Flipping the Switch: How Risk of Interference Determines the Occurrence of Proactive or Retroactive Dual-Task Interference

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Abstract

All multi-taking behaviour comes with a cost, namely that one task is processed preferentially. Typical findings in the dual-task literature show, in various paradigms, proactive interference, and, thus, a preferential processing of the first task (Task 1). A central bottleneck has been proposed to gating processing order, following a first-come first-served principle (Strobach, Hendrich, Kübler, Müller, & Schubert, 2018). However, a recent study by Nieuwenstein, Scholz, and Broers (2014) showed that retroactive interference can be induced if the probability of the occurrence of Task 2 is reduced. They argue for an Interference Control Theory (ICT), in which an attentional suppression mechanism, protecting Task 1 processing, is either activated or deactivated depending on the risk of interference. Here we show, in two experiments, that the findings of Nieuwenstein et al. (2014) replicate, and that the ICT follows an all-or-nothing principle. We recommend additional studies to fully understand the dichotomous nature of this suppression mechanism. Our results demonstrate that time of arrival at the central bottleneck is not the only determinant of processing priority, but that risk of interference plays a crucial role. In conclusion, our research shows that risk of interference should be taken into account in the design of cognitive experiments, to both validly answer prominent research questions and investigate multi-taking behaviour in daily life.

Keywords: Dual-task interference, retroactive interference, proactive interference, central bottleneck, all-or-nothing principle, direct replication, Interference Control Theory

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Dual-task interference

With the rise of various media devices, people resort to multitasking much more in daily life. We tend to use our smart phone while biking, listen to music in the grocery store, or clean when studying for the upcoming exam. However, this behaviour is accompanied by multi-task costs, which means that the effectiveness with which we are carrying out these tasks is lower than if we focused on only one of them. To investigate these costs, what causes them, and their boundary conditions, relatively simple tasks are used in order to minimize ambiguity and obscurity. Memory formation tasks – a participant has to memorize and recall a letter or a symbol – or response selection tasks – a participant is asked to react to a stimulus according to a certain rule and often under time pressure – are typical tasks used in dual-task research. If these tasks are presented shortly after another, the processing of the task that was presented first causes interference with the processing of the second task. This phenomenon is called pro-active interference. Evidence for pro-active interference can be seen in studies on the attentional blink (AB), the psychological refractory period (PRP), and studies employing a hybrid of these methodologies. In the following, we will give a short summary of the research using these paradigms, before turning to a consideration of how the typical finding of proactive interference is explained theoretically.

Various dual-task paradigms have repeatedly shown evidence that processing of the first target is usually prioritized leading to performance decrease on a second task. The attentional blink occurs when participants have to report two target stimuli which are presented at a stimulus onset asynchrony (SOA; time separating the onsets of the two targets) of 100-700 ms in a rapid stream of distractors. Here, the typical result is that task 2 accuracy follows a U-shaped function across these SOAs such that performance notably plummets at SOAs of 200-400 ms. However, task 1 performance remains relatively stable from SOAs longer than 100 ms on, where a slight decrease in accuracy can be noted (Martens & Wyble, 2010). In a similar vein, studies featuring two punctate speeded tasks that are presented in short succession reveal a slowing of the response time of the second task which was coined the psychological refractory period (PRP) effect (Pashler, 1994). Similar to the pattern observed in the AB paradigm, task 1 response time typically does not suffer from interference. Lastly, studies employing a combination of a memory task and speeded task have shown similar results. In a series of studies, Jolicœur and Dell'Acqua (1998) investigated performance when a first target had to be memorized followed by a speeded discrimination task for an auditory stimulus. The authors found that performance on the second task was worse if SOA was short, and they showed that this effect was amplified by increasing the number of memoranda for the first target. In addition, the performance on the first task remained stable across SOA’s. Taken together, the evidence from these different paradigms converges into showing that under various circumstances processing the first of two temporally successive tasks is prioritized and relatively unaffected by dual-task interference whilst performance on the second task is reduced, and, thus, indicating proactive interference.

In accounting for the finding of proactive interference observed in studies using the AB, PRP and AB-PRP hybrid paradigms, many theories agree in proposing the existence of a central bottleneck (Chun & Potter, 1995; Jolicœur & Dell'Acqua, 1998; Martens & Wyble, 2010; Pashler, 1994; Tombu et al., 2011; Zylberberg, Slezak, Roelfsema, Dehaene, & Sigman, 2010). One of the commonalities of these theories is that processing is divided into two stages. The first stage is defined by the encoding and identification of target candidates. This is assumed to occur rapidly and in parallel for different inputs, regardless of their modality. During the second stage, inputs selected from the first stage can be engaged in more in-depth processing needed to activate an appropriate response, or to store an item in working memory for later report. Crucially, this second stage of processing is assumed to involve capacity limited processing, leading to a bottleneck.

The explanation that central bottleneck theories offer for proactive interference is that processing order is dependent on arrival time of competing target candidates at the bottleneck stage. In a dual-task paradigm employing a visual followed by an auditory task, Strobach et al. (2018) investigated the occurrence of response reversals (that is the response order varying from stimulus presentation order) when either the pre-bottleneck stage (i.e., Stage 1) or the bottleneck stage of processing the first task stimuli were prolonged. The results showed an increase in response reversals at short SOA’s if the pre-bottleneck stage for processing the visual stimulus of the first task was protracted. Thus, arrival time of a target candidate at the bottleneck stage (response selection) as opposed to stimulus presentation order was found to be a key determinant of processing order. In turn, processing order, thus, seems to determine the occurrence of either proactive or retroactive interference. However, a protracted bottleneck stage of the first task did not increase the amount of response reversals but only led to a delay in response, which was propagated to task 2 response time. Based on these findings, Strobach et al. (2018) proposed a “first-come, first-served”-principle entailing that whichever target candidate arrives first at the bottleneck will be processed and responded to first, thus explaining why studies involving two successively presented targets typically find evidence for proactive interference.

Aside from being supported by behavioural findings, the notion of a two-stage bottleneck model is also supported by neuroimaging and electrophysiological data (e.g., Marois & Ivanoff, 2005). For instance, EEG studies on the AB show that even when a second target cannot be reported due to an attentional blink, it still elicits an N400, signifying the occurrence of semantic processing, as expected during Stage 1. Importantly, however only successfully reported second targets led to a P300, which presumably marks a working memory update (i.e., Stage 2). In this vein, the first event-related potential, or ERP, (N400) would be an indicator for a target being processed during the first, unlimited stage and the failure to produce the latter (P300) can be interpreted as a target not being fully processed during the second, capacity-limited stage, and, thereby, forgotten. Furthermore, the bottleneck theory of the AB, PRP and AB-PRP hybrid paradigms also finds support in fMRI studies trying to pinpoint the areas involved in dual-task interference. Specifically, these studies converge in showing the activation of a fronto-parietal network in all three instances of dual-task interference, thus offering support for the notion that a shared attentional bottleneck, mediated by a fronto-parietal network, is involved in all three instances of dual-task interference (Marois & Ivanoff, 2005; Tombu et al., 2011).

Evidence against an Immutable First-Come, First-Serve Bottleneck

Recently, the notion of an immutable central bottleneck gating the priority in dual-tasks was challenged by evidence that the occurrence of proactive and retroactive interference depend on the context of the task. In an effort to ascertain the latest point in time when the processing of a working memory consolidation task can be disturbed, Nieuwenstein and Wyble (2014) used a hybrid AB-PRP paradigm to examine the effect of the presence and absence of a speeded 2-alternative forced-choice task on performance for remembering a preceding target. The results of this study showed a disruption of memory at SOAs up to 1000 ms when the second task was present, independent of the presence of a mask after the target for the first task. In addition, the results of this study yielded little-to-no evidence for proactive interference, such that response times on the speeded 2-AFC task did not show a clear psychological refractory period effect. Apart from offering novel insight into the time course of working memory consolidation, these findings offered a markedly different pattern of results than the typical finding of proactive interference and no retroactive interference, hence, providing evidence against a first-come, first-served bottleneck theory.

In considering the possible reasons for why Nieuwenstein and Wyble (2014) found evidence for retroactive instead of proactive interference, Nieuwenstein et al. (2014) noted that a key difference in methodology pertained to the presence of the second task. Specifically, while previous studies showing evidence for proactive interference always included a second task, the studies by Nieuwenstein and Wyble (2014) only included a second task on half the trials, with the task-2 present and absent trials being randomly intermixed. To determine whether the probability of task-2 presence could explain the different outcomes, Nieuwenstein et al. (2014) compared the effect of task-2 probability between participants by either presenting the second task every trial or including the second task on half the trials in the same fashion as Nieuwenstein and Wyble (2014) did. The results showed that if a second task was always included, task-1 performance was relatively unaffected while task-2 performance was poor at short SOAs demonstrating weak retroactive but strong proactive interference, or, in other words, a psychological refractory period effect. However, if the second task was included in half the trials and its occurrence was unpredictable, the pattern of interference reversed when the second task was, indeed, presented in a trial. Thus, in this group, the results indicated strong retroactive and a weak proactive interference mimicking the results by Nieuwenstein and Wyble (2014).

To account for the effect of task-2 probability, Nieuwenstein et al. (2014) offered an explanation, coined interference control theory, entailing an attentional control mechanism which is activated depending on the risk of interference during T1 processing. If the risk of interference is relatively high (e.g. task-2 probability is high), activation of this control mechanism will lead to suppression of other stimuli, and, therefore, a protection of T1 processing at the expense of proactive interference for T2 responses. However, if the control mechanism is not activated due to a low risk of interference (e.g. task-2 probability is low), no suppression of subsequent stimuli will occur, and, thus, T2 can be processed without delay, at the expense of disrupting the consolidation of T1.

To test this theory, Nieuwenstein et al. (2014) conducted a study in which a different potential source of interference was introduced, namely the presence of distractors that could interfere with T1 processing. The reasoning was that given the presence of distractors, the risk of interference would be high, and, therefore, the processing of T1 would be protected even if T2 was present on only 50% of the trials. To examine this hypothesis, the study used a three-way within-subject design where the presence of rapid serial visual presentation (RSVP) of distractors, the presence of a second task, and the SOA were manipulated. Thus, in this study, the second task was included in only half the trials, with the task-2 present and absent trials being randomly intermixed. The RSVP of distractors was present in one block of trials and absent in another with block order randomly assigned to participants. Based on the aforementioned theory, the block containing distractors was expected to yield a high risk of interference, leading to a psychological refractory period effect as found in many previous studies, whereas the block without distractors was expected to yield a low risk of interference, leading to the reversal of the interference pattern similar to Nieuwenstein and Wyble (2014) results. As predicted, retroactive without proactive interference only occurred in absence of distractors. In the block including distractors, the results instead revealed strong proactive interference and a lack of retroactive interference. Taken together, these results were interpreted as support for the idea that the pattern of proactive and retroactive interference is dependent on the risk of interference on processing of the first task in a dual-task design, regardless of whether this risk is induced by distractors or the likelihood of the presence of a second target.

The Current Study

We dedicate the current study consisting of two experiments to further investigate the robustness of the findings of Nieuwenstein et al. (2014) complex three-way within-subject experiment. Furthermore, we expand upon this work by also examining how the presence of two sources of risk of interference – namely a high probability of T2 presence and the presence of distractors – would impact the results. To this end, we first conducted an exact replication of Nieuwenstein et al. (2014) earlier experiment with 50% T2 probability[1], and we then conducted a second experiment that was identical except for the fact that T2 was presented on every trial. In comparing the results of these two experiments, the main question of interest was whether the absence vs. presence of distractors would interact with T2 probability in determining the pattern of proactive interference. Would the degree to which T1 processing is protected be even stronger, resulting in stronger proactive interference, in the presence of RSVP and a high probability of T2 presence, or would the presence of one source of interference (i.e., either high T2 probability or presence of distractors) be sufficient to saturate the degree to which T1 is protected?

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Aside from conducting an exact replication of the earlier study by Nieuwenstein et al. (2014) we also preregistered this exact replication attempt, thus following recent recommendations stemming from the replication crisis in psychological research (Pashler & Wagenmakers, 2012; Simmons, Nelson, & Simonsohn, 2011; Wagenmakers, Wetzels, Borsboom, van der Maas, & Kievit, 2012; Wicherts et al., 2016).

Experiment 1

The goal of this experiment was to attempt to test the replicability of the findings of Nieuwenstein et al. (2014) using the same methods (see Woytaszek & Nieuwenstein, 2018, for the pre-registration). As described above, the earlier experiment showed a strong retroactive interference effect and a weak proactive interference effect when the second target was present in only 50% of the trials, and they showed that this pattern of interference reversed when the targets were embedded in RSVP of distractors.

Methods

Participants

We sampled 24 first-year psychology students from the Rijksuniversiteit Groningen who received course credits as compensation for their participation. The participants' age ranged from 18 to 26 (*Mean* = 20.67, *SD* = 2.33) and the sample included 15 female participants (62.50%). All participants gave informed consent and the Ethics Committee of Psychology approved the study.

The choice of a sample size of 24 participants was based on two considerations, namely to achieve sufficient power for a replication test of the findings by Nieuwenstein et al. (2014) and to achieve sufficient power for a proper test of any change of the findings in Experiment 2, in which T2 was always present. With regard to the former, Nieuwenstein et al. (2014) found a three-way interaction between SOA, T2 Presence, and RSVP on T1 recall accuracy with $F(3, 90) = 3.98$, $p = .01$, $\eta^2_p = .117$. In order to replicate this effect with 95% power and an alpha of 5%, we would need at least 9 participants. Unpacking the interaction further, Nieuwenstein et al. (2014) found a two-way interaction between SOA and T2 presence in the RSVP-absent condition, $F(3, 90) = 14.76$, $p < .001$, $\eta^2_p = .327$, whereas this interaction was absent in the

RSVP-present condition, $F(3, 90) = 0.98$, $p = .40$, $\eta^2_p = .032$. The replication of the interaction effect in the RSVP-absent condition with 95% power and α = 0.05 requires a minimum of 5 participants. Furthermore, the analysis on T2 response times yielded a two-way interaction effect between SOA and RSVP with $F(3, 90) = 10.18$, $p < .001$, $\eta^2_p = .253$. To replicate this effect with 95% power and α = 0.05, at least 6 participants would have to be tested. Thus, a properly powered replication attempt for the earlier findings by Nieuwenstein et al. (2014) would require only 9 participants.

The reason for choosing a sample size of 24, instead of only 9, was the fact that we also aimed to compare the outcomes of Experiment 1 – with a 50% probability of T2 presence – to those of Experiment 2, in which T2 was present on every trial. For this comparison, our main aim was to test whether the degree of proactive interference, hypothesized to index the protection of T1 processing, would be stronger for the condition with RSVP in Experiment 2 than in Experiment 1. Assuming a medium effect size $f = .25$ and α = 0.05, we required at least 20 participants to achieve 95% power for such an increase.

Materials

The experiment was conducted in a laboratory at the Rijksuniversiteit Groningen, which featured dimmed light and closed-off cubicles. For the presentation of the stimuli and recording of the responses, E-Prime version 2.0 (SP1) (Schneider, Eschman, & Zuccolotto, 2002) was used. The stimuli were presented on monitors with a 1,024 * 768 resolution whose refresh rate was set to 100 Hz.

T1 comprised three uppercase letters that were shown in red and drawn randomly with replacement from all letters of the alphabet excluding vowels, ‘M’, and ‘W’. The T1 mask consisted of three instances of superimposed “#” and “$” symbols. T2 consisted of a string showing three repetitions of one randomly drawn digit from the set 2-9. RSVP distractors were presented in black and randomly drawn with replacement from the same pool of letters as T1. Every character was displayed in a 20-point Microsoft Sans Serif font (see also, Maki, Bussard, Lopez, & Digby, 2003).

Design and Procedure

Experiment 1 had a within-subject design with three factors, specifically the stimulus onset asynchrony (SOA) between the two targets, the presence of the parity-judgement task (T2 presence), and the presence of a rapid serial visual presentation of distractors (RSVP). The SOAs could be 300, 400, 600, or 800 ms, whilst T2 was present in 50% of the trials. T2 presence as well as the SOA conditions were randomly intermixed. RSVP presence, however, was blocked resulting in one block during which the target was integrated in the RSVP sequence and one block in which no distractors were presented. Whether a participant started with the RSVP block or not was based on the parity of the participant’s ID. Each participant performed 20 trials per combination of SOA, T2 presence, and RSVP presence amounting to 320 trials in total.

Before the experiment commenced, the participants were led to a cubicle that only contained a chair and a computer on which the instructions for the first block were displayed. Each block started with 16 practice trials. At the beginning of each trial, a fixation cross was shown at the centre of the screen and the trial sequence could be initiated by pressing the space bar (for an illustration see Figure 1). In the RSVP condition, a sequence of rapidly alternating strings of three letters and blanks appeared each for 50 ms. In this stream, T1 was always presented in the fifth position, followed by a 50 ms long blank which was trailed by a mask lasting 50 ms. The RSVP sequence then continued with another blank and at least one more distractor followed by a blank with a maximum of seven distractors following T1 depending on the SOA (300-800 ms). The trials culminated in either a 400-ms presentation of T2 in the T2-present condition, or, in a distractor shown for 400 ms in the T2-absent condition. If T2 was present, participants needed to indicate the parity of T2 by pressing “1” for uneven and “2” for even with their right hand on the numeric keypad. To equate the retention intervals for T1 across the T2 present and T2 absent conditions, we included a 1000-ms blank after the last distractor in the T2 absent condition. Afterwards, participants were asked to enter the letters for T1. Participants received negative feedback if they needed longer than 1000 ms to respond to T2 or if they recalled none of the target letters correctly. If necessary, the feedback screen finalised the trial, and the subsequent trial began. After 160 trials, the first block was concluded and instructions for the second, respective block were stated on the screen, which followed the same structure, only differing in the presence or absence of the RSVP stream surrounding the targets. Following completion of the experiment, participants were fully debriefed on the underlying intentions of the study, and thanked for their participation.

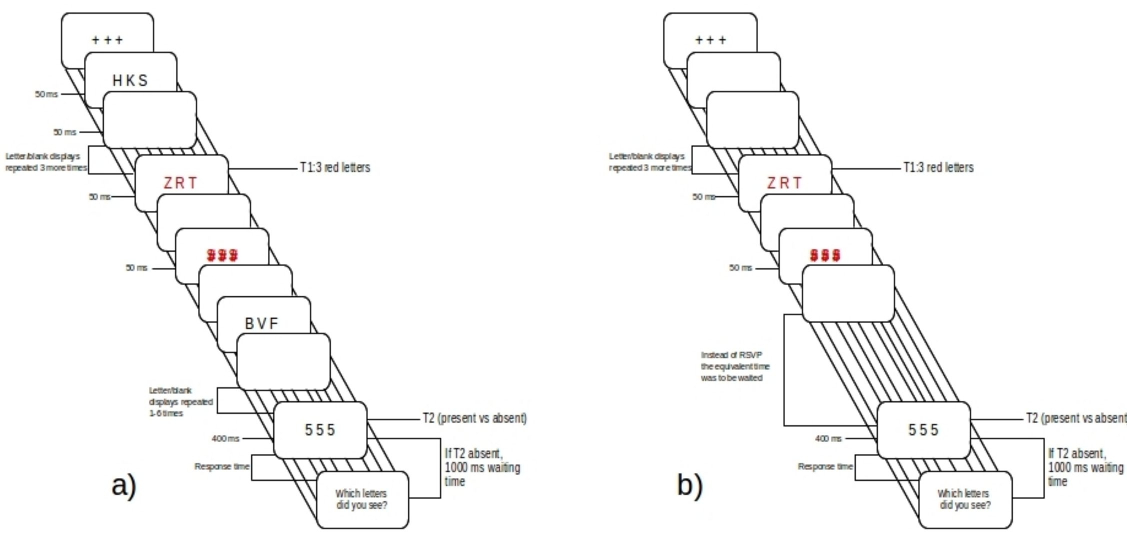

Figure : A depiction of the trial procedure for the RSVP-present condition (a) and the RSVP-absent condition (b).

Data analysis

The data analysis for both Experiment 1 and 2 was performed in R 3.6.2 (R Core Team, 2019), and the Bayesian analyses were performed in JASP (JASP Team, 2020). Prior to our main analyses, data were excluded based on the following criteria:

1) Participants were excluded if they did not complete the task

2) Participants were excluded if their performance on T1 was not in range of 2.5 *SD* of the overall mean

3) Individual trials were excluded if no letters were recalled for T1 or if the response to the parity-judgment task was incorrect.

4) Individual trials were excluded which exceeded a cut-off of 2.5*SD* above the mean of T2 response time.

The latter criterion was applied because we intended to investigate the interactive effects of consolidation and response choice. Yet, if one of the tasks has not been completed accurately, the exact object of our measurement remains obscure.

For the repeated measures ANOVAs, we used the afex-package (version number 0.26-0, Singmann, Bolker, Westfall, & Aust, 2018). Our main analyses consisted of repeated measures ANOVAs on the total number of letters recalled for T1 and on response time for correct responses to T2, using SOA, RSVP, and T2 presence for the analysis of T1 accuracy and SOA and RSVP for the analysis of T2 response times.

Results

In Experiment 1, we tested the replicability of the findings of Nieuwenstein et al. (2014) who found evidence for retroactive interference from a speeded parity-judgement task on the consolidation of an earlier shown string of three letters, only in the absence of an RSVP stream.

If the targets were embedded in an RSVP sequence, the processing of the letters proactively interfered with, and, thereby, delayed the response to the second task. Accuracy on the memory task (T1) was determined by the amount of correctly identified letters regardless of their order of report, and performance on the parity-judgement task was quantified by response time in milliseconds, for trials with a correct response. Accordingly, we used these measurements for our dependent variables in our main analysis.

Outlier Exclusions

Prior to performing our main analyses, we applied the exclusion criteria mentioned before. We had to exclude three participants (12.5%) who were not able to complete the task and one participant was excluded since accuracy on T1 was more than 2.5 *SD* lower than the group mean. Furthermore, all trials were excluded in which the participant either responded incorrectly to the parity-judgement task or failed to recall any letters for T1. Lastly, we excluded individual trials in which the T2 response time was above the 2.5 *SD* cut-off from the mean. In total, 9.69% and 13.23% of the recorded observations of T1 accuracy and T2 response time, respectively, were excluded by the aforementioned procedure.

Analyses T1 Accuracy

For T1 accuracy, we conducted a repeated-measures analysis of variance (RM-ANOVA) incorporating SOA, T2 presence, and RSVP presence as within-subject factors. Figures and tables concerning test assumptions can be reviewed in the supplementary materials (Appendix 1). An overview of the results of this analysis can be found in Table 1 and a plot depicting the effects can be seen in Figure 2. As can be seen in Table 1, contrary to our prediction, the analysis did not yield a statistically significant three-way interaction effect of SOA, T2 presence, and RSVP presence. However, the presentation of the effects in Figure 2 do show similar results to the original study since the presence of T2 caused interference with T1 performance at short SOA in absence of RSVP, but not in the presence of RSVP. Indeed, a follow-up RM-ANOVA using only the T2 Present conditions, and examining the results for the effects of SOA and RSVP Presence showed statistically significant effects for SOA, $F(3, 57) = 5.61$, $p < .01$, RSVP, $F(1, 19) = 742.02$, $p < .001$, and the interaction between SOA and RSVP, $F(3, 57) = 3.62$, $p = .02$, with adjusted alpha levels for multiple testing ($\alpha = 0.025$). This interaction was driven by the presence of a statistically significant effect of SOA in the RSVP absent condition, $F(3, 57) = 6.22$, $p < .001$, reflecting retroactive interference, and the absence of an effect of SOA in the RSVP present condition, $F(3, 57) = .87$, $p = .46$ ($\alpha = 0.0125$). Additionally, to verify the absence of an effect of SOA on T1 performance if both RSVP and T2 were present, as opposed to RSVP absent and T2 present, we performed a Bayesian RM-ANOVA. The analysis yielded a $BF_{01} = 7.46$ for the effect of SOA, indicating substantial evidence in favour of the null hypothesis (Jeffreys, 1961). Thus, the data are 7.46 times more likely under a model, which excludes SOA rendering SOA very unlikely to have affected T1 performance if both RSVP and T2 were present. It, thus, appears to be the case that the lack of a statistically significant three-way interaction did not reflect the lack of the hypothesized modulation of retroactive interference depending on RSVP, but, rather, arose due to the surprising drop of performance on T1 accuracy across SOA when RSVP was present but T2 was absent.

Table 1

Experiment 1: Analysis of T1 Accuracy

Effect	MS	Df	F	P	Greenhouse-Geisser	η^2_G
SOA	<.01	3, 57	.26	.84	.81	<.001
T2 Presence	1.06	1, 19	24.37	<.001	<.001	.03
RSVP	11.67	1, 19	152.87	<.001	<.001	.54
SOA * T2 Presence	.19	3, 57	13.02	<.001	<.001	.02
SOA * RSVP	.14	3, 57	5.87	<.01	<.01	.01
T2 Presence * RSVP	.06	1, 19	9.44	<.01	<.01	<.01
SOA * T2 Presence * RSVP	.02	3, 57	0.93	.40	.43	<.01

Note: The output of the repeated measures ANOVA on T1 accuracy comprises the results of all main and interaction effects. Here, SOA denotes stimulus onset asynchrony, T2 Presence signifies whether a second task was present in a trial, and RSVP conveys the presence or absence of a stream of distractors. Respective *p*-values and *p*-values based on the Greenhouse-Geisser-correction have been added to each effect. η^2_G expresses the effect size in terms of generalized eta-squared.

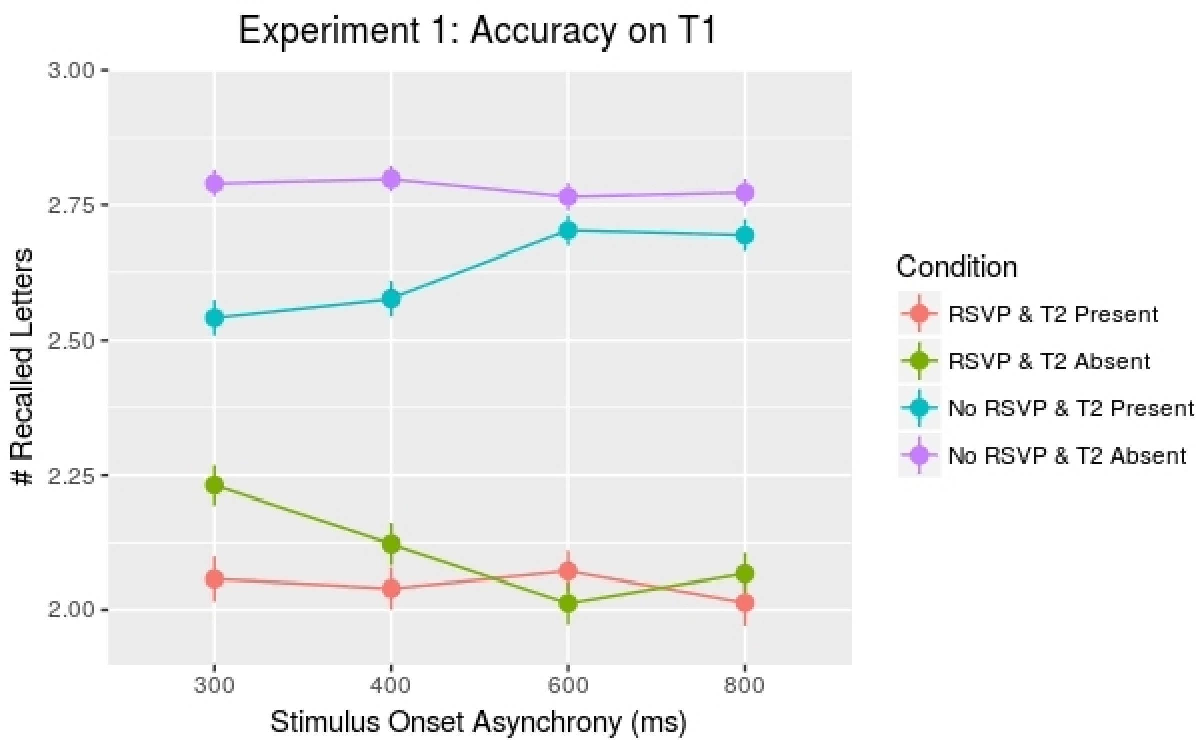

Figure : The effects of SOA, RSVP and T2 presence on T1 accuracy. Error bars depict the standard error of the means.

Analysis T2 Response Times

In total, 3.32% of all responses to the parity-judgement task were incorrect and these trials were excluded from the RM-ANOVA on T2 response times. Specifically, we analysed T2 response times, including SOA and RSVP as within-subject factors (see Table 2). The effects are plotted in Figure 3. The analysis yielded a statistically significant main effect of SOA, $F(3, 57) = 18.14$, $p < .001$, and an interaction of SOA and RSVP, $F(2.9, 55.09) = 6.82$, $p < .01$. Analogous to the analysis of T1 accuracy, we conducted two RM-ANOVAs as a follow-up to the statistically significant interaction splitting the data set according to either RSVP condition. In the RSVP present condition, T2 response times showed a statistically significant effect of SOA, $F(3, 57) = 18.46$, $p < .001$ ($\alpha = 0.025$). Surprisingly, the RSVP absent trials also showed a statistical significant effect of SOA, $F(3, 57) = 5.43$, $p < .01$ ($\alpha = 0.025$). Since the latter finding was unexpected in that the earlier study by Nieuwenstein et al. (2014) did not reveal this effect, we conducted a follow-up analysis by contrasting all SOA conditions with another (full table to be found in Table 10, Appendix 1). The analyses showed that there were statistically significant differences between SOA 300 and both 400 and 600 ($t(10.7, 57) = 4.5$, $p < .001$ and $t(10.7, 57) = 4.3$, $p < .001$, respectively) but not between 300 and 800 ($t(10.7, 57) = 1.7$, $p = .35$).

Table 2

Experiment 1: Analysis of T2 Response Time

Effect	MS	Df	F	P	Greenhouse -Geisser	η^2_G
SOA	33300	3, 57	18.14	< .001	< .001	.04
RSVP	8791	1, 19	.75	.40	.40	< .01
SOA * RSVP	13291	3, 57	6.82	< .01	< .01	.02

Note: The output of the repeated measures ANOVA on T2 response time comprises the results of all main and interaction effects. Here, SOA denotes stimulus onset asynchrony and RSVP conveys the presence or absence of a stream of distractors. Respective *p*-values and *p*-values based on the Greenhouse-Geisser correction have been added for each effect. η^2_G expresses the effect size in terms of generalized eta squared.

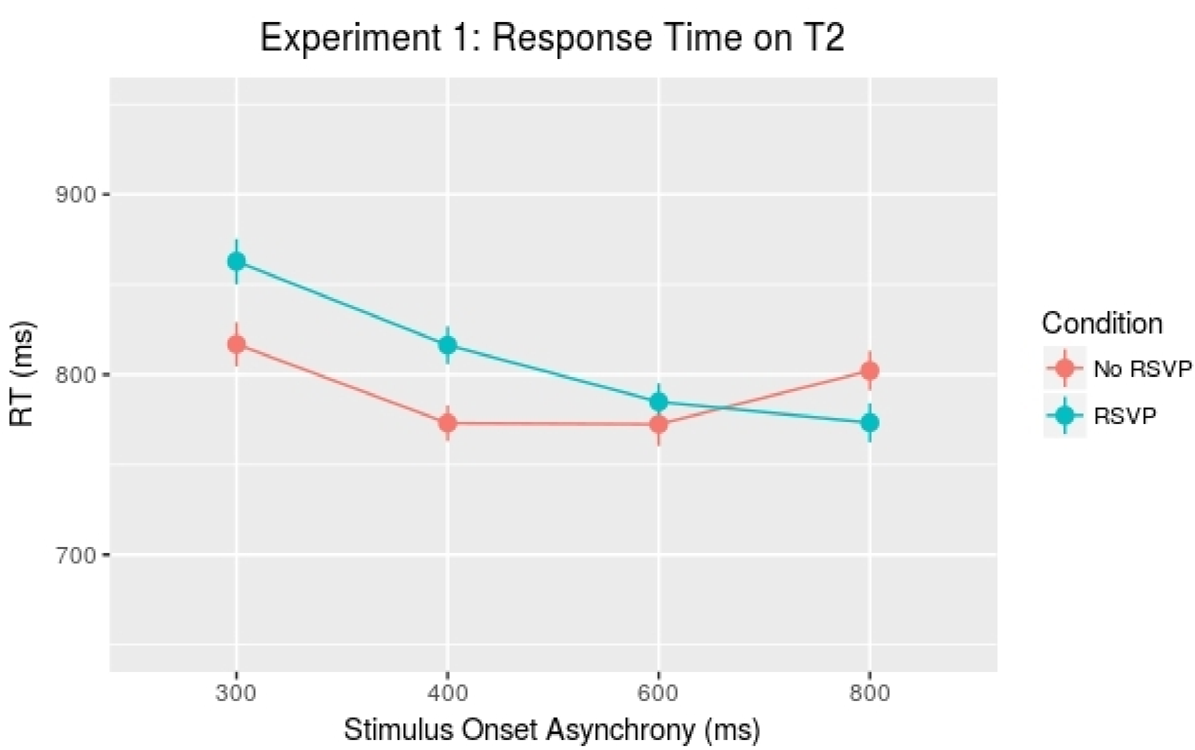

Figure : The effect of SOA and RSVP presence on T2 response times. Error bars depict the standard error of the means.

Comparison of the original and replication experiment

Lastly, we examined whether the replication attempt succeeded by comparing the data of both experiments directly. Therefore, we pooled the samples of the original and the replication study to analyse potential differences with the help of a frequentist RM-ANOVA on T1 accuracy including 'Experiment' (original/replication) as a between-subjects factor. We also visualized the differences between the original and the replication in Figure 4.

Here, the main effect of Experiment did not reach statistical significance with $F(1, 49) = 0.45$, $p = .51$. Apart from that, none of the interaction effects involving Experiment reached

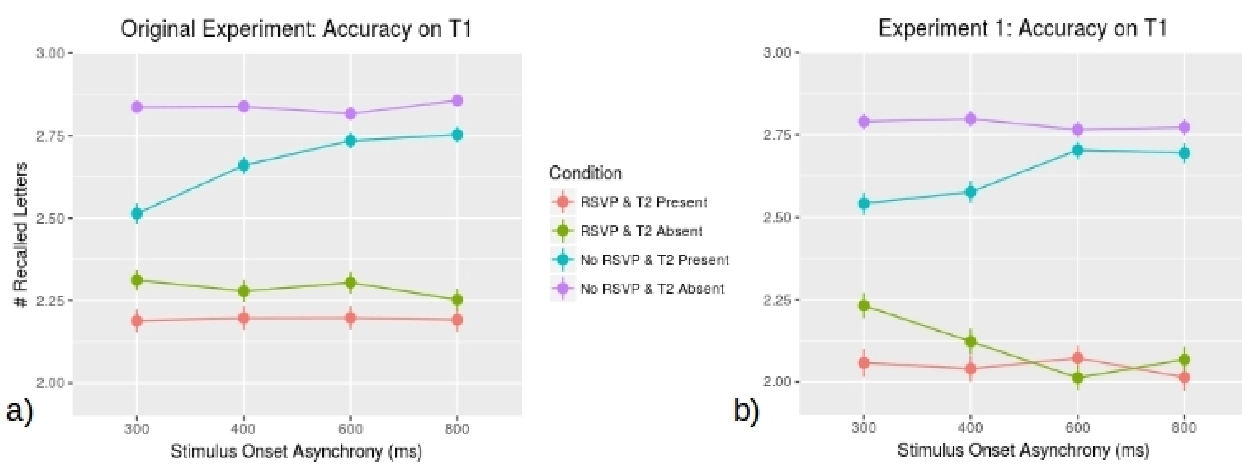

Figure : The plots depict a comparison between the original experiment and our replication focusing on the effects of SOA, RSVP, and T2 presence on performance on T1.

statistical significance: Including Experiment*SOA ($F(3, 147) = 2.43$, $p = .07$), Experiment*RSVP ($F(1, 49) = 2.68$, $p = .11$), Experiment*T2Presence ($F(1, 49) = 0.53$, $p = .47$), Experiment*SOA*RSVP ($F(3, 147) = 0.63$, $p = .60$), Experiment*SOA*T2Presence ($F(3, 147) = 2.23$, $p = .09$), Experiment*RSVP*T2Presence ($F(1, 49) < 0.01$, $p = .95$), and Experiment*SOA*RSVP*T2Presence ($F(3, 147) = 2.52$, $p = .06$).

We decided to utilize a Bayesian RM-ANOVA to shed light on these null findings. To this end, we conducted an analysis of effects to investigate the four-way interaction. To avoid biases, the models that were compared with another only differed in the presence or absence of the four-way interaction, as opposed to comparing all models with another (Nelder, 1977). The analysis showed that the BF_{Incl} = .13 for the four-way interaction across these comparisons. Thus, given the data, models excluding the four-way interaction are 7.75 times more likely. Overall, the results on T1 accuracy indicate that the replication was a success.

In a similar vein, a frequentist RM-ANOVA on response time to T2 showed comparable results across the original and replication experiment. A visual demonstration between the replication and the original can be found in Figure 5. The main effect of Experiment was not found to be statistically significant with $F(1, 49) = 0.03$, $p = .86$. The interaction effects of interest featuring Experiment also did not reach statistical significance including Experiment*SOA ($F(3, 147) = 1.37$, $p = .26$), Experiment*RSVP ($F(1, 49) = 2.08$, $p = .16$), and Experiment*SOA*RSVP ($F(3, 147) = 0.29$, $p = .77$).

Analogous to the analysis of T1 accuracy, we applied a Bayesian RM-ANOVA testing the effects of the three-way interaction between SOA, RSVP, and Experiment on T2 response time. The comparisons resulted in a BF_{Incl} = .09 which means that the data under models excluding the three-way interaction are 11.11 times more likely. To wit, these results give relatively little reason to believe that performance on T2 response time differed across the original and our experiment.

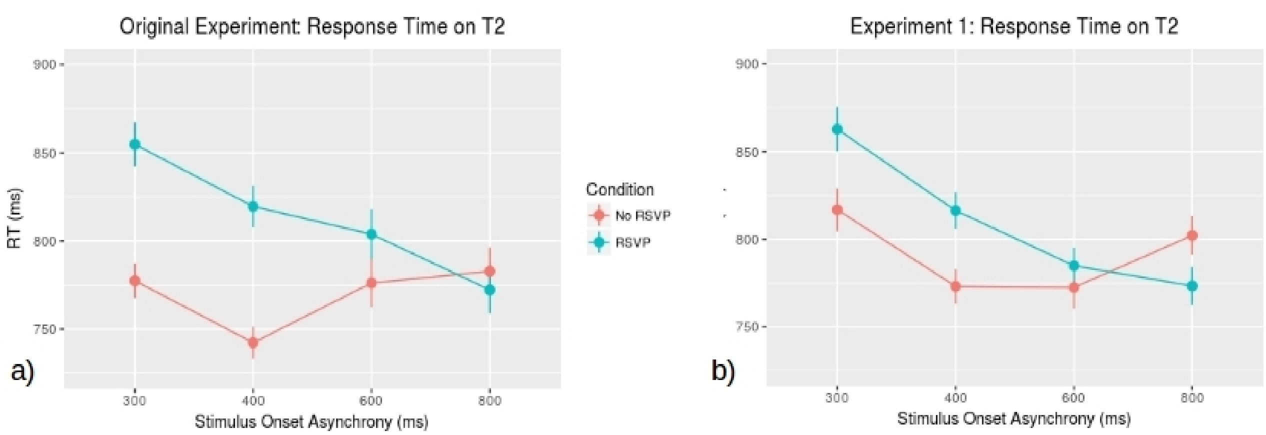

Figure : These plots compare the effects of RSVP and SOA on T2 response time between a) the original experiment by Nieuwenstein, Scholz, and Broers (2014) and b) our experiment 1.

Summary

In conclusion, we were able to replicate the primary outcomes of the experiment conducted by Nieuwenstein et al. (2014). Thus, the original study as well as the current replication show that if no stream of distractors was displayed (no RSVP) but T2 followed rapidly (short SOA), T1 accuracy suffered retroactive interference, whereas no such retroactive interference was found in the presence of RSVP. In addition, we replicated the interaction of SOA and RSVP on T2 performance. More specifically, without distractors (no RSVP), very little to no proactive interference on T2 response times was observed (except for a small dip in response times at SOA 400 and 600). However, if targets were embedded in distractors, a clear and unmistakable proactive interference was evident.

Experiment 2

The goal of Experiment 2 was to investigate the effects of the presence of RSVP given that T2 is always present. Furthermore, we intended to compare Experiment 1 and 2 to test whether T2 would show an even stronger proactive interference effect if both sources of risk of interference (i.e., RSVP as well as a high T2 probability) were present in Experiment 2 as compared to when only one of these two source sources of interference (i.e., RSVP) was present in Experiment 1, where T2 probability was relatively low.

Methods

Participants

Since we expected to find a hitherto unrecorded effect when comparing the experiments' conditions with the respectively highest interference, we inferred the sample size based on assuming a medium effect size of f = .25 for the interaction effect between experiment and SOA in the RSVP present condition on T2 response time. In order to detect this effect with 95% power, and α = 0.05, we would need at least 20 participants. Due to administrative reasons, we were only able to sample 18 first-year psychology students from the Rijksuniversiteit Groningen who received course credits for participation. The participants' age ranged from 18 to 25 (*Median* = 20, *SD* = 1.83) and the data of 11 females (61%) and seven males were obtained. The participants gave informed consent and the Ethics Committee of Psychology approved the study.

Materials, Design, Procedure, and Data analysis

In Experiment 2, we used the same materials, procedure, and design as in Experiment 1. The only difference was that T2 was presented on all trials. Accordingly, Experiment 2 had a within-subject design with two factors: SOA (300, 400, 600, 800 ms) and RSVP presence (in blocks), and it included 40 trials per combination of SOA and RSVP presence. In addition, the procedure was slightly altered. Specifically, the feedback screen that was presented if participants responded too slowly to T2 was only shown if participants took more than 1500 ms to respond to T2, since we expected longer response times to T2 in Experiment 2. We only detected that this change had to be incorporated after we had already tested the first four participants.

Results

Outlier exclusion

Similarly, to Experiment 1, we had to exclude individual trials as well as participants prior to the analysis. Only one participant (5.6%) was not able to complete the task. In addition, we excluded individual trials due to an incorrect response to the parity-judgement task or if no target letter for T1 was identified. Combined with the exclusion criterion based on the 2.5 *SD* cut-off for T2 response times, 12.98% of the recorded observations were not used for the analysis.

Analyses T1 Accuracy

Similarly, to the analysis of our first experiment, we investigated the effects of SOA, and RSVP presence on T1 accuracy by means of an RM-ANOVA. By nature of the design, the factor T2 presence was excluded from the analysis. An overview of the results can be found in Table 3 and the effects of SOA and RSVP on T1 accuracy are depicted in Figure 6. The frequentist approach indicated that only the RSVP effect was statistically significant, as neither SOA nor the interaction between SOA and RSVP affected performance on the first task.

Table 3

Experiment 2: Analysis of T1 Accuracy

Effect	MS	Df	F	P	Greenhouse-Geisser	η^2_G
SOA	<.01	3, 48	.41	.75	.70	<.001
RSVP	14.79	1, 16	56.6	<.001	<.001	.35
SOA * RSVP	.01	3, 48	.61	.56	.61	<.001

Note: Analogous to Table 1, this table represents the repeated measures ANOVA on T1 accuracy with the respective main and interaction effects based on the data of Experiment 2.

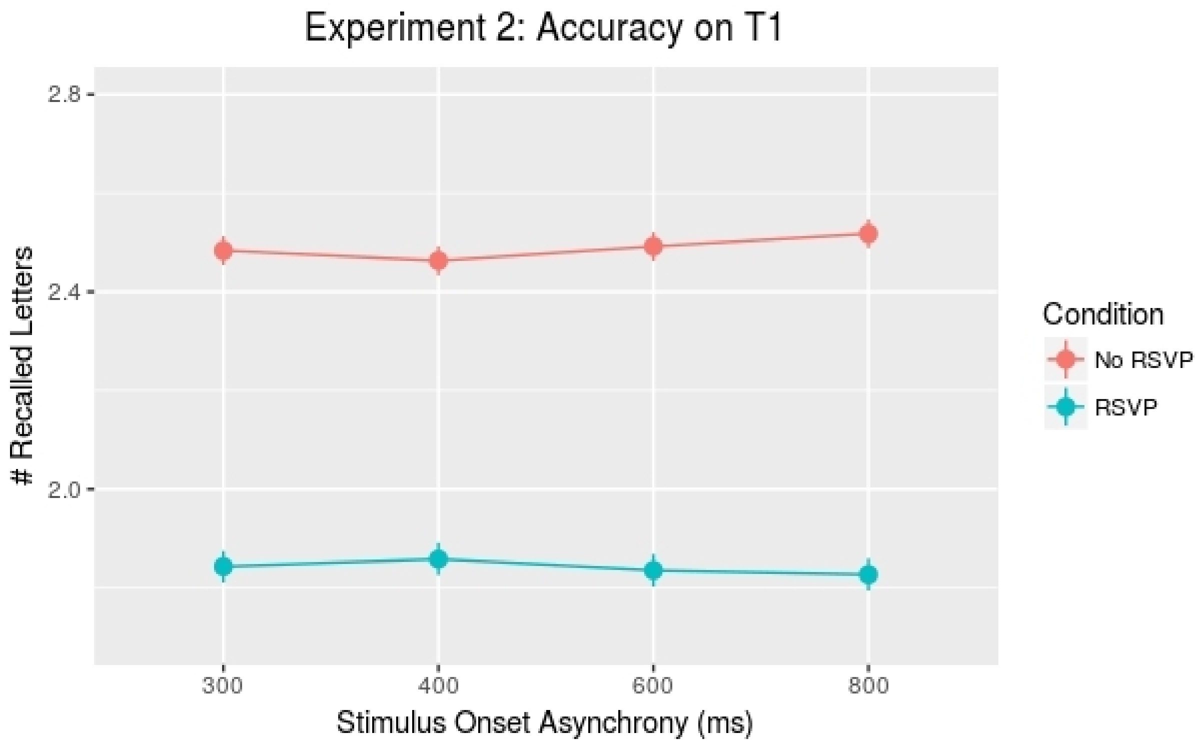

Figure : This depiction shows the effect of RSVP on T2 response times.

To confirm the absence of an effect of SOA on T1 accuracy, we performed a Bayesian RM-ANOVA incorporating SOA and RSVP presence as within-subject factors (see Table 4). The analysis provided strong evidence against an effect of SOA or the SOA-RSVP interaction (BF_{10} = .043 and BF_{10} = .04, respectively).

Table 4

Experiment 2: Bayesian Analysis of T1 Accuracy

Model Comparison

Models	P(M)	P(M|data)	BF M	BF 10	error %
Null model (incl. subject)	0.200	1.251e -33	5.004e -33	1.000	
SOA	0.200	4.945e -35	1.978e -34	0.040	0.548
RSVP	0.200	0.955	85.232	7.635e +32	0.916
SOA + RSVP	0.200	0.041	0.171	3.278e +31	1.159
SOA + RSVP + SOA ✻ RSVP	0.200	0.004	0.015	3.055e +30	1.350

Table 4

Experiment 2: Bayesian Analysis of T1 Accuracy

Model Comparison

Models	P(M)	P(M|data)	BF_M	BF_{10}	error %
Null model (incl. subject)	0.200	1.251e -33	5.004e -33	1.000	
SOA	0.200	4.945e -35	1.978e -34	0.040	0.548

Note: The output represents the Bayesian counterpart to the previously shown RM-ANOVA for T1 accuracy.

Analyses T2 Response Time

Analogous to the analysis of Experiment 1, we also examined performance on Task 2. In total, 7.53% of responses to the parity-judgement task were incorrect. These incorrect responses were excluded from an analysis using a RM- ANOVA to test the effects of RSVP and SOA on T2 response time. For an overview of the results and a depiction of the effects, see Table 5 and Figure 7, respectively. The results show that only the effect of SOA on T2 response time was statistically significant. As can be seen in Figure 7, response times became gradually faster with increasing SOA, regardless of the RSVP condition.

Table 5

Experiment 2: Analysis of T2 Response Time

Effect	MS	Df	F	P	Greenhouse-Geisser	η^2_G
SOA	210945.67	3, 105	101.75	<.001	<.001	.23
RSVP	93	1, 35	<.01	.95	.95	<.001
SOA * RSVP	4453.33	3, 105	2.18	.10	.12	<.01

Note: The output of the repeated measures ANOVA on T2 response time comprises the results of all main and interaction effects. Since the assumption of sphericity was violated, the Greenhouse-Geisser correction was used in order to avoid biases. Non-corrected *p*-values were added for the sake of completion.

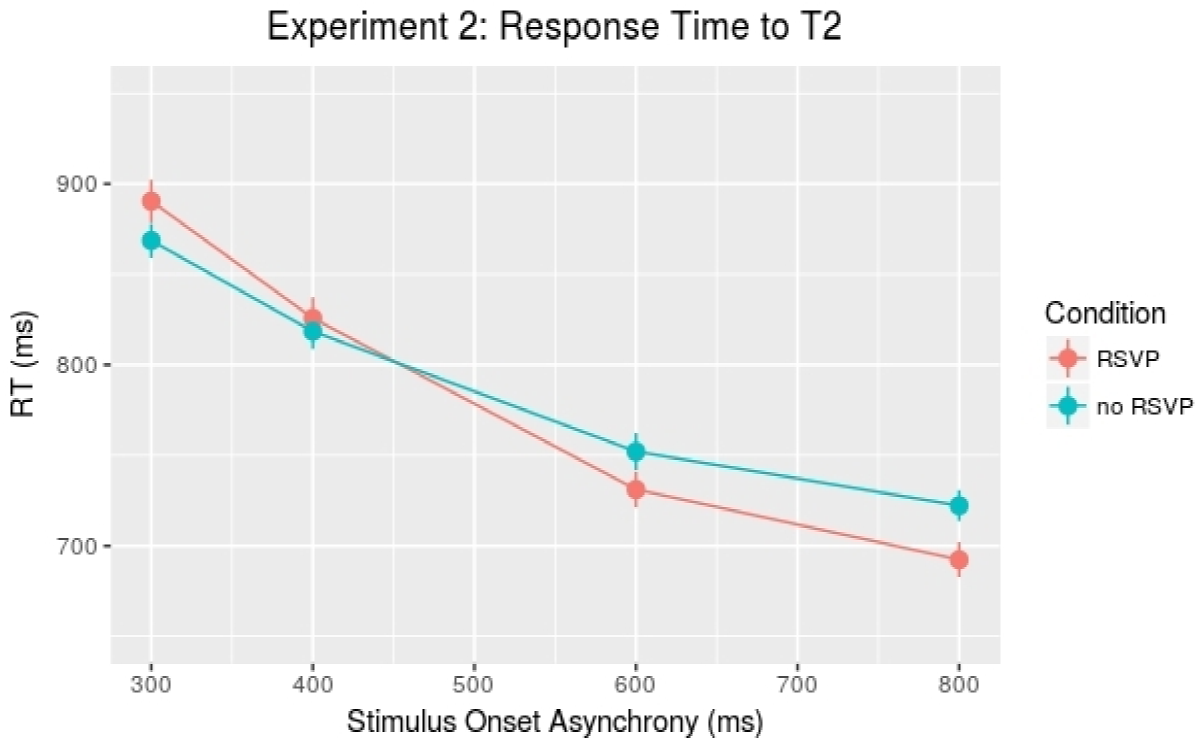

Figure : Here, the effect of SOA on T2 response times is depicted

Moreover, a Bayesian RM-ANOVA of SOA and RSVP on T2 response time was employed to obtain a clearer picture of the statistically non-significant effects (see Table 6). This analysis provided decisive evidence in favour of including SOA in a model predicting T2 response time. A comparison of a model solely based on SOA with models including both main effects (SOA and RSVP) or even adding their interaction effect revealed that the data would be 5.47 times less likely or even 28.11 times less likely under these latter models, respectively. These results indicated that the presence of RSVP did not have an effect on T2 response times.

Table 6

Experiment 2: Bayesian Analysis of T2 Response Time

Model Comparison					
Models	P(M)	P(M|data)	BF_M	BF_{10}	error %
Null model (incl. subject)	0.200	2.515e -16	1.006e -15	1.000	
SOA	0.200	0.821	18.331	3.264e +15	0.582
RSVP	0.200	4.524e -17	1.810e -16	0.180	0.935
SOA + RSVP	0.200	0.150	0.706	5.962e +14	1.238
SOA + RSVP + SOA ✻ RSVP	0.200	0.029	0.120	1.161e +14	1.261

Note: The output represents the Bayesian counterpart to the previously shown RM-ANOVA for T2 response times.

Comparison of Experiment 1 and 2

Lastly, we pooled both data sets of Experiment 1 and 2 together in order to analyse their differences. Concerning T1 accuracy, the only question of interest was whether we can replicate the original T2 probability effect (50% versus 100%) found in between-subjects design by Nieuwenstein et al. (2014). Therefore, we performed an RM-ANOVA of SOA, RSVP, and the newly added ‘Experiment’ factor on T1 performance. Since T2 was always present in Experiment 2, the T2 absent condition from Experiment 1 was omitted from the analysis. Figure 8 serves as a visual representation of the results. The analysis revealed that the main effect of Experiment was not statistically significant, $F(1, 35) = 3.19$, $p = .08$, $\eta^2_G = .07$. Furthermore the main effect of RSVP, $F(1, 35) = 165.58$, $p > .001$, $\eta^2_G = .40$ and SOA, $F(2.49, 87) = 2.94$, $p = .05$, $\eta^2_G < .01$ as well as an interaction effect of SOA and RSVP, $F(2.88, 100.8) = 3.03$, $p = .03$, $\eta^2_G < .01$ (Greenhouse-Geisser correction was applied on the latter two) were statistically significant.

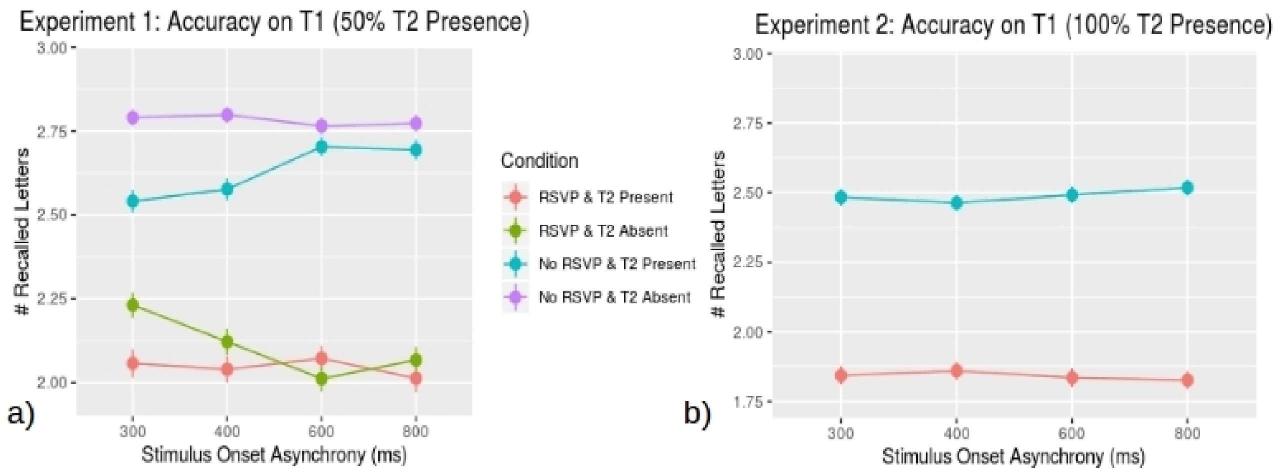

Figure : A comparison of T1 performance across both experiments. For sake of completion, T2 absent trials were added as well.

We would expect to find a statistically significant two-way interaction between SOA and Experiment in the RSVP-absent condition, which equates to testing for retroactive interference. We, therefore, conducted a follow-up analysis similar to the analyses displayed in the comparison between the original and the replication (Experiment 1) but focusing on RSVP absent trials. The analysis yielded a statistically significant effect of SOA, $F(3, 105) = 3.89$, $p < .001$ but defied expectation for the two-way interaction between SOA and Experiment, $F(3, 105) = 1.37$, $p = .1$ ($\alpha = 0.025$). The most likely reason for this null finding is a lack of statistical power necessary for demonstrating this interaction effect.

The focus of the comparison between Experiment 1 and 2 was the differences in T2 response times. Accordingly, we administered a frequentist RM-ANOVA to test the effects of SOA, RSVP and Experiment on T2 response times. The results of the analysis can be reviewed in Table 7 and a visualisation is presented in Figure 9. The analysis yielded statistically significant effects for the main effect of SOA, the interaction between SOA and Experiment, as well as the three-way interaction of SOA, RSVP and Experiment.

Table 7

Experiment 1 & 2: Comparing T2 Response Time

Effect	MS	Df (num/den)	F	P	Greenhouse -Geisser	η^2_G
Exp	8023	1, 35	.08	.78	.78	<.01
SOA	203392,67	3, 105	104.41	<.001	<.001	.12
RSVP	5668	1, 35	.34	.56	.56	<.01
SOA * RSVP	1215,67	3, 105	.61	.61	.60	<.001
Exp * SOA	56190,33	3, 105	28.85	<.001	<.001	.04
Exp * RSVP	3732	1, 35	.23	.64	.64	<.001
Exp * SOA* RSVP	14981	3, 105	7.49	<.001	<.001	.01

Note: The output of the repeated measures ANOVA on T2 response time comprises the results of all main and interaction effects for the combined data sets of Experiment 1 and 2.

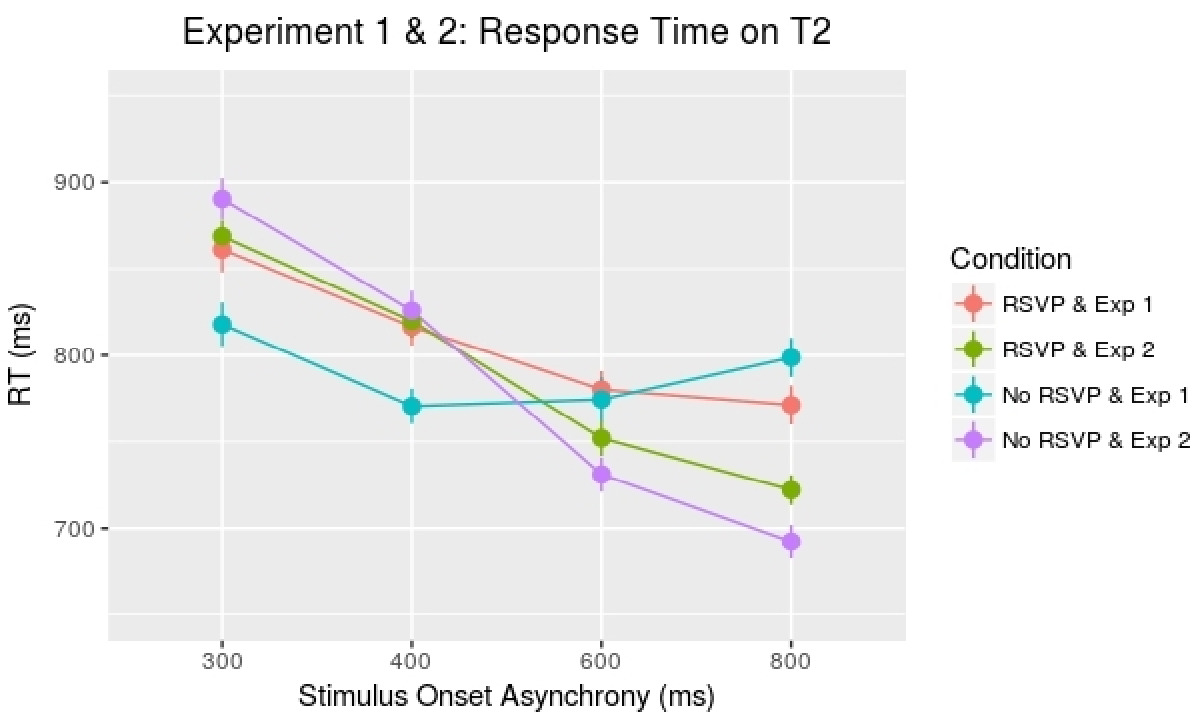

Figure : The figure depicts a comparison of T2 response times for all conditions in both experiments.

Since we were interested in the difference of response times between Experiment 1 and 2 in the RSVP present condition, we decided to follow-up on the statistically significant three-way interaction effect by using an RM-ANOVA based on only those trials. The analysis revealed that the effects of SOA, $F(3, 105) = 54.9$, $p < .001$ and the interaction effect between SOA and Experiment, $F(3, 105) = 3.3$, $p = .02$ were statistically significant but the main Effect of Experiment was not, $F(1, 35) = .69$ $p = .41$ ($\alpha = 0.025$). The interaction effect suggests that the influence of SOA on T2 response times differed across experiments in the RSVP present condition - as we hypothesized earlier – but fails to reveal where exactly the difference lays which was our main research interest for Experiment 2. More specifically, we were interested whether participants showed slower response times during Experiment 2 if the RSVP-embedded second task was presented in rapid succession to the first (SOA 300). Therefore, we employed a Bayesian independent samples t-test on the T2 response times for the RSVP-present and SOA 300 condition comparing both experiments. The test revealed a $BF_{10} = .32$, thus providing us with substantial evidence for H_0. To wit, the data were 3.11 times more likely given that there is no difference between the SOA 300 conditions of Experiment 1 and Experiment 2 on T2 response time.

These results primarily indicate that the absence of distractors in Experiment 1 combined with the somewhat surprising presentation of task 2 (50% probability) resulted in relatively levelled response time. This response time was initially fast, did not improve in Experiment 1, which was not the case in Experiment 2. However, if RSVP was present, response times in both experiments were slow at SOA 300 and gradually improved. Although, the gain of speed was higher in Experiment 2.

Summary

In conclusion, the results of Experiment 2 showed worse performance on T1 if tasks were embedded in a stream of distractors independent of SOA. However, response times to T2 did not differ between RSVP conditions. In both cases, response times improved as SOAs increased, indicating proactive interference in absence of retroactive interference in Experiment 2. The comparison of Experiment 1 and 2 revealed that response times to T2 in Experiment 2 improved more across all SOAs as compared to response times to T2 in Experiment 1. Nevertheless, T2 response times at SOA 300 and if distractors were present did not differ across experiments, thus, failing to show a stronger proactive interference effect in Experiment 2 than in Experiment 1 in the RSVP present condition.

General Discussion

In this study, we aimed to replicate Nieuwenstein et al. (2014) finding that risk of interference influences whether proactive or retroactive interference occurs in a dual-task study and investigated whether the degree of proactive interference can be adjusted by adding another source of interference.

Summary

In Experiment 1, we replicated the findings presented by Nieuwenstein et al. (2014) who revealed the presence of retroactive interference in a dual-task experiment in a low risk of interference condition (no RSVP and T2 50% present) without proactive interference. These findings were contrary to most studies where tasks were embedded in a rapid stream of distractors (RSVP) or T2 was presented in all trials. Moreover, we replicated that T2 response times were relatively stable in this condition. However, if distractors were present, and, thus, interference was expected, the effects reverted to the typical finding of proactive interference in absence of retroactive interference. We conducted a second experiment to investigate whether the protection of T1 could be influenced by adding another source of interference or whether one source suffices to reach maximal protection of T1 processing. To this end, we presented T2 at all trials in Experiment 2 and compared the RSVP present conditions between experiments with, therefore, either one or two sources of interference. Our results showed that there was a difference between response times in both experiments, however, it only manifested at longer SOA's. If T2 was presented very shortly after T1 (SOA of 300), the response times were unaffected by risk of interference, hence not showing an increased proactive interference effect.

Interference Control Theory

Our results provide additional evidence for the Interference Control Theory postulated by Nieuwenstein et al. (2014). In the replication, the RSVP-absent condition can be identified as offering low risk of interference which resulted in retroactive interference accompanied by a lack of proactive interference. In these scenarios, even though T1 was presented first, the sudden occurrence of T2 disrupted T1 processing resulting in a lower accuracy of recalling targets. It can be postulated that the control mechanism responsible for protecting T1 processing is not activated, and, thus, subsequent stimuli were not suppressed. On the contrary, the RSVP-present condition produced high risk of interference and the participants' performance showed proactive interference at short SOA's and no retroactive interference at all. Presumably, as a response to the high risk of interference, T1 was protected against incoming distractors leading to a postponement of T2 processing along with it. These findings present further evidence against the central bottleneck theory since, in case of retroactive interference in absence of proactive interference, the processing of T2 was preferred at cost of processing of T1 by disrupting it despite its faster arrival time at the bottleneck stage. Arrival time was proposed as the main determinant for processing priority by Strobach, Hendrich, Kübler, Müller, and Schubert (2018) and coined the “first-come, first-served”-principle. We could not find support for this principle nor the notion of a central and immutable bottleneck based on our research.

Relationship to previous Theories

In an effort to understand the intrinsic variability of cognitive control, other theories point to modes of control as the mechanism influencing processing priority in a dual-task setup. In a similar vein to the Interference Control Theory (ICT), Braver presented the dual mechanism of control framework which differentiates between proactive and retroactive control (Braver, 2012; Braver, Gray, & Burgess, 2007; Chiew & Braver, 2017). Here, a mode of proactive control is engaged in anticipation of and to prevent interference in order to actively maintain task goals. Reactive control, however, is focused on detecting and resolving interference and shows more probe-triggered activity. This research was corroborated by neuroimaging studies such as one utilizing the recent probes task (D'Esposito, Postle, Jonides, & Smith, 1999), in which an increased BOLD-response was seen in areas related to proactive control if the interference of the task was high but if the interference was low, areas associated with reactive control showed higher activity instead. A more recent summary of the neural substrates corresponding to proactive and reactive control specifically relating to working memory is provided by Irlbacher, Kraft, Kehrer, and Brandt (2014). Which mode is more engaged at any given time seems to be depending on the context. While reactive control might be interpreted as a latent, late correction mechanism whose efficacy is dependent on retrieval and stimulus salience (Irlbacher et al., 2014), recent findings showed that the proactive control mode can be artificially relaxed by changing external expectations explicitly (Bugg, Diede, Cohen-Shikora, & Selmeczy, 2015), potentially leading to a higher reliance on reactive control. Over the course of five experiments, Bugg et al. (2015) tested the effects of pre-cueing (indicating mostly congruent versus mostly conflicting beforehand) lists for the Stroop task on participants performance. The analysis of the first-position items showed larger Stroop effects if pre-cueing and actual congruency did not align, leading the researchers to believe that attentional control was relaxed for at least the first trial of the list. Relating back to the dual mechanism of control framework, Braver (2012) explained that, indeed, subtle changes in circumstances can influence which mode of control is dominant, however, it is possible that both modes are simultaneously active to varying degrees. The prioritization of one mode over the other might be an effective response to the quickly fluctuating external circumstances that are faced. The focus on external circumstances – specifically the expectation of interference and relaxation of cognitive control – influencing dual-task performance more than initially thought is reminiscent and neatly ties into the findings of our replication (Experiment 1). Braver’s (2012) modes of control could be translated into the suppression of attention based on high risk of interference (proactive mode) versus the lack thereof (reactive control).

Furthermore, the threaded cognition model (Taatgen, Juvina, Schipper, Borst, & Martens, 2009) offers another theoretical approach to phenomena pertaining to proactive interference such as the attentional blink (AB). As this model is based on the ACT-R architecture, various sources, which are tasked to either detect or ensure consolidation of a target, are competing for temporary control over cognitive resources. Since this control is only relinquished as soon as the need for the resource dissipates, the ‘protect consolidation’-rule following the presentation of a first target can hinder a second target from being detected as long as the consolidation process is not resolved, resulting in an AB. In this case, an overexertion of control, implicating suppression of detection of a secondary target, leads to similar results as the ICT suggests. To wit and akin to the

ICT, the threaded cognition model explains the commonly produced proactive interference effect in dual-task studies by introducing a rule to tackle anticipated interference with an attentional suppression mechanism. Taken together, these perspectives and results show that external restraints have to be taken more into consideration in research designs in order to avoid biases and artefacts.

“All-or-none” principle

Experiment 2 showed that one source of interference resulted in saturated protection of T1 processing which could not be increased by adding another source of interference. Referring to Interference Control Theory, it could be hypothesized that once attention is suppressed, it is not possible to intensify this suppression, thus, there seems to be no gradation or level of suppression. It can only be influenced in a way that either protection of T1 processing is activated or deactivated. Consequently, and relating back to our initial main question whether or not an additional source of interference would result in stronger proactive interference, we can state that we did not find evidence in favour of this hypothesis. We, therefore, postulate that the protection of the processing of T1 has an underlying “all-or-nothing” mechanism.

In an EEG-study, Sergent, Baillet, and Dehaene (2005) found results corroborating this all-or-none hypothesis for attentional suppression. In order to disentangle the neural basis of conscious access, Sergent et al. (2005) investigated ERP components in an AB paradigm where they compared seen and missed second targets after subtraction of a condition in which T2 was not present at all. Interestingly, a divergence between blinked and seen trials was only found in later components (N3, P3a, and P3b) but not in earlier ones (N1, P1). The authors suggested that these findings can translate to a two-stage processing model in which the earlier components reflect superficial detection of a target and the later signify the capacity-limited second stage.

Most notably, the statistically non-significant results for these later components in AB trials were also reflected in the behavioural data in a rather extreme fashion. As participants had to rate the visibility of T2, items that were rated below 50% visibility did not evoke any statistically significant N3, P3a, or P3b activity at all. Furthermore, Sergent et al. (2005) found that in long SOA conditions early components evoked by T2 temporally coincided with late components signifying T1 processing which did not seem to affect each other. However, if T2 was presented shortly after T1, the tail end of the later P3b component evoked by T1 potentially overlapped with the timing for the N2 elicited by T2. The success or failure of T2 processing was dependent on stochastic variation of the duration of the T1-evoked P3b component, i.e. only if T1 processing happened to be fast and intense, T2 was not missed. Given these results, we witness older results cross-validating what we have found in our experiments. The waveforms reported by Sergent et al. (2005) acquired a dichotomous character depending on the presence or absence of total suppression which is comparable to our lack of a stronger proactive interference effect in experiment 2.

Future research

After our study, many questions are left unanswered. Among other things, we suggest that the minimal threshold of interference required to induce the protection of T1 processing should be investigated. Thus, future studies may focus on the degree of interference that has to be present to trigger this protection and various sources of interference that might cause this mechanism to activate. Furthermore, it is unclear whether the perceived risk of interference could be enough to trigger T1 protection since Bugg et al. (2015) showed that explicit, external expectation affected which mode of control was adopted. Additionally, the current study does not shed light on the underlying mechanism of T1 processing protection. Therefore, future studies may aim to uncover why or how exactly T1 processing is protected rather than to prefer processing of T2 if interference is expected.

Aside from that, our research raises questions about how dual-tasks paradigms should be used and focuses more on the context-dependent outcomes. How freely can we use interferences such as RSVP or simply a presentation of T2 at all trials in study designs? For instance, it could be argued that the high level of interference due to the high prevalence of the second task induced proactive interference in many attentional blink studies and that results might be different if T2 presence was manipulated. Nevertheless, other paradigms we did not touch on might have to be revisited as well. In the operation span (Ospan), participants are tasked with solving a math operation and memorizing a word. The amount of these items usually varies and the paradigm has been linked to measures of general fluid intelligence (gF; Unsworth & Engle, 2005). In fact, Unsworth, Fukuda, Awh, and Vogel (2014) already stated that a multitude of reasons causes this relationship including attentional control rather than solely focusing on individual differences working memory capacity limitations. However, based on our results, much more consideration has to be given to the role risk of interference plays in the Ospan and whether its results are context-dependent as well. The Ospan and attentional blink studies are merely examples for paradigms. Naturally, risk of interference could affect results of a multitude of tasks including task-switching paradigms or any other setup that necessitates the presence of multiple tasks. We, therefore, strongly recommend taking risk of interference in experimental designs into account.

Even though, we replicated the main results of Nieuwenstein et al. (2014), we failed to find the exact statistically significant three-way interactions between RSVP, T2 presence, and SOA on T1 accuracy that the original authors displayed. As stated earlier, we reason that this is caused by the unexpected and inexplicable decline in performance with increasing SOA if T1 was embedded in a stream of distractors without showing T2. The interesting part about this is that participants' performance did not generally deteriorate as a function of SOA. Furthermore, the time to wait until the response to T1 can be recalled and entered on the computer did not differ between the RSVP present or absent conditions. Considering T2 was absent in these conditions does not help solving this conundrum since it could not even have interfered with T1 processing. Future research could explore moderators that may cause this difference across studies.

General conclusion

In conclusion, our current study provided further evidence against an immutable, central bottleneck and supported the notion of a potential attentional control mechanism, which is activated depending on the anticipated interference. The activation that leads to suppression of incoming stimuli and protection of target processing can, however, not be increased by adding another source of interference and seems to follow an "all-or-nothing"-principle. This dichotomous nature of the mechanism leaves the question of when the threshold is reached that triggers the switch in attentional control. Apart from that, our replication continued to show that risk of interference is affecting research outcomes in the current cognitive-psychological literature and has to be taken into account in study designs in order to answer the desired questions and to study multi-tasking in daily life.

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Appendix 1: Supplementary Materials

Tables

Table 8

Experiment 1: Mauchley's test for sphericity on T1 Accuracy

Fixed Factors	Test Statistic	P Value
SOA	.66	.20
SOA * T2Presence	.76	.44
SOA * RSVP	.38	<.01
SOA * T2Presence * RSVP	.88	.81

Note: Mauchley's test for sphericity indicates whether the variances of the differences between all pairs of conditions is equal. If the p value is lower than the set α-level, sphericity is violated and an inflation of Type I errors might occur. In case sphericity is violated, a correction of the degrees of freedom should be applied.

Table 9

Experiment 1: Mauchley's test for sphericity on T2 Response Time

Fixed Factors	Test Statistic	P Value
SOA	.53	.05
SOA * RSVP	.89	.84

Note: For additional information on Mauchley's test see supplementary materials Table 8.

Table 10

Experiment 1: Post-hoc analysis of T2RT in RSVP absent only condition

Effect	Estimate	SE	df	P
400-300	-47.87	10.7	57	<.001
600-300	-45.49	10.7	57	<.001
800-300	-17.77	10.7	57	.35
600-400	2.38	10.7	57	.99
800-400	30.1	10.7	57	.03
800-600	27.72	10.7	57	.06

Note: Due to the multitude of post-hoc testing, the Tukey correction was performed in order to preserve unbiased results.

Table 11

Original and Replication: Mauchley's test for sphericity on T1 Accuracy

Fixed Factors	Test Statistic	P Value
SOA	.92	.52
SOA * RSVP	.88	.3
exp*SOA	.92	.52
exp*SOA*RSVP	.88	.3
SOA*T2Presence	.94	.68
exp*SOA*T2Presence	.94	.68
SOA*RSVP*T2Presence	.98	.97
exp*SOA*RSVP*T2Presence	.98	.97

Note: For additional information on Mauchley's test see supplementary materials Table 8.

Table 12

Original and Replication: Mauchley's test for sphericity on T2 Response Times

Fixed Factors	Test Statistic	P Value
SOA	.74	.02
SOA * RSVP	.76	.02
exp*SOA	.74	.02
exp*SOA*RSVP	.74	.02

Note: For additional information on Mauchley's test see supplementary materials Table 8.

Table 13

Experiment 2: Mauchley's test for sphericity on T1 Accuracy

Fixed Factors	Test Statistic	P Value
SOA	.66	.29
SOA * RSVP	.51	.08

Note: For additional information on Mauchley's test see supplementary materials Table 8.

Table 14

Experiment 2: Mauchley's test for sphericity on T2 Response Time

Fixed Factors	Test Statistic	P Value
SOA	.41	.02
SOA * RSVP	.65	.27

Note: For additional information on Mauchley's test see supplementary materials Table 8.

Table 15

Experiment 1 & 2: Mauchley's test for sphericity on T1 Accuracy – T2 Present only

Fixed Factors	Test Statistic	P Value
SOA	.69	.03

SOA * RSVP	.94	.82
exp*SOA	.69	.03
exp*SOA*RSVP	.94	.82

Note: For additional information on Mauchley's test see supplementary materials Table 8. Here, only T2 present trials were used.

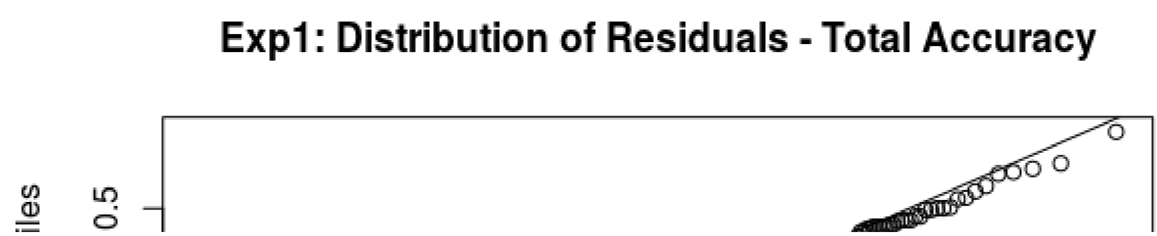
Table 16

Experiment 1 & 2: Mauchley's test for sphericity on T2 Response Times

Fixed Factors	Test Statistic	P Value
SOA	.68	.02
SOA * RSVP	.88	.54
exp*SOA	.68	.02
exp*SOA*RSVP	.88	.54

Note: For additional information on Mauchley's test see supplementary materials Table 8.

Figures



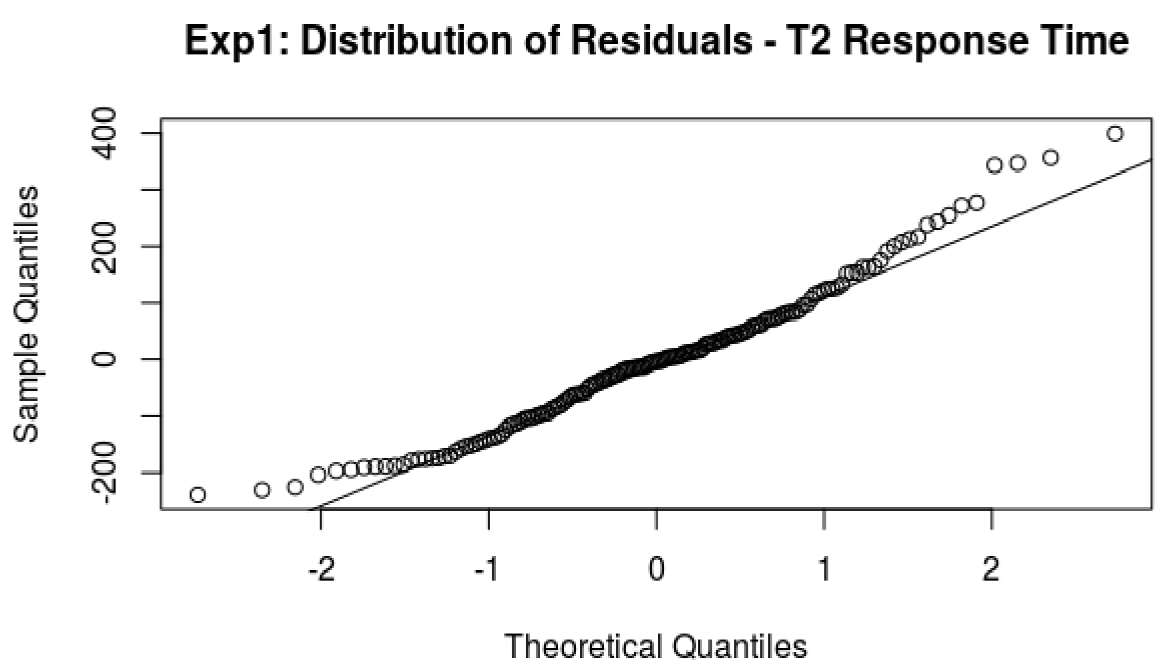


Figure : The distribution of the sample residuals compared to a theoretical normal distribution as obtained by a qq-plot. The model used to acquire this qq-plot was comprised of SOA and RSVP with T2 response time being the dependent variable.

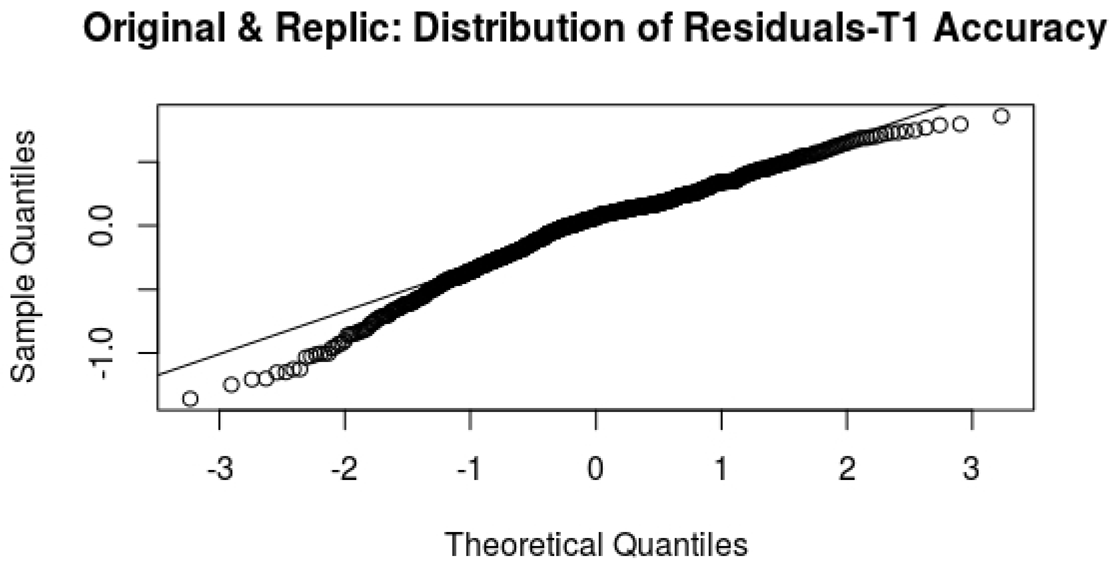


Figure 1: The distribution of the sample residuals compared to a theoretical normal distribution as obtained by a qq-plot. The model used to acquire this qq-plot was comprised of SOA, T2 Presence, and RSVP with T1 accuracy being the dependent variable.

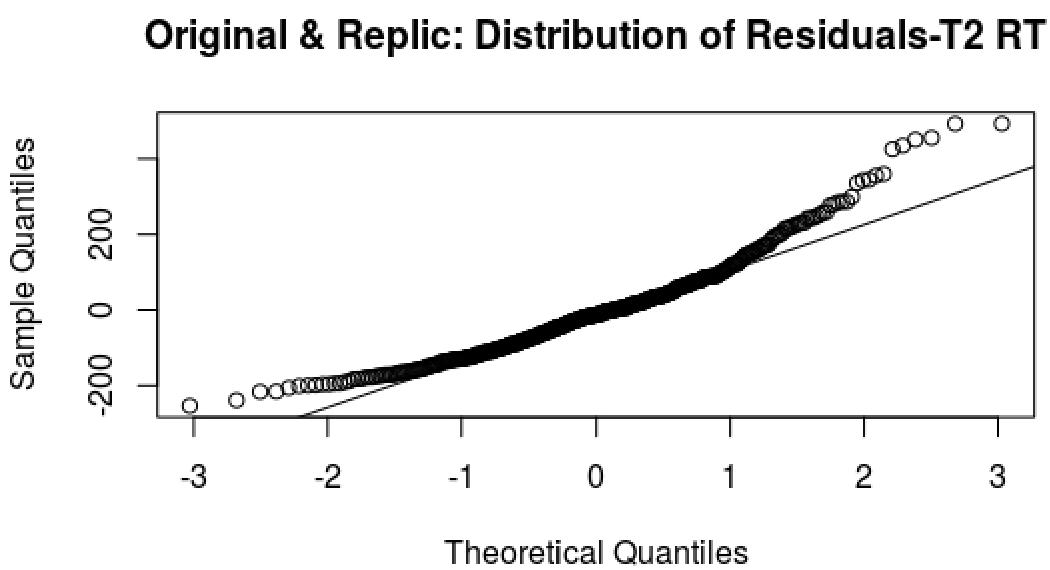


Figure 2: The distribution of the sample residuals compared to a theoretical normal distribution as obtained by a qq-plot. The model used to acquire this qq-plot was comprised of SOA and RSVP with T2 response times being the dependent variable.

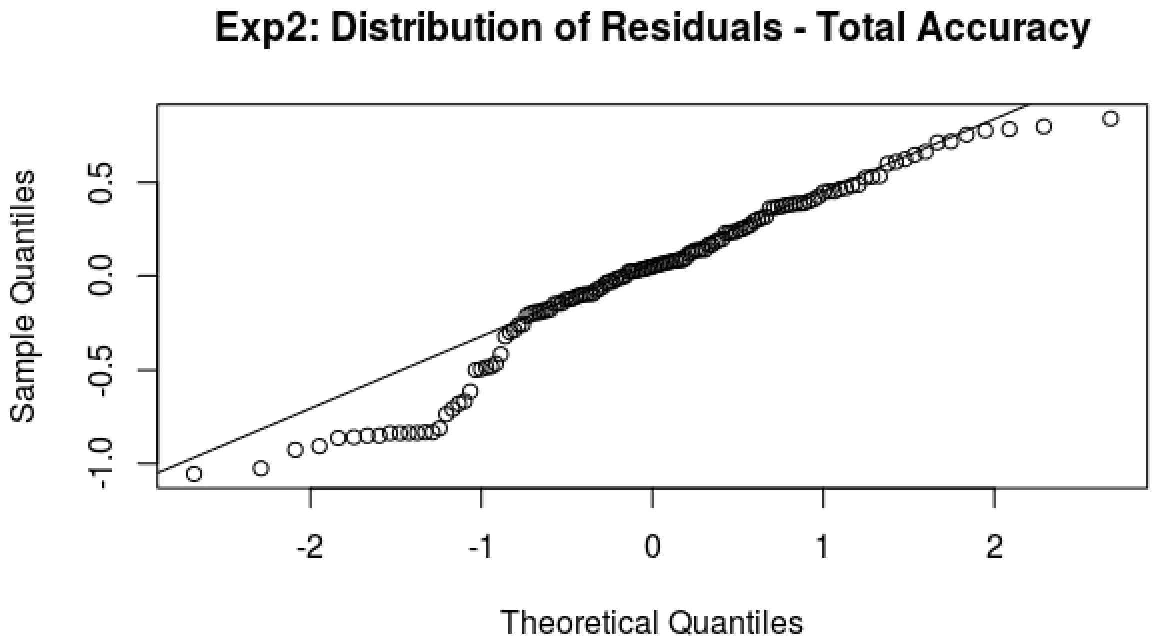


Figure 3: The distribution of the sample residuals compared to a theoretical normal distribution as obtained by a qq-plot. The model used to acquire this qq-plot was comprised of SOA and RSVP with T1 accuracy being the dependent variable.

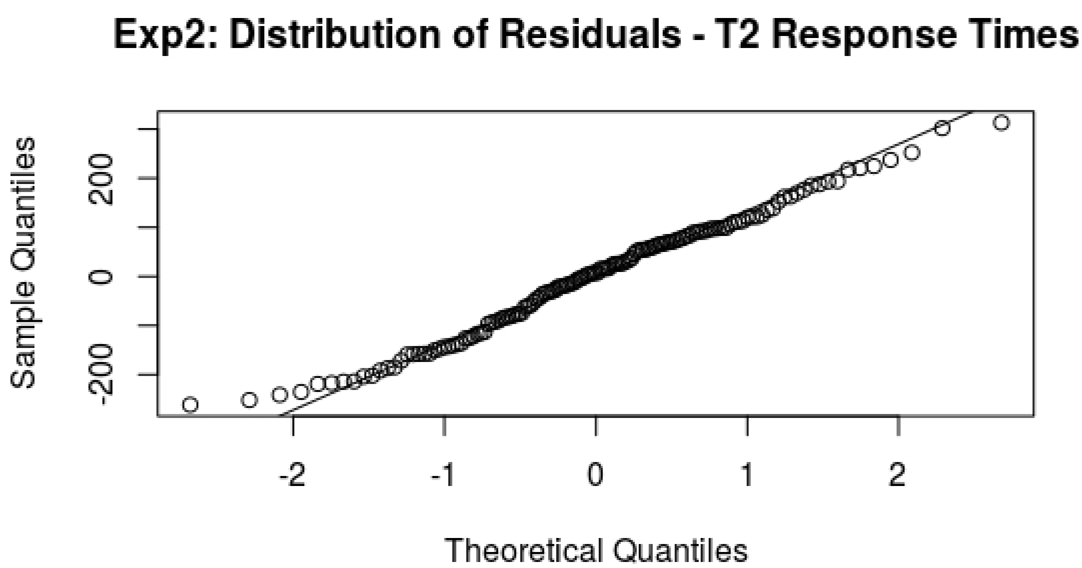


Figure 4: The distribution of the sample residuals compared to a theoretical normal distribution as obtained by a qq-plot. The model used to acquire this qq-plot was comprised of SOA and RSVP with T2 response times being the dependent variable.

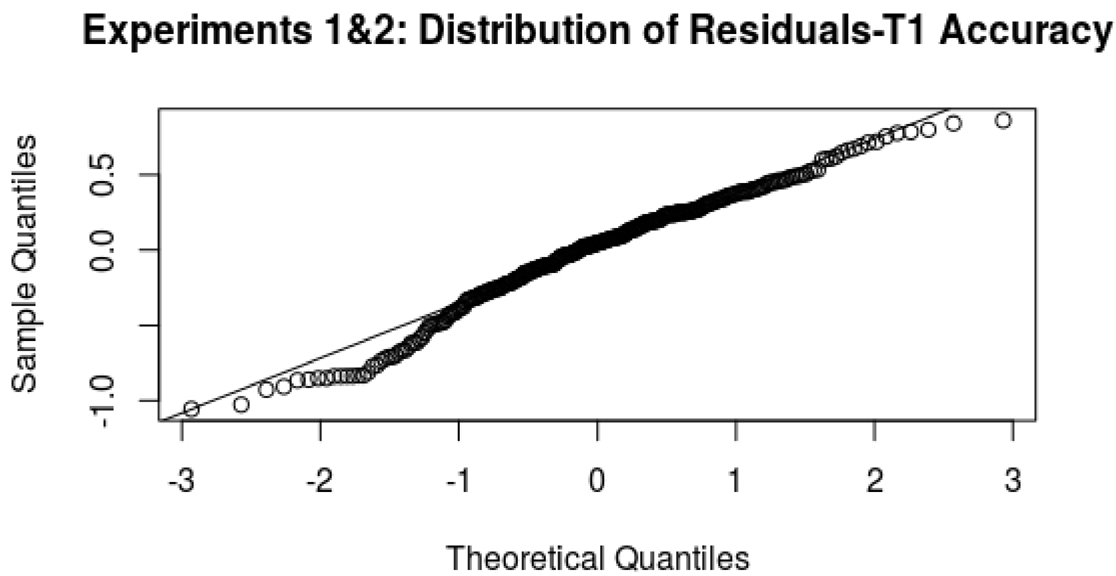


Figure 16: The distribution of the sample residuals compared to a theoretical normal distribution as obtained by a qq-plot. The model used to acquire this qq-plot was comprised of SOA and RSVP with T1 accuracy being the dependent variable.

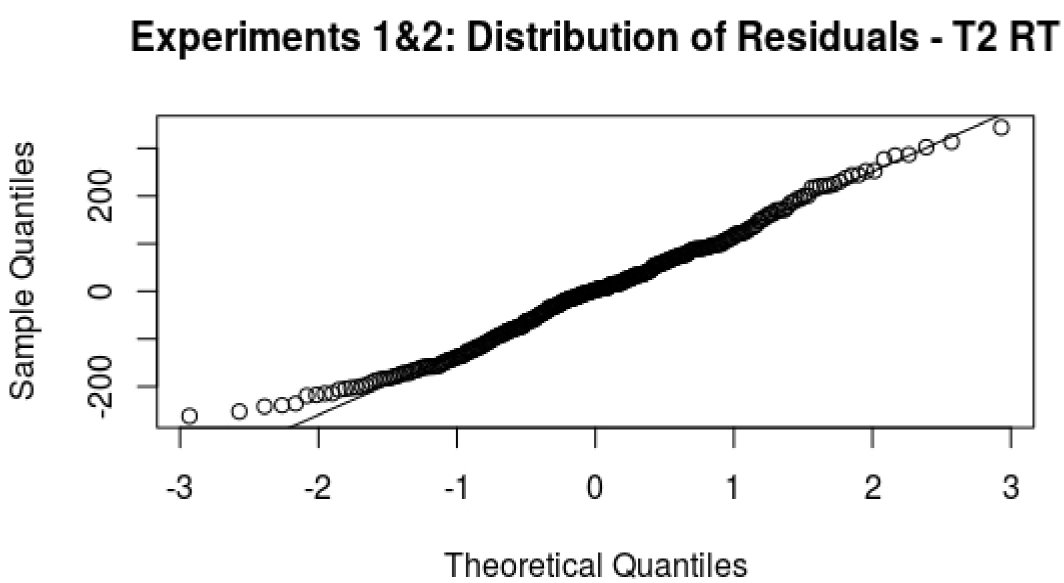


Figure 17: The distribution of the sample residuals compared to a theoretical normal distribution as obtained by a qq-plot. The model used to acquire this qq-plot was comprised of SOA and RSVP with T2 response times being the dependent variable.