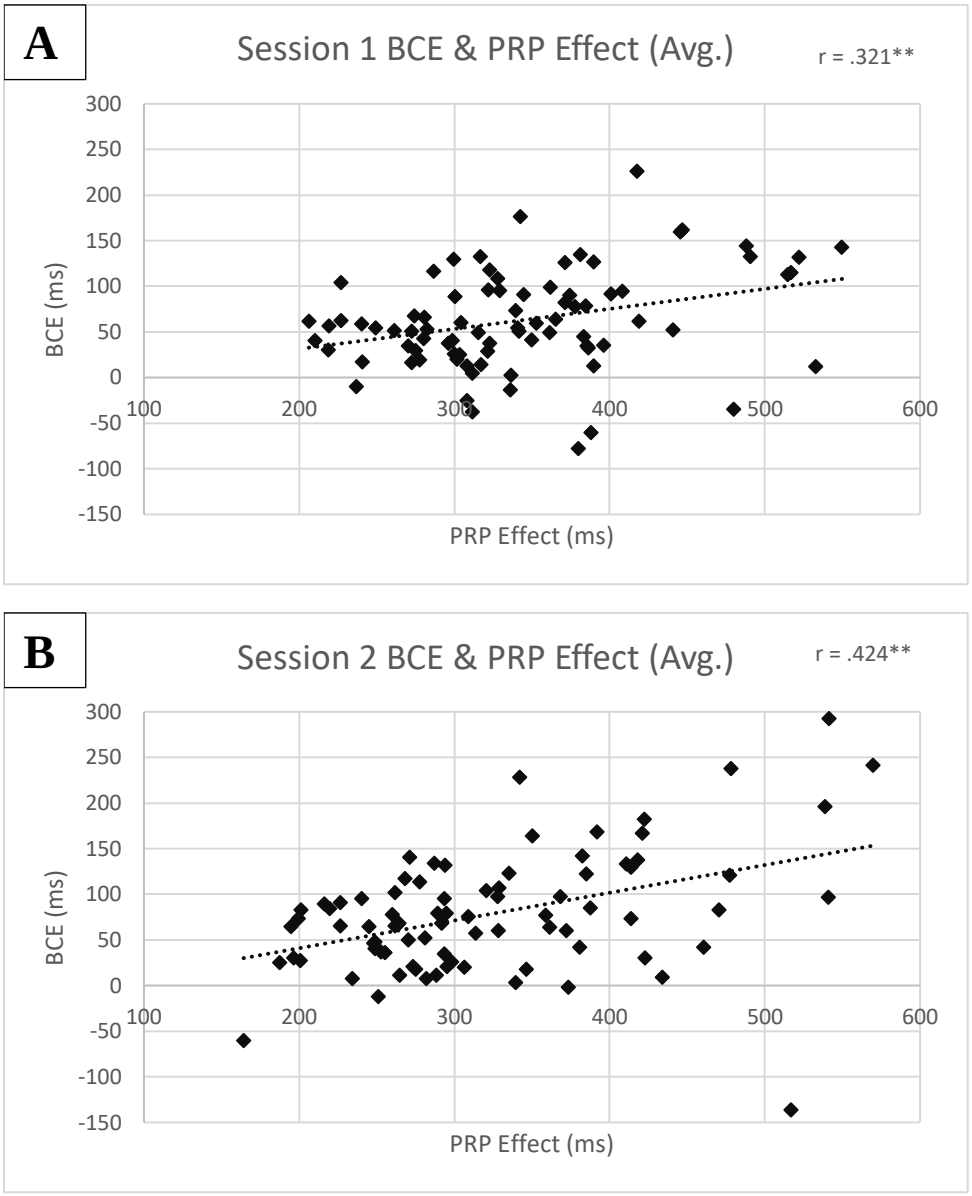
Session	PRP Effect Avg.	PRP Effect RC+	PRP Effect RC-
Session 1 BCE	.321**	.030	.507**
Session 2 BCE	.424**	.146	.584**
Session 3 BCE	.486**	.206	.643**

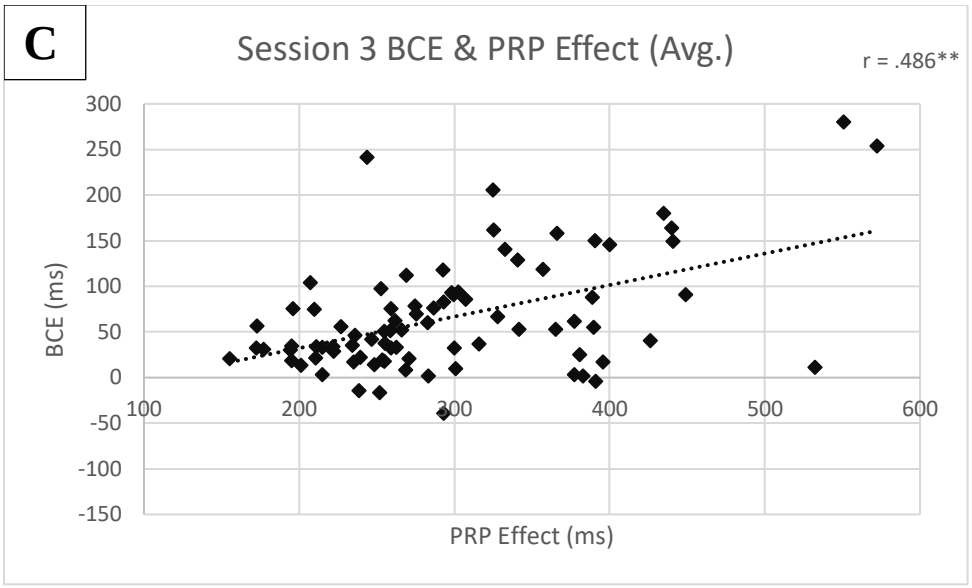
Note: Correlations between the BCE and the PRP Effect averaged across compatibility, the PRP effect for RC+ trials, and the PRP effect for RC- trials.

** Correlation is significant at the .01 level (2-tailed).

Figure 8.

Correlations of BCE and Averaged PRP Effect Between Sessions



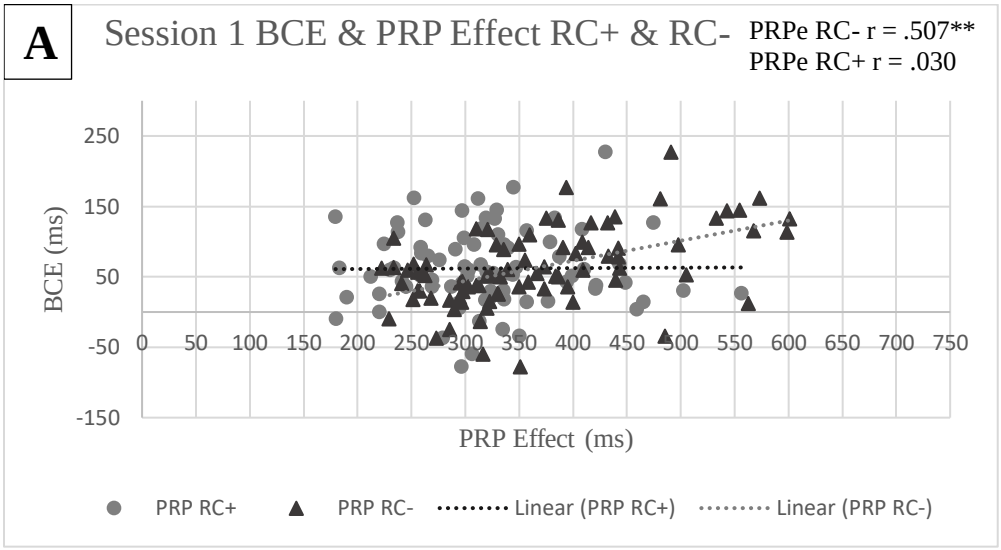


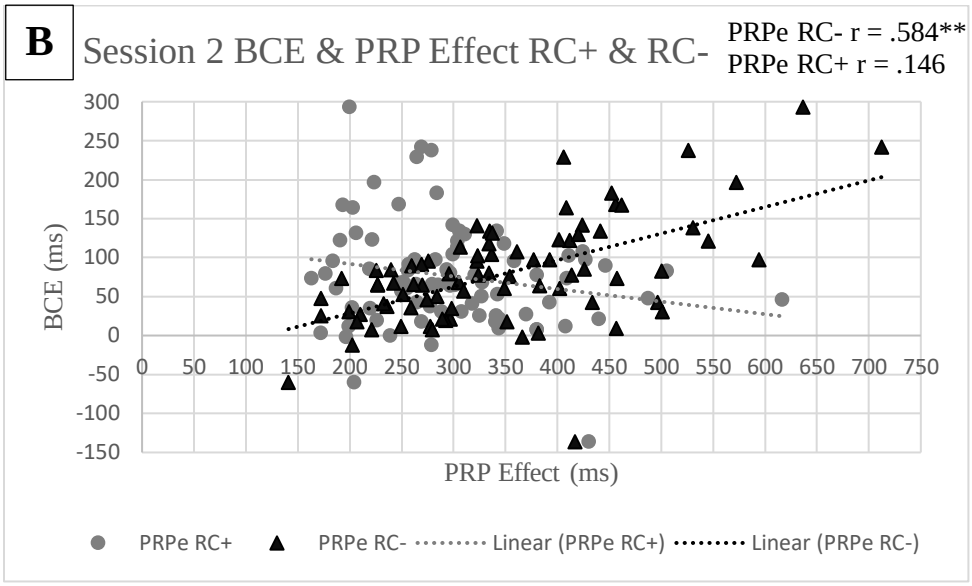
** Correlation is significant at the .01 level (2-tailed)

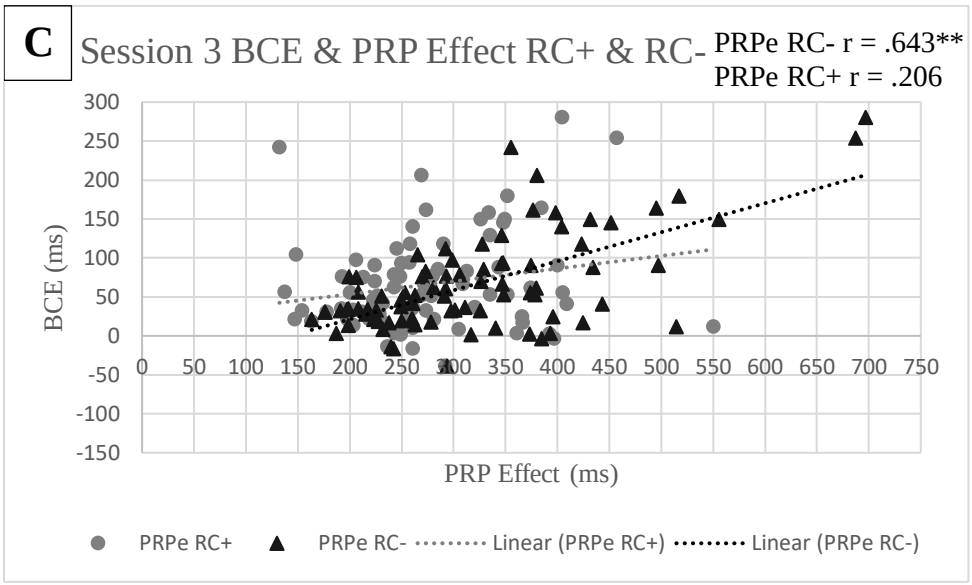
Note. Figure 8A shows the positive correlation between the PRP Effect and the BCE in Session 1. Figures 8B and 8C demonstrate the same positive correlation in Sessions 2 and 3, respectively. The dashed line on all scatterplots represents the linear trendline.

Figure 9

Correlations of BCE and PRP Effect on Response Compatible and Incompatible Trials within Sessions







** Correlation is significant at the .01 level (2-tailed)

Note. Figure 9A shows the correlation between the PRP Effect and the BCE in Session 1. Here, the black triangle data points depict the correlation of the BCE with the PRP Effect on RC-.trials, while the grey data points depict the correlation between the BCE and the PRP Effect on RC+ trials. The dotted lines depict the linear trendlines. Figures 9B and 9C demonstrate the corresponding correlations for Sessions 2 and 3, respectively.

DISCUSSION

As outlined above, the purpose of this thesis is to explore the reliability of the BCE and PRP Effect observed in a PRP paradigm for use in future individual differences research. The PRP paradigm is composed of two tasks, with the BCE being measured in T1 performance and PRP Effect in T2. Thus the effects are evaluated in two distinctly different tasks that participants must complete in each experimental trial. Recall, the BCE is the T1 RT difference score between RC+ and RC- trials at short SOAs (in this thesis the 0ms SOA was used) and the PRP Effect is measured by the difference in RT at short versus long SOAs (here, 0ms and 800ms) in T2.

Seeing as both the BCE and PRP Effect are used to investigate parallel processing and cognitive control, it would be valuable to compare them to other measures of executive functioning and attentional control to assess individual differences. However, it is important to first ensure that each measure is itself reliable. As both of these effects are calculated as RT difference scores, there is reason to be cautious when interpreting their correlational reliability (Draheim et al., 2019). While both effects have consistently been shown in multiple previous experiments, as discussed earlier, experimental and correlational reliability are not defined the same way. From the perspective of experimental reliablilty, a task or effect is considered reliable if it is robust and easily replicates across individuals. This form of reliability is produced in part due to low between-participant variability. Correlational reliability, which is used in the context of individual differences research, refers to the extent that a measure consistently ranks individuals. With this type of reliability, high between-participant variability is ideal, as it

provides a wider range of values and therefore a greater ability to dependably rank individuals.

Participants in this study completed three dual-task sessions over two days and these data were analyzed to investigate the reliability of the BCE and PRP Effect. I first explored the experimental reliability of the BCE and PRP Effect separately, by comparing the effects across three dual-task sessions and found both effects to be observed in each sesssion and thus experimentally reliable. Prior research using the PRP paradigm has established experimental reliability in these dual-task measures before, therefore the findings of reliability of these effects are previously established and reaffirmed in this study. As previously documented in PRP training studies, the size of the PRP Effect decreased across sessions in this experiment, reflecting expected practice effects in performance.

Next, I correlated each effect to itself across dual-task sessions to explore the correlational reliability of the BCE and PRP Effect and to evaluate their potential use as individual differences measures. Again, both effects produced significant reliable correlational findings, reflected by significant positive correlations for each effect across dual-task sessions. These findings demonstrate that the magnitude of each effect is consistent within individuals across experimental sessions; reflecting that participants who have the largest BCEs in Session 1 also tend to have the largest BCEs in Session 2. It is valuable to mention that this thesis is the first to establish the correlational reliability of these separate dual-task effects.

Since the reliability of both the BCE and PRP Effect were established individually in terms of experimental and correlational reliability, I analyzed the association between the BCE and PRP Effect by correlating them to each other. Although both of these tasks occur in the same experimental trials, they are separate tasks and performance on T1 (and the resulting BCE) can impact performance on T2 (and the resulting PRP Effect). The BCE acts on the T1 RS stage of processing (Thomson et al., 2015), but it also has downstream, propagation effects on T2 RT as well. For example, if the duration of T1 RS increases on a RC- trial relative to an RC+ trial, the locus-of-slack logic described previously suggests there will be more slack time before T2 RS can start at short SOAs (see Figure 2), and thus a longer T2 RT on these trials. This contributes to a Forward Compatibility Effect (FCE) commonly observed in T2 RTs. If the T1 BCE is affecting T2 RT in this manner at short SOAs, we should expect the size of the BCE to also be related to the size of the PRP Effect, as the increased T2 RT on incompatible relative to compatible short SOA trials should produce a larger PRP effect on those trials. It is valuable to correlate these effects to each other to confirm this association.

While exploring the correlation between the BCE and PRP Effect, a significant positive correlation was noted between the effects on all three dual-task sessions. To further understand the relationship between the two effects, I examined the PRP Effect separately on response compatible and incompatible trials, and assessed the relationship of each PRP Effect to the BCE. A strong positive correlation was discovered between the BCE and PRP Effect on RC- trials, but there was no correlation between the size of the BCE and PRP Effect measured on RC+ trials. This result indicates that the correlational

relationship of the PRP Effect to the BCE is being driven exclusively by incompatible trials.

While the above findings suggest that the BCE is more related to the PRP Effect on RC- trials than RC+ trials, it is crucial to rule out an alternative possibility that the PRP Effect itself is more reliabile on RC- trials than on RC+ trials as we know if a measure is not reliabile itself we cannot interpret its correlation with other effects. To rule out this possibility, I reexamined the PRP Effect correlations across sessions in greater depth, separating trials based on response compatibility. The PRP Effect found in Session 1 was correlated to the PRP Effects from both Sessions 2 and 3, and the Session 2 PRP Effect was correlated with the effect in Session 3, separately for RC+ and RC- trials. Significant positive correlations were found for both RC+ and RC- trials when correlated to their respective response compatibilities across sessions. The correlations for response incompatible trials were slightly larger, with r-values ranging from 0.74 to 0.81 and RC+ trials ranging from 0.61-0.74.[1] The modest differences between these correlational values is unlikely to be driving the observable effect found in the correlation of the BCE and RC- PRP Effect trials. Therefore, it is more probable that propagation effects between the T1 BCE and T2 RC- PRP Effect are driving the observable differences between the PRP Effect on RC+ and RC- trials and their

[1] The PRP Effect on RC- trials in Session 1 was positively associated with the PRP Effect on RC- trials in Session 2, $r(81) = .744$, $p < .001$. Similar positive correlations were seen in Sessions 2 and 3, $r(81) = .814$, $p < .001$, and Sessions 1 and 3, $r(81) = .760$, $p < .001$. The PRP Effect on RC+ trials was also significantly correlated between sessions: Sessions 1 and 2, $r(81) = .663$, $p < .001$, Sessions 2 and 3, $r(81) = .742$, $p < .001$, and Sessions 1 and 3, $r(81) = .607$, $p < .001$.

relationship to the BCE. It is possible that this may be supported by increased variance, ideal when using measures of correlational reliability, as more time is required to process RC- trials for both the BCE and PRP Effects.

This interesting observation, that the BCE has a much stronger relationship with the PRP Effect on incompatible trials relative to compatibile trials also suggests the BCE may be driven by interference on T1 response selection processing when the T2 response is incompatible, versus facilitation on compatible trials. To assess this more directly I explored the the relationship between the BCE and T1 RT in regards to response compatibility. Recall, the BCE is the difference between RC+ and RC- trials at the 0ms SOA. I correlated the BCE to T1 RT of 0ms SOA trials that were separated by response compatibility. It was discovered that across all experimental sessions, the BCE significantly correlates only with T1 RT on RC- trials[2]. This relationship reflects that the increased RT required for T1 RC- trials is directly driving the BCE, such that the T2 response activation interference is impacting performance on T1 RT. Therefore, the size of the BCE depends on the duration of RC- trials in T1, but is unrelated to the duration of RC+ trials. Trials with larger BCEs also have slow incompatible RTs and vice versa, but RT on RC+ trials does not vary with the size of the BCE. Although participants are encouraged to respond serially to T1 prior to T2, it appears some T2 peripheral response activation on RC- trials is interacting with the ability to execute T1 performance in a way that does not occur with RC+ trials. This suggests the BCE is driven by the level of

[2] The BCE was positively associated with the T1 RT on RC- trials in Session 1, $r(81) = .434$, $p < .001$, Session 2, $r(81) = .556$, $p < .001$, and Session 3, $r(81) = .571$, $p < .001$. $p < .001$. The BCE did not significantly correlate with T1 RT on RC+ trials across all sessions (all ps > .1).

interference on an incompatible trial. Due to the propagation effects of T1 RT onto T2 RT, we see the same effect carry forward, such that the BCE is related to the size of the PRP Effect only on RC- trials. This is an interesting observation that warrants further study and exploration in parallel processing and task switching literature.

While exploring the limitations of this study, it is important to recall that difference scores in correlational research should be used with caution. Difference scores are used to calculate both the BCE and PRP Effect. In the correlational findings exploring the BCE across sessions within an individual, it is important to recall two main points. First, the BCE is being correlated across different dual-task sessions, thus learning and practice effects are present and we are unable to correlate the T1 performance to itself within a single session. Additionally, the BCE is a relatively small effect (e.g., compared to the PRP Effect), and is obtained using subtraction methodology, thus less variance is available for ranking correlational reliability. Here, we have a small difference score, therefore there is less variance in the measure. When exploring correlational reliability, we ideally want high between-subject variance so that ranking of individual differences can be more clearly established. However, the finding of significant correlations despite these challenges signifies that there is something consistent happening in the BCE. The observable effects of this study are stable and intriguing, warranting further investigation.

To clarify, this thesis found evidence supporting both the experimental and correlational reliability of the BCE and PRP Effect that are observed in the PRP paradigm. Having established the reliability of these effects and their association to each other, it is now possible to consider using these dual-task effects as reliable and valid measures by comparing these tasks to other measures of executive control and attention.

It would be useful to explore the reliability of the correlations of the BCE and PRP Effect to other tasks frequently used to measure executive functioning (e.g. Eriksen Flanker, Stroop, and go/no-go tasks) to see if these tasks are measuring the same processes of attention and executive control. It would be beneficial to conduct a follow-up experiment in which multiple measures are taken of the same task, to clarify the experimental and correlational reliability of the task prior to correlating findings to those of different tasks used to assess task scheduling, resistance to interference, and general cognitive functioning.

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