Probing the dual-task structure of a metacontrast-masked priming paradigm with subjective visibility judgments

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Abstract

Experiments contrasting conscious and masked stimulus processing have shaped, and continue to shape, cognitive and neurobiological theories of consciousness. However, as shown by Aru et al. (2012) the contrastive approach builds on the untenable assertion that there are no interactions among the stimulus- and response-related components of a task. While no-report paradigms avoid this violation of pure insertion, it seems necessary to understand the cognitive interactions in other paradigms where the removal of response-related components is not an option. Our research will therefore start from the simple observation that report-based paradigms often qualify as dual-tasking situations.

We will investigate the dual-task architecture of the most widely used report-based paradigm in the study of unconscious processing. In masked priming, the prime's visibility can be assessed with a subjective measure on a trial-by-trial basis. Despite the inverse order of stimuli (prime-target) and responses (target-prime), and although only the target response is speeded, the experimental setup meets the criteria of a dual-task paradigm. Our aims are twofold: to estimate the influence of response-related parameters on the masked priming effects, and to study the neural underpinnings of our dual-tasking manipulations.

In a metacontrast masking experiment using event-related potentials (ERPs), participants will discriminate a target stimulus by quickly pressing one of two keys, and then indicate the subjective visibility of the prime stimulus, either by vocal response or by key-press (factor "modality"). The visibility measure will be a variant of the perceptual awareness scale (PAS) with either two or four items (factor "complexity"). We will investigate in what way response modality and task complexity influence the masked priming effect (i.e., incongruent trials – congruent trials). With regards to the ERPs, we expect that both experimental manipulations are related to the amplitude and latency of the target-related P3b component.

Introduction

Whether and to what extent unconscious processing is possible has sparked research interest for decades. One very commonly used paradigm is the masked priming paradigm, the idea that the prime facilitates a speeded reaction to the target when both stimuli are congruent, e.g., arrows point in the same direction, or inhibits it when stimuli are incongruent, e.g., arrows point in different directions. This so-called priming effect can be observed even when the prime is not consciously perceived.

Various aspects of the masked priming experiment have been looked at. Among these were the type of priming: semantic (Dehaene et al., 1998; Kiefer~~, Harpaintner,~~ et al., 2023b) vs. response priming (e.g., Mattler, 2003; Vorberg et al., 2003), the masking technique used: metacontrast masking (e.g., Mattler, 2003; Vorberg et al., 2003), continuous flash suppression (Benthien & Hesselmann, 2021; Handschack et al., 2022) and backwards masking (e.g., Balsdon & Clifford, 2018; Stein et al., 2020) to only name a few, the type of the direct, prime-related task: objective or subjective measures of prime visibility (Biafora & Schmidt, 2022; Kiefer~~, Harpaintner,~~ et al., 2023b), and the analysis approach: standard dissociation, sensitivity dissociation or double dissociation (for an overview, see Schmidt & Vorberg, 2006).

We will be exploring the concept response priming, utilising arrows as primes and targets, for which priming is the result of visuomotor processes. In semantic priming, in contrast, priming stems from access to word meaning (see Martens et al., 2011 for more detail).

In a typical masked priming experiment, the masked prime is followed by the target, to which the participant has to react first in a speeded forced-choice identification task, the indirect task. The direct task then follows and typically requires a non-speeded reaction of some sort to the prime. The masked priming effect is then calculated by quantifying the difference in reaction times (RTs) between congruent and incongruent trials.

Indirect and direct task have been presented together (e.g., Stein et al., 2021) as well as in separate trials (e.g., Biafora & Schmidt, 2019). Biafora and Schmidt (2022) combined both approaches and compared a single-task condition (either only indirect or direct task) with a dual-task condition, for which they instructed participants to perform both a target (mask) identification task and a prime identification task on the same trial (experiment 2). The authors observed increased RTs and larger priming effects in the dual-task as compared to the single-task condition.

It is a relatively new aspect to consider the experiments' inherent dual-tasking character, which arises when both tasks occur in the same trial. In the study of dual-tasking, it was shown that trials without a prime-related response, i.e., single-task, lead to shorter target-related RTs than trials with an online prime-related response, i.e., dual-task (Biafora & Schmidt, 2022; Hesselmann et al., 2018; Jimenez et al., 2023; Lamy et al., 2017). Lamy and colleagues (2017) found RTs up to 150 ms slower than RTs in comparable single-task response priming experiments, like that of Vorberg et al. (2003). This increase in RT is also called dual-task costs, a term describing the result that people tend to perform worse in dual-task as compared to single-task (Janczyk et al., 2015).

The potential implications of this phenomenon for the masked priming paradigm remain an open question, specifically, to what extent and in what direction dual-tasking may influence the masked priming effect (Hesselmann et al., 2018). Research findings could demonstrate a greater priming effect in single-task when compared to dual-task scenarios, as reported by Ansorge (2004) and Avneon & Lamy (2018), as well as an increased priming effect in dual-task when compared to single-task scenarios, as observed by Biafora & Schmidt (2022). Lamy, Carmel and Peremen (2017) found similar response priming effects in single and dual-task situations utilizing pattern backward masking. The authors paired a typical target identification task with an online prime visibility rating using the PAS scale (dual-task condition), as did Jimenez and colleagues (2023), who did not find a priming effect at all.

Kiefer and colleagues (Kiefer~~, Harpaintner,~~ et al., 2023b) tested participants in a semantic priming experiment, in which they had to assess the prime's visibility via a perceptual awareness scale (PAS) on a trial-by-trial basis or in a separate session. This study found that semantic priming effects vanished in the trial-by-trial PAS condition. Similarly, Fischer and colleagues (2011) observed a reduction of semantic priming to a non-significant level in the presence of a dual-tasking context. Interestingly, current research suggests that trial-wise prime visibility ratings lead to a decrease in semantic priming, as observed in the studies mentioned above, but to an increase in response priming (e.g., Biafora & Schmidt, 2022). Kiefer and colleagues (Kiefer~~, Harpaintner,~~ et al., 2023b) describe mechanisms altering prime-related processes, that offer an explanation. The trial-by-trial awareness rating may lead to (1) an emphasis of an attentional focus to perceptual features of the prime, to (2) a reduction of attentional capacity or an addition of attentional demands as compared to a single-task situation, and to (3) response-related interference due to an increase of non-decisional process components like response-related processes. While the first mechanism would enhance response priming, the latter two would reduce it, and therefore, depending on the net contribution of these mechanisms, trial-wise visibility ratings can either lead to enhanced or reduced response priming as compared to a single-task situation (Kiefer~~, Frühauf,~~ et al., 2023a). In our study, we are therefore interested in further exploring the influence of the dual-tasking structure of report-based paradigms on the masked priming effect. The unconscious priming experiment acquires the characteristics of a dual-task situation by presenting both tasks in the same trial. Lamy et al. (2019) argue for doing so, as it ascertains that “the measures of conscious perception and of prime processing are collected under the same stimulus, attention, and motivational conditions” (p.123). Otherwise, the problem of task comparability may arise. One could also argue that, while no-report paradigms avoid this violation of pure insertion, only products of cognitive functions (i.e., verbal report, key press) allow for consciousness to be studied empirically (Cohen & Dennett, 2011), and that no-report paradigms may be considered as problematic, since participants may be engaging in post-perceptual cognitive processing even in the absence of reports (Block, 2019).

In the following paragraphs, we will describe our choice of the metacontrast-masked response-priming paradigm for the purpose of exploring dual tasking in the study of unconscious processing, the rationale behind our experimental manipulations of response modality and response complexity, as well as the concurrent recording of event-related potentials (ERPs).

Masked priming and Dual-tasking

We aim to utilize an unconscious priming paradigm that would promise relatively robust priming effects. In response priming experiments, the crucial variation is whether the prime (e.g., left or right pointing arrow) is either compatible or incompatible with the response the target requires (e.g., left or right, Haase & Fisk, 2015; Vorberg et al., 2003). That is, in case of compatibility, or congruency, the prime facilitates the response to the target, and in return inhibits it in case of incompatibility, or incongruency. One commonly used experimental design in the line of masked (unconscious) priming research is metacontrast masking (e.g., Breitmeyer, 2015; Mattler, 2003; Vorberg et al., 2003). In metacontrast masking, the prime's visibility is reduced by an ensuing visual masking stimulus, and is therefore said to be a special form of visual backward masking (Kraut & Albrecht, 2022). Crucially, the target simultaneously functions as the mask and fits snugly around the prime contours without overlapping it. The prime's visibility is assessed to ensure that the masked prime was in fact not consciously perceived. As outlined above, if both tasks are presented together on a trial-by-trial basis, the masked response-priming paradigm acquires the structure of a dual-task.

A prototypical example of a dual-task situation is the psychological refractory period paradigm (PRP), where response times (RTs) for task 2 slow down with decreasing SOA when compared to single-task (Telford, 1931; Tombu & Jolicœur, 2003). However, studies have also found increasing RTs for task 1 when performed in a PRP paradigm instead of in isolation (Jiang et al., 2004; Reinert & Brüning, 2022; Scerra & Brill, 2012; Sigman & Dehaene, 2006). The Backward Crosstalk Effect (BCE), i.e., "the observation that task 2 characteristics can even influence task 1 processing" (Janczyk et al., 2018, p. 1) provides an explanation for this phenomenon. According to Janczyk and colleagues, the task 2 stimulus might unintentionally and simultaneously activate (features of) the task 1 response if the two responses share characteristics. We are therefore interested in how manipulations of the task 2 (our direct task) characteristics might influence RTs and consequently priming effects for task 1 (our indirect task)[1]. We expect RTs to be prolonged in the dual-task as compared to the single-task condition. Based on the study by Biafora and Schmidt (2022) who observed a larger priming effect in the dual-tasking situation as compared to the single-task, we also expect priming effects to be enhanced in the dual-task.

Studies in the research of dual-tasking have focused on different aspects of the paradigm like individual preferences for task coordination strategies (e.g., Brüning, Mückstein, et al., 2020; Brüning, Reissland, et al., 2020), order and temporal sequence of tasks (e.g., Strobach et al., 2018; Tombu & Jolicœur, 2002) or the kind of task (e.g., Goh et al., 2021; Hazeltine et al., 2006). We chose to focus on the two aspects task modality and task complexity, which are described in the following.

Response Modality

Scerra and Brill (2012) tested participants in several multitasking experiments, in which the input of both tasks was either presented in the same modality (unimodal dual-task condition) or via different modalities (visual prime and target; tactile and visual or tactile and auditory, cross modal dual-task condition). The authors observed a decrement in performance in all dual-task conditions compared to the single-task condition, which was especially pronounced in the unimodal dual-task condition. We argue that this might be of relevance for an unconscious

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[1] Please note that we will use the following nomenclature in our manuscript: stimulus 1 denotes the prime, stimulus 2 the target/mask, while task 1 is the speeded response to the target, and task 2 is the unspeeded response to the prime (i.e., in chronological order, as instructed).

priming paradigm, since the input of both tasks, i.e., the prime and the target, are typically presented in the same modality (visual). If the two responses also share features, it could be that the stimulus of task 2 simultaneously activates (features of) the task 1 response, which may then lead to between-task crosstalk (Janczyk et al., 2018).

Since the input modalities of both tasks cannot be changed in the case of masked response priming, the question arises what may happen, when the output, i.e., the response modalities, are manipulated. Göthe et al. (2016) tested multiple variations of input-output modality pairings and observed higher dual-task costs for non-standard modality pairings (e.g., visual stimulus mapped to vocal response and auditory stimulus mapped to manual response) as compared to respective standard pairing (e.g., visual stimulus mapped to manual response and auditory stimulus mapped to vocal response). The authors conclude that for non-standard pairings, crosstalk was present, but for standard feature pairings is was absent. These findings were replicated by Stelzel et al. (2006).

Since dual-task costs arise in the form of prolonged RTs in task 2, but as was shown, in task 1 as well, this may have considerably consequences for the observed priming effects. Following this line of arguments, it seems advisable to keep the input/output modality pairings for both tasks concordant, as otherwise dual-task costs due to crosstalk may arise.

However, as early as in the 1970s it was observed that the decrement in performance (measured via error scores), that is typically observed in dual-task situations, was affected by the modality of the second, added task: the error rates were larger when both tasks had to be responded to manually as compared to a cross-modal condition of manual and vocal responses (McLeod, 1977). The author explained this with response interference, which is to be expected when the two tasks share one common processing requirement. Liu and Wickens (1987) found a similar effect: they observed a greater performance decrement (measured via reaction time and weighted workload ratings) in a tracking task when the second task required a manual response than when it required a vocal response. The authors argue that the multiple resource model is capable of predicting the interference of the tracking task, which is greater for a manual than a vocal response to the second task.

According to resource theories, the performance of two tasks suffers when both draw from the same resources (Schacherer & Hazeltine, 2021). When tasks on the other hand require distinct resources, dual-task costs are reduced. In line with this is the observation that manual and vocal responses can be timeshared to a relatively high degree of efficiency, which has been explained by the separation of spatial and verbal resources (Wickens, 2002).

Arnell and Duncan (2002) observed a drop in accuracy for auditory and visual identification tasks when moving from single to dual-task, and the “performance was very much worse, however, when both streams were in the same modality, either both auditory or both visual” (p.110). Since responding to two tasks with the same response modality (key press) requires drawing from the same resource, resource theories predict higher interference for both tasks.

It will therefore be the first main purpose of the proposed study to test whether a unimodal response condition, i.e., manual response in both tasks, leads to prolonged RTs, i.e., dual-task costs as compared to a cross modal response condition, i.e., manual and vocal response.

The addition of a trial-wise prime visibility rating may introduce response-related interference, which might reduce response priming (Kiefer~~, Harpaintner~~ et al., 2023b) and could be further enhanced in a unimodal response condition. Therefore, we will also test whether a unimodal response condition leads to decreased priming effects as compared to a cross modal response condition.

Since the first task, the speeded two-choice identification of the shown target, is crucial to calculate a priming effect, we decided against changing any aspect of it for a block-wise manipulation and therefore varied the response modality for the second, direct task. Following the study by Göthe and colleagues (2016) we will instruct participants to provide their response to the direct task either via key press or via vocal response into a microphone.

Task Complexity

For the observation of increasing RTs for both task 1 and task 2 (e.g., Tombu & Jolicœur, 2002, 2003), Wickens (1981) offers an explanation, arguing that tasks require resources for their performance, which are limited in their availability. When more resources are needed than are available the efficiency with which both tasks are shared decreases, and this will be more likely so with increased difficulty of either tasks.

In line with this argument are observations from Sigman and Dehaene (2005), who tested participants in a dual-task experiment and found increased subject's mean RTs in the more complex condition (two key presses as compared to one), as well as from Vaportzis and colleagues (2013), who found greater dual-task costs in their complex choice RT condition, in which they had manipulated the amount of stimuli being presented as well as the amount of choices participants could choose from for their response. The authors measured dual-task costs by means of RTs and error rates.

Fischer et al. (2007) manipulated difficulty of task 2, in which participants had to judge numbers as smaller or larger than 5, by varying the numerical distance of target numbers, and interpreted their findings "as an overall effect of task 2 difficulty on RT1" (p.1694). The authors argue that a greater distance (i.e., 2 is farther away from 5 than 4) makes for low resource demands in task 2 processing and leads to faster responses in task 1, whereas increased resource demands in task 2 predict larger RT1.

The literature offers no consensus as to what 'task difficulty' and 'task complexity' specifically are. Important to note is that both terms are used interchangeably in the literature (Peng Liu, 2012). In a study by Tombu and Jolicœur, *difficulty* refers to different manipulations, like visual contrast or difficulty of stimulus-response mapping. Vaportzis and colleagues (2013) manipulated *complexity* by different amounts of presented stimuli and options to choose from, as did McDowd and Craik (1988), who defined the increase in complexity as "associated with a greater degree of choice" (p.276). In our study, we will follow the definition by McDowd &

Craik (1988) and will therefore vary the number of options participants will need to choose from for their response. We will call this manipulation *task complexity*. It will be the second main purpose of the proposed study to test whether a high task complexity leads to prolonged RTs i.e., dual-task costs as compared to a low task complexity. The addition of a trial-wise prime visibility rating might also add attentional demands (Kiefer~~, Harpaintner~~ et al., 2023b), which we expect to be even more enhanced by our complexity manipulation: a greater degree of choice might reduce attentional capacity even more. We will therefore also test whether a high task complexity leads to decreased priming effects as compared to a low task complexity. In our study, we decided to use the subjective PAS. See the section below for our reasoning behind this choice.

In order to manipulate task complexity, we will change the number of items participants can choose from. For the high-complexity condition there will be four items, and we adapted the original labels (‘No experience’, ‘brief glimpse’, ‘almost clear image’ and ‘absolutely clear image’) to mirror more accurately our experimental setup. We decided on a scale ranging from 0 to 3 comprising the elements: “I did not see the arrow at all”, “I had a brief glimpse of the arrow but cannot say in which direction it pointed”, “I saw the arrow almost clearly”, and “I saw the arrow clearly“. For the low-complexity condition, there will only be two items: 0 – “I have not seen the arrow” and 1 – “I have seen the arrow”, and we coined this the dichotomous subjective measure. All items were translated into German.

Choice of visibility measure

In masked priming experiments, objective visibility measures generally exist in form of a forced-choice discrimination of the prime, and performance above chance level is taken as an indicator for awareness of the stimulus (Hesselmann, 2013; Jimenez et al., 2023). Subjective visibility measures, on the other hand, require participants to introspectively report their experience of the prime stimulus (Lin & Murray, 2014; see Overgaard, 2015 for an overview of both approaches). While it has been reported that the extent of unconscious information processing is influenced by the measurement approach (Stein et al., 2021), recent evidence also shows that subjective and objective measures can converge, indicating that both measures allow to validly capture the content of awareness (Kiefer et al., 2023a; Kiefer & Kammer, 2024). In our study, we chose a variant of the subjective PAS because: a) it allowed us to straightforwardly vary the level of task complexity by using different numbers of labels, and b) it is widely used in current research.

ERPs

A number of previous ERP studies investigating the PRP effect have targeted the amplitude and latency of the P3b component, which is characterized by a positive deflection broadly distributed over the scalp, with a focus over parietal electrodes (Picton, 1992). The P3b has been associated with post-perceptual processes such as the context-updating of working memory (Donchin, 1981; Donchin & Coles, 1988), decision-related processing (Verleger et al., 2005), and the access of a target stimulus to a global neuronal workspace necessary for conscious report (Del Cul et al., 2007; Sergent et al., 2005; see Verleger, 2020 for a review). Previous dual-task investigations have provided evidence for a sensitivity of P3b amplitude to dual-task interference (Kok, 2001). Based on the observation that P3b latencies showed significant postponement directly proportional to the PRP effect, some studies have proposed that the P3b component primarily indexes the central cognitive processes mediating the PRP effect (Dell'Acqua et al., 2005; Hesselmann et al., 2011; Sigman & Dehaene, 2008).

Previous studies also examined effects on the P3b amplitude and found a significant reduction in dual-task as compared to single-task conditions (Kida et al., 2012a, 2012b), which has been interpreted as the P3b amplitude being affected by allocated attentional resources (Thurlings et al., 2013). Other studies, on the other hand, observed no difference in P3b amplitude under single- and dual-task conditions (e.g., Kasper et al., 2014).

The latencies of earlier sensory ERP components, such as the P1 and N1, have been consistently reported to remain stimulus-locked to both targets and show no postponement related to dual-tasking (Brisson & Jolicœur, 2007; Sigman & Dehaene, 2008). In this context, the main question of our study was whether the target-related P3b responses would show a differential amplitude depending on the different dual-task manipulations.

The literature offers suggestions as to what effects might be expected from our manipulations. While, to our knowledge, effects of task difficulty on P3b latency were not observed, task difficulty was found to lead to a decrease in the P3 amplitude in dual-task situations (Isreal et al., 1980; Liebherr et al., 2018). Isreal and colleagues observed a monotonical decline in P3 amplitude with the increase in task difficulty, which was defined as display load from zero to four to eight elements, while Liebherr and colleagues observed a reduction in the positivity between 350 and 500 ms after stimulus onset when participants had to differentiate between odd and even numbers as well as between consonants and vowels, instead of just between numbers and letters. We therefore expect P3b amplitude to decrease with increasing task complexity.

To our knowledge, the influence of response modality on the P3b has not been studied so far; therefore, no leads are available within the literature as to which effects may be reasonably expected. Previous studies have only looked at the effects of input modality on the P3b, and found, for example, larger P3b amplitudes for the visual as compared to the auditory input modality in single tasks (Kasper et al., 2014; Knott et al., 2003) as well as in dual-task situations (Sangal & Sangal, 1996). We are therefore agnostic to the way in which a manipulation of response modality of the direct task might influence the target-related P3b in a dual-tasking paradigm.

Methods

We report how we determined our sample size, all data exclusions, all manipulations, and all measures in the study (Simmons et al., 2012). The procedures of the priming experiment were approved by the local ethics committee (approval number EK2024/3),.

Participants

Participants will be recruited via advertisement on our department's homepage. We expect to recruit mainly students of the Psychologische Hochschule Berlin (PHB), who will be able to attain course credit as a reward for participation. To be included in the study, participants will be required to have normal or corrected-normal vision, which will be assessed via self-report. Criteria for exclusion from the study will be a history of any neurological illness and general feelings of ill-being like headaches or colds at the time of the experiment. Participants will have the freedom to stop the experiment at any time and to withdraw their consent to the use of their data. Participants will be excluded from data analysis if they fail to complete the experiment as intended by protocol. Reason may be an erroneous answering to the tasks or interruption of the experimental session due to failures of apparatus or software. All participants will provide informed written consent.

~~In G*Power 3.1.9.7 (Faul, Erdfelder, Lang, & Buchner, 2007) we calculated the sample size for the repeated measures 2x2x2 ANOVA using a medium effect size f (0.25; partial eta squared = 0.06) for the main effects (Cohen, 1988). Assuming a mean correlation between repetitions of 0.5, we determined that for f = 0.25, and alpha = 0.05, a sample size of N = 34 was required to achieve a power of 0.80 (measurements: 2; groups: 1).~~ In G*Power 3.1.9.7 (Faul, Erdfelder, Lang, & Buchner, 2007) we calculated the sample size for main effects (modality, complexity and consistency; measurements: 2; groups: 1) and 2x2 interaction effects (modality x consistency, complexity x consistency; measurements: 4; groups: 1) in a 2x2x2 ANOVA, with factors modality, complexity, consistency. We also calculated the sample size for main effects (task type, consistency; measurements: 2, groups: 1) and a 2x2 interaction effect (task type x consistency; measurements: 4, groups: 1) in a 2x2 ANOVA, with the factors task type and consistency. Assuming a mean correlation between repetitions of 0.5, we determined that for a medium effect size f (0.25, partial eta squared = 0.06, Cohen, 1988) for the main effects, and alpha = 0.05, a sample size of N = 34 was required to achieve a power of 0.80. For a medium effect size f for the interaction effects and alpha = 0.05, a sample size of N = 24 was required to achieve a power of 0.80. The largest calculated N determines our sample size: N = 34 (see Design Template for details).~~In G*Power 3.1.9.7 (Faul, Erdfelder, Lang, & Buchner, 2007) we calculated the sample size for main effects (measurements: 2; groups: 1) and interaction effects in a 2x2 ANOVA (measurements: 4; groups: 1). The largest calculated N determines our sample size. Assuming a mean correlation between repetitions of 0.5, we determined that for a medium effect size f (0.25, partial eta squared = 0.06) for the main effects (Cohen, 1988), and alpha = 0.05, a sample size of N = 34 was required to achieve a power of 0.80.~~

Apparatus and Stimuli

The participants will be seated in a dimly lit room in front of a Samsung Samtron 98PDF CRT-Monitor (1280 x 1024 pixels, refresh rate 85 Hz, grey: 31 cd/m^2) at a viewing distance of approximately 60 cm. They will be asked to rest their chin on an adjustable chin rest, to assure that they will be as still as possible so as not to introduce noise in form of muscle artefacts to the EEG data, and to assure a consistent distance to both microphone and monitor.

The experiment will be created in the PsychoPy (v2022.2.4) Builder interface of Python and will be aided by Code components to implement the microphone. The prime and mask stimuli we will use are provided in Figure 1. All stimuli are black arrows. Primes will have an edge length of 0.8 cm, (0.76° x 0.29° of visual angle), and targets/mask will have an edge length of 2.8 cm (2.67° x 0.86°). Both appear in the centre of the screen. Targets, which simultaneously function as masks, have an additional cut-out corresponding to the superposition of both left and right prime-arrow, so that prime and mask share adjacent but nonoverlapping contours and both prime shapes can be masked by metacontrast (Haase & Fisk, 2015). Each trial will start with a black fixation cross in the centre of a grey background (edge length 0.3 cm).

In blocks A to D, the experiment consists of two different tasks that have to be performed within the same trial (dual-tasking condition). Participants will perform a speeded target/mask identification task (speeded two-choice identification task) and a non-speeded visibility rating of the prime using a PAS.

Block E will contain the single-task condition and will only require participants to perform in the speeded two-choice identification task. Block F, finally, will hold a non-speeded two-choice prime identification task, to attain an objective measure for prime visibility. Block F will be administered the same day as the other blocks if participants' time and patience allow to do so. Otherwise we will ask participants to return for a second session, which will not require EEG.

With the two-choice identification of the target, we will be measuring response priming as a measure of prime processing in congruent and incongruent trials (i.e., indirect task). The PAS will serve as the subjective measure of prime visibility(i.e., direct task).

Design

Our experiment will hold a total of 10 conditions: congruency (congruent vs. incongruent) and block (A, B, C, D, E). Please note that we will use only a single SOA due to time constraints We are primarily interested in a paradigm of low or reduced visibility (Handschack et al., 2022, 2023), since the main purpose of this study is to investigate the influence of a dual-tasking structure and that of manipulations of task 2 on RTs and priming effects.

Following a recommendation of Schmidt et al. (2011) there will be 60 trials per condition, so that each participant will test in 600 trials. Bartholow and colleagues (2009) advise the utilization of around 30% of prime-only trials, in order to be able to calculate corrected target ERPs that are not confounded by prime-related activity. However, since we are interested in only the target-related ERPs, which will be assessed during the indirect task, and all blocks will contain the same confounding because the experimental manipulations will only affect the direct task, our design will not include prime-only trials. We will employ five catch-trials, i.e., trials without a prime stimulus, to ensure correct use of the PAS.

EEG acquisition

Continuous EEG recordings will be acquired from 32 channels using an actiCHamp Plus EEG amplifier with one 32-channel module and the actiCAP electrode cap with 32 active electrodes (BrainProducts, Germany); the EEG electrodes will be placed on the scalp according to a customized 10-20 system. Four additional electrodes will be dedicated to the horizontal and vertical electrooculogram (EOG). Electrode impedances will be kept close to 25kΩ EEG will be sampled at 500 Hz and bandpass-filtered online between 0.016 and 250Hz.

EEG pre-processing

EEG data will be preprocessed and analyzed using EEGLAB 2023.1 (Delorme & Makeig, 2004) running on Matlab R2019b (The Mathworks, USA) for all further pre-processing and analysis. EEG data will bandpass-filtered offline (.1-40 Hz), and epoched (.2-1.2 sec, time-locked to target onset). Independent-component analysis (ICA) will be performed on the ~~concatenated single-trial~~continuous EEG data, using the extended INFOMAX algorithm as implemented in EEGLAB (Bell & Sejnowski, 1995). The resulting 32 ICs will be automatically classified using the ADJUST toolbox (Mognon et al., 2011) and rejected if classified as artifact (i.e., eye blink, eye movement, and generic discontinuity).

Procedure

Participants will be asked for written informed consent, and will then be instructed regarding the procedure of the experiment. These instructions involve the blocks, for which the participants will be tested, because tasks are slightly different in each block, and the used PAS ratings, for it is important that participants memorise these before the start of the experiment.

For light skin abrasion which helps reduce electrode impedances, participants will be asked to comb their hair with a plastic comb, concentrating on the scalp (Farrens et al., 2021). The EEG cap will then be applied. Participants will be required to sit on a chair in front of the experimental screen, rest their chin on the chin rest to ensure a constant viewing distant of approximately 60 cm, and to position their hands, so that their right hand can reach the number pad and their left hand the spacebar and the number row alike.

Each trial starts with the black fixation cross, that will appear after one of six onset times (approx. 1000, 1165, 1330, 1495 and 1824 ms), which were chosen to let trial durations vary. The fixation cross is followed by a prime stimulus after approx. 500 ms, a black arrow pointing either left or right. The prime is presented for 24 ms (2 frames). After a fixed SOA (8 frames = approx. 94 ms) the target/mask follows, which is presented for 106 ms and points in either the same direction as the prime (congruent trial) or the opposite direction (incongruent trial). Participants will have to react as fast and accurately as possible to the direction of the target/mask by pressing '1' for left and '3' for right on the number pad of the keyboard with their right hand. See Figure 1 for a schematic depiction of the experimental paradigm.

In blocks A and B, the speeded two-choice target identification task will be followed by a PAS. The response modality will be a vocal response into a microphone that is positioned in front of the chin rest. Participants will be required to assess how well they perceived the prime by speaking the associated number of the chosen label.

In block A, the high-complexity condition, participants will have to use the PAS with four items to choose from (0, 1, 2 and 3), and in block B, the low-complexity condition, they will be required to use the dichotomous subjective measure (0 and 1). In block C and D, the main task is the same, but participants will be asked to respond to the prime's visibility assessment by pressing keys on the keyboard. The numbers 1 to 4 will be covered by stickers so as to show 0 to 3. In block C, the high-complexity condition, again the PAS will be used, and in block D, the low-complexity condition, the dichotomous subjective measure.

Block E is the single-task condition and participants will be required to complete only the speeded two-choice identification task. The order of blocks will be randomized for each participant as to avoid order effects.

Block F will serve as a control block to measure objective prime visibility, and it will require participants to react to the direction of the prime in a non-speeded prime-identification task. Again, they will be asked to press '1' for left and '3' for right on the number pad of the keyboard. Block F will consist of 60 trials, while blocks A-E will consist of 120 trials and will be preceded by 20 practice trials. Each block (A-E) will last for approximately 10 minutes, bringing the estimated total duration of the session to an hour. Participants will be advised to take small breaks between the blocks, to avoid fatigue.

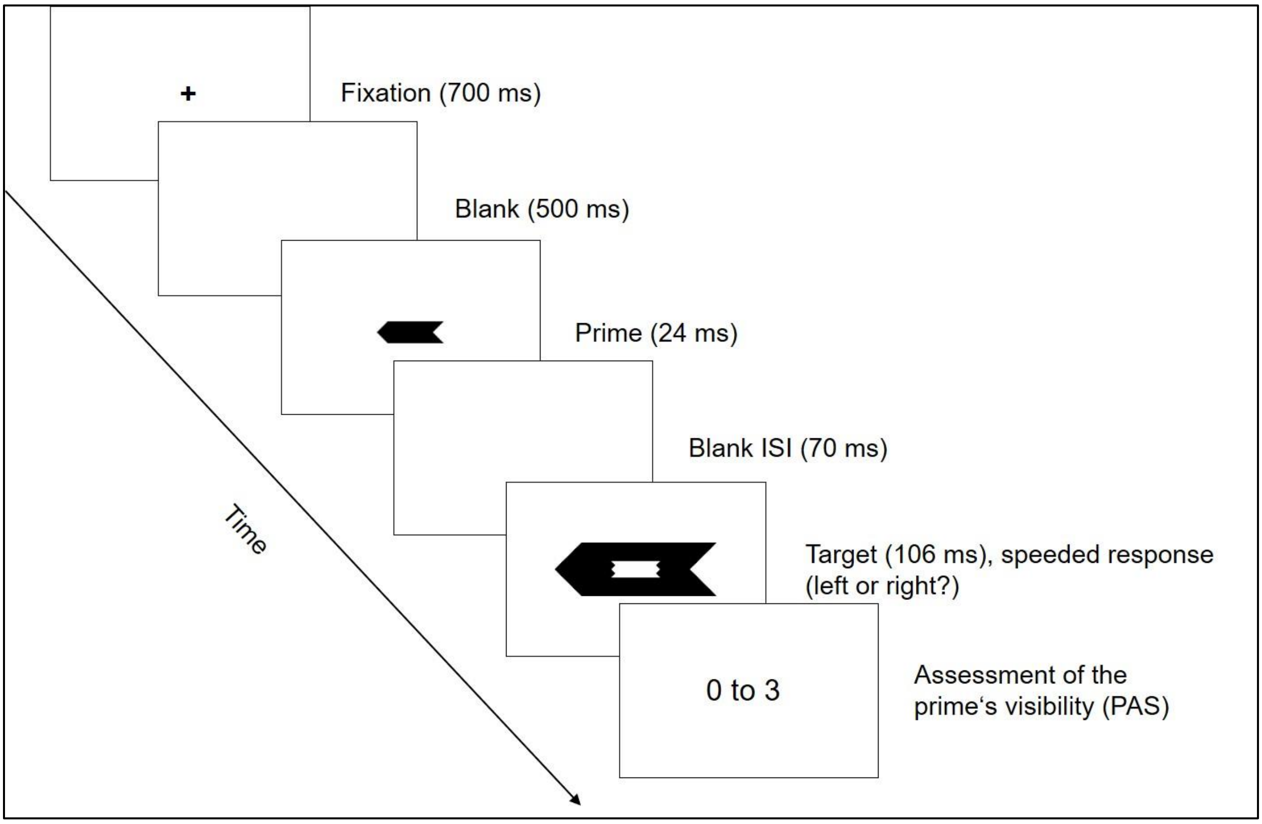

Figure 1. Sequence of stimulus events in a typical trial in our experiment. Note that the first task requires a speeded response to the second stimulus (target), and that the second task requires an unspeeded visibility assessment of the first stimulus (prime).

Hypotheses

We aim to study the influence of the direct task’s characteristics on the dual-task costs, i.e., RTs and on the priming effect in a metacontrast-masked priming paradigm. Specifically, we will look at the task characteristics of response modality and complexity.

As outlined above, we expect slower RTs and larger priming effects for the dual than for the single-task. We therefore predict that (hypothesis 1) the dual-task condition (indirect &direct task) will lead to slower RTs and larger priming effects as compared to the single-task condition (indirect task only).

Resource theories state, that the performance of two tasks suffers when both draw from the same resources (Schacherer & Hazeltine, 2021), while dual-task costs are reduced when tasks require distinct resources. Accordingly, manual and vocal responses can be timeshared relatively efficiently (Wickens, 2002). An unimodal response condition, on the other hand, can lead to response-related interference, a mechanism expected to reduce response priming effects (Kiefer~~, Harpaintner,~~ et al., 2023b). We therefore predict that (hypothesis 2) the manual response modality condition of the direct task (key press) will lead to slower RTs and smaller priming effects as compared to the vocal response modality condition.

As stated above, studies found slower RTs for more complex experimental conditions as compared to less complex conditions (e.g., Sigman & Dehaene, 2005; Vaportzis et al., 2013) and even more specifically higher RT1 for a more difficult direct task due to increased resource demands (Fischer et al., 2007). This increase of demands, that a higher complexity poses, is expected to reduce response priming effects (Kiefer~~, Harpaintner,~~ et al., 2023b). We predict that (hypothesis 3) the high task complexity condition of the direct task (4 options to choose from for an answer) will lead to slower RTs and smaller priming effects than the low task complexity condition (2 options to choose from).

Analysis Plan

R and RStudio in their current versions will be used for all statistical analyses (R Core Team, 2021; RStudio Team, 2021). Only participants, who completed the experiment fully, will be included in the preregistered analysis. We will use the “2sd” method to define outliers (Berger & Kiefer, 2021). In addition, to exclude anticipatory responses we will also discard trials with RTs faster than 100 ms.

We will only include correct trials in our analyses, i.e., trials in which participants answered correctly to the direction of the target arrow. All correct trials will be included in the analyses, regardless of subjective visibility rating.

The priming effects will be calculated by subtracting the mean RT in congruent trials from the mean RT in incongruent trials per participant and condition. We will conduct one repeated-measures three-way ANOVA comprising the factors “response modality” (vocal vs. manual), "response complexity" (high vs. low), and "prime-target congruency" (congruent vs. incongruent) to test for RT differences between conditions, as well as a repeated-measures two-way ANOVA comprising the factors "task type" and "congruency" to test for RT differences between single and dual-task. To check our directed hypotheses, we will conduct targeted post-hoc t-tests, controlled for false discovery rate (FDR, 457 Benjamini & Hochberg, 1995).~~Multiple t-tests controlled for false discovery rate (FDR, Benjamini & Hochberg, 1995) will be used as post-hoc analysis.~~

Exploratory Analyses

Regarding the RTs, we will also investigate other aspects of the distribution, for we expect distributions to be wider for dual as compared to single-task, and are interested in whether priming effect are still observed in the quickest responses, and whether there are fast errors, i.e., whether errors are as fast as the fastest correct responses.

In addition to RTs, error rates are utilized as measures for dual-task costs (e.g., McLeod, 1977; Vaportzis et al., 2013). We did not include error rates in our main hypothesis, but are interested nevertheless in the possible affects our manipulations could have on error rates. The same ANOVAs will be calculated to test for significant difference between the levels of the two factors modality and complexity, as well as between single and dual-task.

Regarding the ERPs, we are cautious making any predictions, since, to our knowledge, the influence of task modality and task complexity on the target-related P3b amplitude and latency has not been studied so far. However, we expect that P3b amplitude and latency will be affected by both task manipulations in some way.

ERPs will be time-locked to the onset of the stimulus and then averaged per participant, condition and electrode for a time window from -200 to 1200 ms. We will be using the outputs from the three midline channels Fz, Cz and Pz to isolate the P3b, as these are typically used in dual-tasking paradigms probing P3b (Aliakbaryhosseinabadi et al., 2017; Isreal et al., 1980;

Kappenman et al., 2021; Kasper et al., 2014; Knott et al., 2003), and the average of both mastoids as reference (Kiesel et al., 2008) Statistical analyses will be calculated over mean amplitude and onset latency values in a time window recommended for the P3b by Kappenman and colleagues (2021): 300 to 600 ms. We will be using the jackknifed averages for mean amplitudes and, following a recommendation by Kiesel et al. (2008), we will combine jackknifing with the relative criterion technique with parameter 50% for calculating onset latencies. We will use repeated measures ANOVAs comprising the factors “task modality” (vocal vs. manual), “task complexity” (high vs. low) and “electrode site” (Fz, Cz, Pz), as well as the factor “task type” (single vs. dual) in a separate analysis. To control for multiple comparisons we will be using the FDR after Benjamini and Hochberg.

Data and Code Availability

All materials, data and code will be made available at OSF (osf.io/34ydp).

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Appendix

Question	Hypothesis	Sampling plan	Analysis Plan	Rationale for deciding the sensitivity of the test for confirming or disconfirming the hypothesis	Interpretation given different outcomes	Theory that could be shown wrong by the outcomes
How does a dual-task situation due to trial-by-trial prime visibility judgments affect masked response priming effects?	We predict that the dual-task condition (indirect task– reaction to target direction; direct task – assessment of prime visibility via PAS) will lead to slower RTs and larger priming effects as compared to the single-task condition (indirect task only). (H1)	34 participants will be recruited.	One two-way repeated measure ANOVA with 2 (Task Type: single- vs. dual-task) x 2 (Congruency: congruent vs. incongruent) for RTs as the dependent variable.	We used G*Power 3.1.9.7 (Faul et al., 2007) to determine our sample size. For a medium effect size f (0.25; partial eta squared = 0.06, Cohen, 1988) for the main effect of task type ~~(Cohen, 1988)~~, alpha level = 0.05, and a power of .80 for the repeated measures ANOVA a sample size of N = 34 is required. For a medium effect size f (0.25; partial eta squared = 0.06) for the interaction effect between task type and ~~consistency~~ongruency, alpha level = 0.05, and a power of .80 for the repeated measures ANOVA a sample size of N = 24 is required.~~For a medium effect size f (0.25; partial eta squared = 0.06) for the main effects (Cohen, 1988), alpha level = 0.05, and~~	This could find that a dual-task situation *does* lead to decrements in performance and larger priming effects as compared to single task due to higher demands on cognitive resources. The absence of a significant modulation of priming effects would show that trial-by-trial prime visibility judgments do not strongly interfere with the priming effects.	The assumption that task 2 in general, and more specific its characteristics, do not affect task 1 within a dual-tasking paradigm could be shown wrong. The assumption that concordant input/output modality pairings lead to less interference than not concordant input/output modality pairings could be shown wrong.

				~~a power of .80 for the repeated measures 2x2x2 ANOVA comparing priming effects between experimental conditions (i.e., vocal vs. manual response, high complexity vs. low complexity and congruent vs. incongruent trials) a sample size of N = 34 is required.~~		
Does the choice of response modality for task 2 influence performance and the priming effects in task 1?	We predict that the manual response modality condition of task 2 (key press) will lead to slower RTs and smaller priming effects as compared to the vocal response modality condition. (H2)		One three-way repeated measure ANOVA with 2 (Modality: manual vs. vocal) x 2 (Complexity: high vs. low) x 2 (Congruency: congruent vs. incongruent) for RTs as the dependent variable.	For a medium effect size f (0.25; partial eta squared = 0.06) for the main effect of modality ~~(Cohen, 1988)~~, alpha level = 0.05, and a power of .80 for the repeated measures ANOVA, a sample size of N = 34 is required. For a medium effect size f (0.25; partial eta squared = 0.06) for the interaction effect between modality and ~~consistency~~congruency, alpha level = 0.05, and a power of .80 for the repeated measures ANOVA a sample size of N = ~~19~~24 is required.	This could find that a manual response in task 2 *does* lead to slower RTs in task 1 for requiring to draw from the same resource, and smaller priming effects. Or it could find that it *does not.* We will interpret such a finding as pointing towards an advantage of concordant input/output modality pairings. It could also find that there are no differences between the conditions, rendering them not essential for task 1 outcomes.	

Does the level of complexity in task 2 influence performance and the priming effects in task 1?	We predict that the high task complexity condition of task 2 (4 options to choose from for an answer) will lead to slower RTs ~~as well as~~and smaller priming effects than the low task complexity condition (2 options to choose from). (H3)			For a medium effect size f (0.25; partial eta squared = 0.06) for the main effect of complexity~~ (Cohen, 1988)~~, alpha level = 0.05, and a power of .80 for the repeated measures ANOVA a sample size of N = 34 is required. For a medium effect size f (0.25; partial eta squared = 0.06) for the interaction effect between complexity and ~~consisten~~congruency, alpha level = 0.05, and a power of .80 for the repeated measures ANOVA, a sample size of N = ~~1~~24~~9~~ is required.	This could find that a higher complexity of task 2 *does* lead to slower RTs in task 1 because of higher demand of task 2 on limitedly available resources, and to smaller priming effects. Or it could find that it *does not*, because a higher demand of task 2 on resources does not affect performance in task 1, or because our manipulation does not raise demands effectively enough. It could also find that there are no differences between the conditions, rendering them not essential for task 1 outcomes.	