# Sustained control and conflict awareness

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## Abstract

Cognitive control processes modulate information processing in the brain to ensure proper responses to environmental stimuli. According to the much-noticed conflict monitoring hypothesis they are elicited by conflict which arises when two or more possible responses compete for execution. Recent research has focused on whether or not these conflicts need to be induced by consciously perceivable information for control processes to be prompted. The present study investigates this question for a crucial type of control processes, i.e. sustained control processes. In two experimental series, two established effects were investigated: the context-specific proportion congruent (CSPC) effect and the conflict frequency effect. Both are assumed to reflect sustained control processes. The first major goal of the present study was to establish these effects using masked priming paradigms while ensuring that no alternative explanation to cognitive control processes could account for their observation. The second goal was to investigate the need for conscious representations of the conflict eliciting stimuli for these effects to occur. This was done by presenting primes weakly or heavily masked, leading to conscious or unconscious representations of the conflicting information, respectively.

The results suggest that both, the CSPC effect and the conflict frequency effect can be observed in masked priming paradigms (Experiments 1 and 4). However, the control processes underlying these effects seem to depend on conscious representations of conflict information. They were not observed when conflict eliciting information was never consciously perceived (i.e., all primes were heavily masked; Experiments 2 and 5). The control processes also did not emerge when trials with weakly masked primes were mixed with trials containing heavily masked primes (Experiments 3 and 6). This might indicate a need for a high proportion of consciously perceivable conflict information for these effects to occur. The results further suggest that extensions are necessary to contemporary theories of cognitive control.

# 1 Introduction

Acting successfully in the environment requires that behavior is constantly monitored and – if necessary – modulated. It is assumed that this is achieved via so-called cognitive control (e.g., Botvinick, Braver, Barch, Carter, & Cohen, 2001). This term has been introduced to summarize processes that modulate information processing to the end that behavior leads to the intended action goal. These processes include, among others, the modulation of behavior after erroneous responses (e.g., Rabbit & Rogers, 1977), the shielding of actions from task irrelevant stimulation (e.g., Gratton, Coles, & Donchin, 1992), and the use of contextual information for selecting the appropriate response strategies (e.g., Crump, Gong, & Milliken, 2006). They are elicited by conflict that arises in the brain during task processing (Botvinick et al., 2001) and first have been assumed to be closely linked to consciousness (e.g., Baars, 1988). Specifically, this means that a conscious representation of the conflict inducing information is necessary to elicit control processes. While some studies support this suggested dependence (e.g., Kunde, 2003), other studies have shown that cognitive control does not always depend on awareness of the conflict-inducing information (e.g., van Gaal, Ridderinkhof, van den Wildenberg, & Lamme, 2009). In the light of these contradicting findings, the present work was conducted to further investigate when conflict inducing information needs to be consciously perceived for cognitive control processes to become activated – and when not.

Bringing together cognitive control and consciousness is a difficult yet very interesting task that also cognitive psychologists have taken on. The present work is an attempt to shed light on a specific problem: Certain effects that are supposedly mediated by cognitive control processes can be based on the experience of conflict over some amount of time, for example the number of conflict eliciting trials in one experimental block. So far, it is unclear what role consciousness plays in these kinds of processes. To be more specific, a major question of the present work is whether or not the information that elicits conflicts and thus triggers cognitive control processes needs to be perceived consciously.

To lead up to this question, I will first describe what I mean when talking about consciousness, what unconscious information processing is, and what its underlying mechanisms are. This is important for two reasons: First, the experiments conducted in the present work rely on methods that present stimuli outside of awareness. It is therefore advisable to know how this can be done, how stimulus awareness can be tested, and what mechanisms are underlying unconscious stimulus processing. Second, investigating possibilities of unconscious processing may lead to deeper insights in the mechanisms and functions of consciousness itself. Since consciousness is not a firmly defined concept it seems necessary to clarify what I understand of it with regards to the present study.

In the next step I will turn to cognitive control processes. A great body of research already dealt with this topic and constitutes much of the basis of the present work. I will present a much-noticed theory regarding when and how they influence information processing, as well as empirical evidence. Finally, I will describe the relation between control processes and unconscious stimulus processing. As already noted, this topic is not entirely new. Still it is important to understand the current state of knowledge to see how the present work fills an eminent gap in this field of research.

# 2 Unconscious processing

Unconscious information processing is a topic that almost everybody has an opinion about. However, considerably less people have factual knowledge about this topic. Maybe one of the most common misunderstandings regarding unconscious information processing is the belief that subliminal advertising messages influence our consumer behavior. This false belief probably goes back to a study presented by James Vicary in the late 1950's. Vicary proclaimed that by flashing the subliminal messages "Eat Popcorn" and "Drink Coke" for the third of a millisecond every five seconds during a movie, the movie theatre's sales of popcorn and coke had significantly gone up (Pratkanis, 1992). Despite the study was never published in a scientific journal, Vicary confessed to the poor quality of the study and its results, and it was never replicated (Pratkanis, 1992) it is still affecting people's opinion on the processing of subliminal information. A quote attributed to Mark Twain goes: "A good lie will have travelled halfway around the world while the truth is putting on her boots."

Despite all rumors you might have heard about subliminal advertising, subliminal audio self-help tapes that cure you from smoking overnight (Moore, 1992; Pratkanis, Eskenazi, and Greenwald 1994), and subliminal satanic messages hidden in tracks of rock- and metal bands (Moore, 1996) there is no proof for these stories. However, it would be equally wrong to say that unconscious information processing is not possible per se. There are many scientific studies showing the influence of subliminally presented stimuli (e.g., Dehaene et al., 1998; Kiesel, Kunde, Hoffmann, 2007; Klotz & Neumann, 1999; Kunde, 2003; Neumann & Klotz, 1994; Vorberg, Mattler, Heinecke, Schmidt, & Schwarzbach, 2003) even on “free” choices (Kiesel et al., 2006; Schlaghecken & Eimer, 2004). However, the influence of unaware stimuli is rather small, and confined to certain conditions (e.g., the intention to respond to certain stimuli; Ansorge, Heumann, & Scharlau, 2002; Klotz & Neumann, 1999; Kunde, Kiesel, &Hoffmann, 2003; Neumann, 1990; Neumann & Klotz, 1994). This chapter deals with unconscious information processing and its behavioral effects in empirical studies. I will also describe how information can be presented in a way that it cannot be perceived consciously and the mechanisms of unconscious information processing.

Although this is not the intention of the present study, one goal of studies regarding unconscious processing is to shed further light on the functions and mechanisms of consciousness, approaching answers to questions like: What is consciousness good for? In which ways is consciousness adaptive, why did it evolve? So first, I will approach the general topic “consciousness” to give you an overview of what one is dealing with when investigating unconscious processing.

## 2.1 Consciousness

Consciousness is a phenomenon everyone experiences. We use expressions like “(un)conscious” or “(un)aware” almost every day. Everybody also has a conscious feeling, meaning the “self” that we refer to when we talk about ourselves, that is believed to make decisions, that thinks about problems, and that is held responsible for our actions. However, despite we are all experts in daily conscious experience and self-perception, it is not easy to say what consciousness really is. First of all, the term “consciousness” can mean very different things. It can describe the difference between being awake and being asleep (or unconscious). In one state people can respond to stimuli and process and use information, in the other they cannot. "Conscious" can also mean reportable (or internally accessible). This includes thoughts as well as stimuli in the outside world. When something is reportable it is often put on a level with a subjective conscious experience. Second, consciousness is still a much noticed topic with questions regarding how it is brought about and what functions it serves. In the course of this, very different aspects of consciousness are investigated[1]. Consciousness research includes questions about awareness and wakefulness of patients (e.g., Laureys, 2005), regarding the mental state or abilities of coma patients or people in anaesthesia (e.g., Deeprose, Andrade, Harrison, & Edwards, 2005), and the function of consciousness, i.e., what is consciousness for? Which processes depend on consciousness and which do not (e.g., Kunde, 2003)? Another question is how consciousness arises, i.e. what brain processes lead to a conscious representation of a stimulus (e.g., Crick & Koch,

[1] Most of the research and theories investigate and describe properties of visual consciousness. This makes sense in several ways: Although we already know a bit about consciousness, most questions and more so the answers still lie in the dark. It would not be helpful to try and explain consciousness in an all-at-once fashion. Instead, approaching one system at a time (and only approaching one question at a time) seems to be the more promising way. Also, human are visual animals, meaning that we rely very much on our visual sense. Imagine you had to go one day without hearing or smelling. Of course, it would reduce the quality of your experiences and it would not make things easier but in comparison to going one day without seeing it seems a lot less difficult. Another point is that the visual system of monkeys is already well understood. Last, the presentation of subliminal stimuli is easiest for visual stimuli. Although there are some studies showing possibilities to present olfactory (Li, Moallem, Paller, & Gottfried, 2007) and auditory (Kouider & Dupoux, 2005) stimuli on a subliminal level, methods of subliminal visual stimulus presentation are well established already. In conclusion, the studies and frameworks I will present in the present work are regarding visual consciousness. For reasons of readability I will simply speak of consciousness. Whether results of similar experiments regarding other senses will point in the same or different directions remains to be seen. Koch (2004) argues that sensory systems are linked (possibly excluding olfaction) and that similar results may be expected for all modalities.

2003) or how conscious and unconscious processes differ (e.g., Dehaene et al., 1998). Before those questions are discussed I will shortly turn towards a (up to now) more philosophical problem, the so-called “hard problem of consciousness”. This problem regards the relation of mere neural activity and personal, conscious experience.

### 2.1.1 Addressing the hard problem of consciousness

David Chalmers (1995, 1997) describes two groups of problems when investigating consciousness, the easy and the hard problems. Although probably all remaining questions in this area are difficult to answer, some problems are easier accessible than others. Chalmers declares as easy problems those that are “directly susceptible to the standard methods of cognitive science”, e.g., how information is integrated in the brain or how attention is distributed. This describes problems regarding the objective mechanisms of the brain, i.e., the processes and structures involved in the origin of conscious experiences. The processes and structures can (given enough time) probably be fully understood using the methods we already have. However, even if all relevant parts of the brain are understood, it may still be unclear how conscious experiences arise.

The hard problem of consciousness is the emergence of experience from neural activation. Why do we feel pain when someone pinches us? How do we experience the warmth of a fire or the deep blue color of the ocean? How do we experience the feeling of emotions? Although a lot is known about what happens on a neural level when a stimulus is processed it is not clear at all how these experiences or qualia emerge from the electric impulses in our brain. In other words, the basic question that makes up the hard problem of consciousness is how conscious experiences (what we feel all the time) can arise from combinations of unconscious biological processes.

There are different approaches to investigating conscious experience. Authors of current neuropsychological theories or frameworks regarding consciousness agree on the strategy to not directly address the hard problem itself but instead try investigating processes that co-occur with conscious experiences of stimuli (e.g., Crick & Koch, 2003; Dehaene & Naccache, 2001). They, in contrast to Chalmers (1995), believe that solving enough easy problems of consciousness may either solve the hard problem or if that is not the case at least give insights in strategies how it can be solved.

### 2.1.2 A framework for consciousness

To describe their approach to this complex problem Crick and Koch (2003; see also Crick & Koch, 1990, 1995, 1998, 2000; Koch, 2004; Koch & Crick, 2001) postulated a framework for consciousness. A framework is a guideline for the investigation of a specific problem consisting of findings from past research and ideas and predictions for future research. It is supposed to be plausible in the light of available data although it is not necessarily correct in all details. A description of frameworks was already well put by Crick and Koch (2003, p. 119): *"A framework is not a detailed hypothesis or set of hypotheses; rather, it is a suggested point of view for an attack on a scientific problem, often suggesting testable hypotheses".* As just mentioned, this framework is a personal scientific view on how the problem of consciousness can be viewed and investigated. Of course, other, partially similar, ideas have been proposed by other researchers. The idea of a global workspace, for example, was put forth in several publications (Baars, 1988, 2002; Dehaene & Naccache, 2001; Dehaene, Kerszberg, & Changeux, 1998).

In general, the global workspace idea states that information is processed by multiple single and unconscious modules that execute specific tasks. The outputs of the modules compete for access to a global workspace. Information is integrated in the global workspace and is then accessible for all modules, i.e., the workspace feeds integrated information back into the modules that the information originated in. This makes the global workspace a connection between modules that are usually separated. By distributing information to the whole system, it becomes conscious. The framework by Crick and Koch can be added to the list of frameworks based on a global workspace, although they do not use this description themselves. I will now describe parts of the framework postulated by Crick and Koch (2003) to further illustrate this idea.

Regarding information processing in the human brain, Crick and Koch distinguish two modes of information processing: conscious processing and processing by what they call zombie modes (Crick & Koch, 1998, 2003; Koch & Crick, 2001). Zombie modes are fast and automatic and can be understood as cortical reflexes (Crick & Koch, 2003; Koch & Crick, 2001). They process information in an unconscious manner, although their results may become conscious. Zombie modes are responsible for activities like walking, driving, or biking, or in general, highly trained (specialized) actions. The function of the conscious mode is to process and plan complex or new information. Crick and Koch argue that it is adaptive to have a fast (first) processing mode that allows you to “respond rapidly, in a stereotyped manner” (Crick & Koch, 2003, p. 120) combined with a slower system that processes information in more detail. This becomes clear when considering possibly harmful situations: It is better to first evade a possible threat and then realizing it was not a threat at all, than to wait to identify the possible threat and have lost time when it turns out that danger is at hand.

For conscious representations to emerge, a complex neuronal structure is necessary. When a visual stimulus enters the brain, it moves up the hierarchy of visual processing units. So-called “*essential nodes*” automatically detect certain features in the visual scene. Features detected by the essential nodes may be ‘face or no face’ or ‘within or outside my reach’. Several essential nodes make up *coalitions of neurons*. The coalitions are very important for consciousness to arise. They are transient, self-sustaining for a short period of time and they can be formed and overridden rapidly. Although several coalitions can be active at one time, only one coalition, the *winning coalition*, determines what information becomes conscious. This winning coalition projects into the front of the brain.

In the front of the brain an unconscious homunculus is postulated (Crick & Koch, 2000; 2003). Although this idea is rather uncommon, this description is chosen by Crick and Koch because one can get the impression that the front of the brain ‘looks at’ the back of the brain. This impression is provided by strong driving connections from the back of the brain to the front and modulatory connections in the opposite direction (Crick & Koch, 1998; 2003; Koch, 2004). The idea of a homunculus has been rejected for the reason that each homunculus that controls a system of any kind by itself creates the need for another control system for the homunculus. However, the unconscious homunculus in the front of the brain is not made responsible for the experience of qualia and is not seen as a “decider” but is instead a regular and furthermore unconscious information processing system (Koch, 2004).

After a new visual input has climbed up the hierarchy of processing units from low to high (thereby forming coalitions) and has reached the front of the brain signals are sent back down the hierarchy (Crick & Koch, 2003; Koch, 2004). These “descending” signals reach high processing levels first which then send feedback to the front of the brain, introducing a double feedback slope: Signals enter the front of the brain, are then sent back and elicit feedback from lower processing levels back to the front of the brain.

Every signal that becomes conscious (mediated by the winning coalition) also activates its so-called penumbra, which consists of basically everything related to former activations of the same coalition. This may be neural representations, memories, firing styles, future plans, etc. (Koch, 2004) that support and enrich the winning coalition. An important point regarding the emergence of consciousness was made by Dennett (2001) who pointed out a possible misunderstanding: In short, Dennett argues that the wide-spread activation in the brain does not give rise to a further conscious process or ignites “the glow of conscious qualia” (p. 223) but instead *is itself* consciousness, i.e., our conscious experience.

The present framework (among others) describes how consciousness may emerge in the human brain. As already mentioned, a method to investigate mechanisms and functions of consciousness is to investigate processing of unconscious stimuli. To do that, of course, one needs to present stimuli outside of awareness. So, in the next chapter I will focus on the “how to?” questions of investigating unconscious stimulus processing. More precisely, I will describe how stimuli can be presented so that they cannot be perceived consciously and how it can be measured whether participants were actually unaware of those stimuli.

## 2.2 Investigating unconscious processing

Attempts to investigate consciousness and unconscious stimuli are reported as early as 1898 (Sidis, 1898, cited according to Merikle, Smilek, & Eastwood, 2001). Sidis presented participants cards with one letter or digit printed on them. The viewing distance was chosen so large that participants reported not to be able to perceive what was printed on the cards. However, when they were forced to decide whether a letter or a digit was presented, or to name the identity of the target, they answered better than at chance level. This shows an interesting dissociation of two measures of consciousness: subjective and objective measures. While participants in Sidis’ study reported that they could not see the target stimuli (subjective measure) their responses were still influenced by them (objective measure).

Long after Sidis’ (1898) experiments a vivid debate has arisen about investigating unconscious processing with some researchers even dismissing the whole phenomenon (cf.

Cheesman & Merikle, 1984; Holender, 1986; Reingold & Merikle, 1993; Shanks & John, 1994). Today, influences of unconscious stimuli on behavior have been demonstrated numerous times and can be considered confirmed (Dehaene et al., 1998; Eimer & Schlaghecken, 1998, 2003; Klotz & Neumann, 1999; Kunde, Kiesel, & Hoffmann, 2003; Mattler, 2003; Neumann & Klotz, 1994; Savazzi and Marzi, 2002; van den Bussche, van den Noortgate, & Reynvoet, 2009; van Gaal et al., 2009). One standard method used to investigate unconscious processing is called masked response priming (Damian, 2001; Dehaene et al., 1998; Dell' Acqua & Grainger, 1999; Greenwald, Draine, & Abrams, 1996; Vorberg et al., 2003). In this paradigm participants usually respond to a certain set of target stimuli by pressing one of two response keys and to another set of target stimuli by pressing the other response key. Crucially, a so-called prime is presented prior to the target.

Primes are stimuli that are usually similar or related to the target stimuli. They can be mapped to the same or another response as the target. The former case is called the congruent condition, the latter the incongruent condition. Usually response times (RT) and error rates are lower in the congruent condition as compared to the incongruent condition and the difference between the conditions is called the priming- or congruency effect. This effect is a common measure of the influence of unconscious stimuli on behavior (as I will describe later, primes can be presented outside of awareness). Of course, response times and error rates are not the only possible measures when investigating unconscious processing but, they are the most common and the ones used in the present work. Other measures include event-related potentials and functional magnetic resonance imaging (e.g., Dehaene et al., 1998; Kiefer & Brendel, 2006). Interestingly, depending on its nature the prime can influence behavior even when it is not perceived consciously.

This, of course, raises the question how stimuli can be presented outside of awareness. The first and probably most obvious method to reduce stimulus visibility is to present them for only very short durations. Further, the most common method to prevent stimuli from reaching consciousness is to mask them (Eimer & Schlaghecken, 1998; Klotz & Neumann, 1999; Dehaene et al., 1998; van den Bussche, van den Noortgate, & Reynvoet, 2009; Vorberg et al., 2003). I will briefly describe two possible methods to mask visual stimuli, pattern masking and metacontrast masking.

In pattern masking the prime is superimposed by a mask. Typical masks consist of strings of letters (e.g., Kunde, Kiesel, & Hoffmann, 2003), symbols (%, &, $, #, etc.; e.g., Kiesel, Kunde, & Hoffmann, 2006), or randomly positioned lines (e.g., Eimer & Schlaghecken, 2002). Masks are usually presented before and after the prime at the same location to overwrite its visual information in the cognitive system (Figure 1A). Together with short presentation times the use of masks can lead to participants not realizing that a prime stimulus was presented at all.

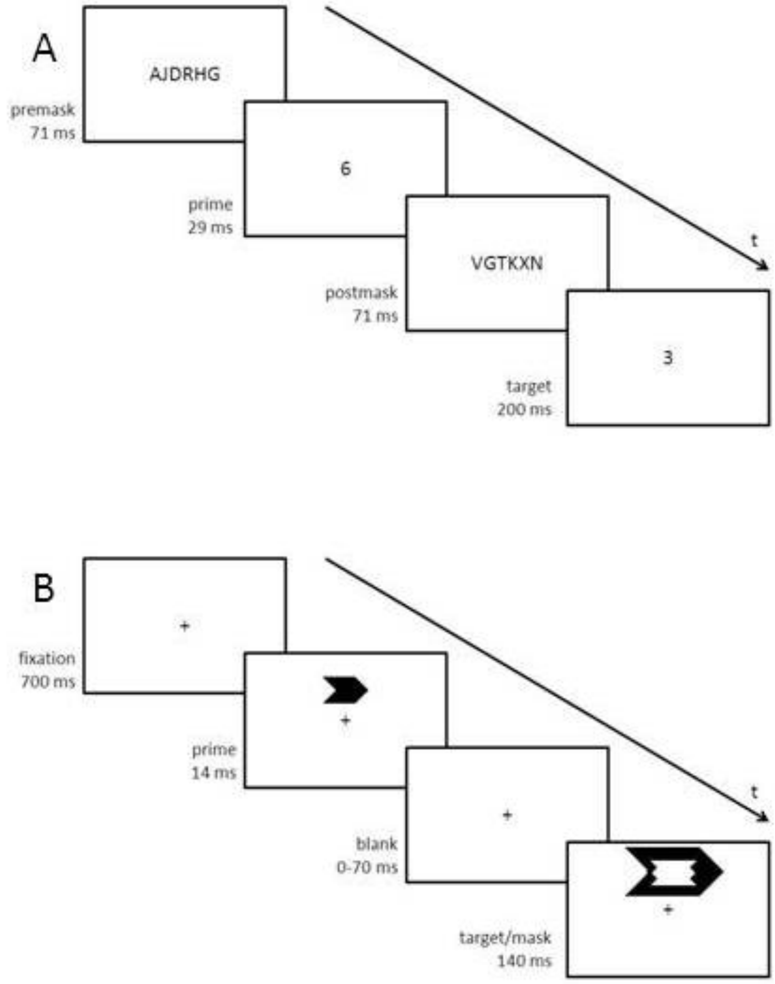


**Figure 1. A)** Pattern masking (trial procedure adopted from Kunde et al., 2003). The prime (6) is presented for 29 ms and is preceded and followed by random letter strings. **B)** Metacontrast masking: The prime arrow fits in the white notch on the target arrow (trial procedure adopted from Vorberg et al., 2003).

In metacontrast masking (e.g., Lingnau & Vorberg, 2005; Vorberg et al., 2003) the mask is not superimposed on the prime. Instead, the prime stimulus is followed by the metacontrast mask (which can also be the target) that shares a contour with the prime, practically surrounding it. This becomes clearest from examining Figure 1B. When the prime 'fits in the mask' (e.g., Kunde, 2003; van Gaal et al., 2009) it becomes less visible and - depending on the stimulus onset asynchrony between prime and mask - even invisible.

Of course, there are other methods of masking stimuli or in general investigating the influence of unconscious stimuli, but they are not of relevance for the present work and are thus omitted (for examples see Di Lollo, Bischof, & Dixon, 1993; Enns & Di Lollo, 1997; Kouider & Dupoux, 2005; Li, Moallem, Paller, & Gottfried, 2007; Savazzi & Marzi, 2002).

Masking stimuli leads to the question how it can be measured whether the stimuli were perceived consciously or not. It is obvious that the simple procedure of presenting stimuli for a short time and masking them does not justify the assumption they had been presented subliminally. To distinguish between consciously and unconsciously perceived stimuli one can rely on two kinds of measures, an objective and a subjective measure. Using the subjective measure would mean that participants are asked either after every presentation of a stimulus or following the experiment whether or not they perceived the stimuli in question consciously or not. Although, as suggested before, we are all experts in conscious experiencing, this method has its drawbacks. Relying on introspective reports appears to be rather "unscientific". They may be influenced by response bias, criterion settings, or withholding of responses (e.g., Cheesman & Merikle, 1986; Holender, 1986). On the other hand, Dehaene and Naccache (2001) make a good point for taking these measures seriously since consciousness is an introspective phenomenon. They and others (Dennett, 1992; Merikle, Smilek, & Eastwood, 2001; Weiskrantz, 1997; cf., Dehaene & Naccache, 2001) suggest using introspective data as primary data and recording it alongside psychophysical data.

Considering the mentioned problems with subjective measures of stimulus awareness some researchers (e.g., Holender, 1986) called for an objective measure of conscious stimulus representation. Data for this measure is usually collected subsequent to the experiment by letting participants discriminate the stimuli that are supposedly presented outside of awareness. Participants are presented the same trials used in the experiment only under different instructions. Instead of responding to a target they respond to the primes (or those stimuli that are believed to be presented outside of awareness) by categorizing or identifying them. If the discrimination rate is not better than chance level one can conclude that participants are unaware of the stimuli. Another way of assessing stimulus awareness is to compute the signal detection measure *d′* (Tanner & Swets, 1954). This measure takes into account the number of *hits* and *false alarms* in a so-called signal detection task. In this task, participants have to categorize the prime into one of two conditions, one of the conditions is labelled *signal* and one is labelled *noise*. This nomenclature dates back to the origin of this measure. Then, if a prime of the signal condition is presented and is categorized correctly, this is called a hit. If a prime of the noise condition is presented and is categorized incorrectly, this is considered a false alarm. From the standardized values of the relative frequency of hits and false alarms the *d′* is computed. If the value of *d′* does not differ significantly from 0, primes are considered to be perceived unconsciously. One of these two rationales (computing *d′* or comparing the identification performance with the guessing probability) is commonly used in studies involving unconscious stimuli (e.g., Dehaene et al., 1998; Heinemann, Kiesel, Pohl, & Kunde, 2010; Klotz & Neumann, 1999; Kunde, 2003; Neumann & Klotz, 1994; Vorberg et al., 2003).

In conclusion, the interest in the impact of subliminal information has been around for a long time. It has been denied, as well as declared omnipotent. Today, it can be considered safe to assume that unconscious information can influence our behavior. This has been demonstrated in several studies and I have described two common methods to present stimuli outside of awareness. They are called masked priming paradigms, and involve presenting the stimuli (i.e. the prime) only for a very short period of time and masking them afterwards. The mask usually superimposes a new image over the respective stimulus, hindering it from being perceived consciously. In studies presenting subliminal stimuli it is common to test the visibility of the primes by having participants categorize the primes and measure their performance in this task. In the next section I will focus on how exactly unconscious stimuli influence responses.

## 2.3 Mechanisms of unconscious processing

After presenting the technical side of how to investigate unconscious processing I will now turn to the mechanisms of subliminal processing. As mentioned above, it is generally accepted that unconscious stimuli can impact human behavior (e.g., van den Bussche et al., 2009). Instead, research focuses on questions regarding how deep, i.e., to what extent, unconsciously presented stimuli are processed.

Basically, three processes can be distinguished: perceptual-, response-related, and central processes describe in ascending order different depths of stimulus processing. Kiesel, Kunde, and Hoffmann (2007) elaborated on these processes. They categorize as perceptual processes that the prime attracts attention to its location, leading to faster processing of a target at the same location (Scharlau, 2002, 2004; Scharlau & Ansorge, 2003; Scharlau & Neumann, 2003). Additionally, in priming experiments the priming effect is largest when prime and target are identical (e.g., Bodner & Dypvik, 2005). In these cases target perception is facilitated, however, unconscious processing can also lead to activation of motor responses. When prime and target are mapped to the same response, RTs are usually shorter as compared to when prime and target are mapped to different responses. Primes and target do not need to be identical for this effect to occur. Primes elicit a motor response shortly before the target does. This was demonstrated by measuring LRP (lateralized readiness potentials; Dehaene et al., 1998; Leuthold & Kopp, 1998).

To describe how primes can activate motor responses, Kiesel, Kunde, and Hoffmann (2007, see also Kunde, Kiesel, & Hoffmann, 2003) presented the *action-trigger account*. This account postulates a two-process model based on the direct parameter specification theory of Neumann (1990; cf. Neumann & Klotz, 1994; Klotz & Neumann, 1999). In short, it is postulated that in a first step, expectations regarding imperative stimuli for the required responses (the so-called action triggers) are built up depending on experience or instructions. In the second step, responses are elicited by stimuli that match these expected action triggers perceptually regardless of whether these stimuli (e.g., primes) are processed consciously or not. The notion that only perceptual features elicit responses stands against the claim brought forth in several studies that (subliminal) primes are processed semantically, i.e., that central processes are involved (Dehaene et al., 1998; Greenwald et al., 1996; Klauer, Musch, & Eder, 2005; Reynvoet, Gevers, & Caessens, 2005; Van den Bussche & Reynvoet, 2007). Kiesel et al. (2007) acknowledge that “semantic features can be used to select an event as an action trigger” (p. 311), however, they state that for a response to be triggered not semantic but perceptual features are responsible.

Semantic priming is still controversially discussed, as priming effects have been shown to be bound to task-specific conditions (Ansorge et al., 2002; Kunde, Kiesel, Hoffmann, 2003). This restriction would not apply if all primes were indeed processed at high levels.

However, van den Bussche, van den Noortgate, and Reynvoet (2009) reported evidence for semantic priming in a meta-analysis. Additionally, van den Bussche, Notebaert, and Reynvoet (2009) reported a priming effect when the target set was large (50 items) but this effect was absent for small target sets (4 items). These authors argue that depending on task requirements, like the target-set size that needs to be represented, a semantic or nonsemantic stimulus processing strategy can be applied. If the target set is small all stimuli can be stored in the working memory or can be recognized by unique target characteristics. If, however, the target set is large these two strategies cannot be applied and thus a semantic strategy is used. Taken together, as evidence for a semantic priming effect accumulates an extension of the existing explanations is needed. The model proposed by van den Bussche et al. (2009) might be a solution that can explain constraints of semantic priming effects according to the pre-existing accounts (e.g., the action-trigger account) and leaves room for semantic priming if easier, i.e., more economical strategies (e.g., relying on perceptual features) do not apply.

## 2.4 Summary

The present chapter dealt with the phenomenon of unconscious processing which is an interesting and important way of investigating consciousness. Current research deals with consciousness in a broad sense: How it is elicited in the brain? What it is good for? How do combinations of electric impulses in the brain evoke sensations in the brain? These are all questions under investigation. Different approaches to this topic can be made from a philosophical, a neurobiological, or a psychological perspective. A framework that proposes how conscious experience arises in the brain has been proposed by Crick and Koch (2003). It is similar to other, so-called global workspace frameworks, as it postulates a hierarchical processing of information with several feedback and feedforward loops between different processing stages.

If one considers consciousness, the claim of unconscious processing seems not to be far to seek. However, unconscious processing is a phenomenon that has been lively debated. Probably all positions regarding this topic have been represented: from the point of view that unconscious processing is non-existent to the view that conscious processing is expendable. Nowadays it is widely acknowledged that unconscious processing is an existing phenomenon, demonstrated in many studies. In the present chapter I described how unconscious processing is investigated and what its underlying mechanisms are.

Masked priming is the method of choice to present stimuli subliminally in an experiment. Primes, i.e., stimuli that are presented for very short durations and masked afterwards, are able to influence responses (commonly measured in RTs and error rates) despite not reaching consciousness. The influence can occur on perceptual-, motor-, or central stages. For the present study, the masked priming paradigm is important because it is an effective and established way to induce response conflicts, which are an important part of investigating cognitive control processes that I will describe in the next chapter.

# 3 Cognitive control processes

Many of our actions can be performed automatically, i.e., there is no need to focus on their performance. This includes walking, driving a car (after some practice), or riding a bike. However, we need to focus on some actions, either because they are difficult or unexpected events come up. For example, if you are driving a car and a person walks on the street in front of you, you need to change your current behavior from driving to breaking. If you sit down to tie your shoe and find a knot in the lace, you need to switch to the new task of untying the knot first. Behaviors that require a focus of attention, planning of actions, changing the current task or goal, inhibiting ongoing behavior, responding to, or correcting errors have in common that they happen in a controlled way. These are all tasks one would say you have to concentrate on. This is already a good description, albeit preliminary, of what is called executive- or cognitive control. Norman and Shallice (2000) pointed out five types of tasks that require "deliberate attentional resources" (Norman & Shallice, 2000, p. 377). They group them as follows: "1) They involve planning or decision making. 2) They involve components of trouble shooting. 3) They are ill-learned or contain novel sequences of actions. 4) They are judged to be dangerous or technically difficult. 5) They require the overcoming of a strong habitual response or resisting temptation." (Norman & Shallice, 2000, p. 377). Given these different groups of tasks or behaviors, one of the first things one has to realize when dealing with cognitive control is that one is not talking about one single-purpose mechanism in the brain. Instead, cognitive control refers to a whole group of processes that can modulate information processing or behavior to the best fit for the current goal. According to Verguts and Notebaert (2009), cognitive control refers to those processes that give us “the ability to suppress dominant responses in favor of less obvious but more appropriate ones” (p. 252), which fits point five of the above list by Norman and Shallice. The description well matches control processes investigated in psychological experiments in general, as well as in the present study.

This introduction, so far, raises several questions: How can cognitive control be observed and tested experimentally? How is cognitive control represented in the brain? Which brain areas are responsible for cognitive control and what are its neural correlates? How does the brain “know” when and what kind of cognitive control is necessary? How is control executed in the brain? Several models have been proposed to answer these questions. One model that received great attention and is supported by evidence from many studies is the conflict monitoring hypothesis by Botvinick et al. (2001) which I will describe in the following section.

## 3.1 The conflict monitoring hypothesis

Cognitive control is not exerted on every task performance. Many tasks can be performed automatically. However, if this is not the case and task performance must be optimized, cognitive control processes are elicited. But how does the cognitive control system “know” when task performance needs to be corrected? One answer to this question is that cognitive control processes are activated when conflict is detected. But what is conflict? And how is it registered in the brain? What happens upon conflict registration? Botvinick et al. (2001; see also Botvinick, Cohen, & Carter, 2004) brought forward the conflict monitoring hypothesis to answer these questions. The basic idea underlying this model is a feedback loop that is activated by conflict in the stream of processing and subsequently modulates the amount of control exerted on a given task. The execution of control is directly linked to conflict that arises during the processing of a task. So first, one needs to understand what conflict means in this context. After that, one needs to ask how conflict is registered in the model and what consequences follow conflict registration.

### 3.1.1 What is conflict?

To describe what conflict is I will use as an example one of the most popular paradigms in experimental psychology, the Stroop task (Stroop, 1935). In this task participants see color words (e.g., RED, GREEN, BLUE, YELLOW) that are presented in different colors. Their task is to name the color that the word is printed in while ignoring the meaning of the word. This leads to two different conditions. In the first, the congruent condition, the meaning of the color word is the same as the ink it is presented in (e.g., the word RED printed in red ink). Usually participants can name the ink color fast and accurately. In the second, the incongruent condition, the meaning of the color word and the ink color differ (e.g., the word RED printed in blue ink). In comparison to the congruent condition, participants respond slower and less accurate to words in the incongruent condition.

This is due to a response conflict. According to the instructions, participants try to focus on the color of the word. However, since reading is an automatic response when seeing a word, they cannot inhibit reading the color word. Now, two responses compete for execution. One is word reading; the other one is naming the color of the word, as one is instructed. Both responses involve color and both responses involve language. On a more abstract level, conflict arises when two processes that run in parallel demand access to the same resources or hardware (Mozer & Sitton, 1998, cited according to Botvinick et al., 2001), just like when two people try to walk through a door at once.

### 3.1.2 How is conflict registered?

The model of Botvinick et al. (2001) is based on models that have previously been developed to explain brain processes in various conflict tasks (Cohen & Huston, 1994; Cohen, Servan-Schrieber, & McClelland, 1992; McClelland & Rumelhard, 1981). These older models consist of several units each of which represents a certain function in the respective task. There are input units that are connected to output units. The units can excite or inhibit each other to pass information from the input stage to the output stage. Take, for example, the model for the Stroop task (Cohen & Huston, 1994; Figure 2A). There are two input units, one for identifying the word color and one for identifying the word identity. The input units are biased by the task-control unit (which represents task instructions). They have subunits that are activated by one color (or one color word) only and inhibit each other. Additionally, the input units are connected to an output unit, which contains the possible responses. Each response is represented in a separate subunit (again, the subunits inhibit each other). Note that the model does not specify how and when this control unit is activated. The same is true for other older models describing other conflict tasks.

Botvinick's et al.'s (2001) model expands the former models in the way that the gap between conflict and the exertion of control on task performance is closed. This is done by adding two things: First, there is a further unit that constantly monitors and measures conflict that arises during task processing. Second, there is a feedback loop going from the conflict monitoring unit back to the control unit that itself can then bias task processing (Figure 2B).

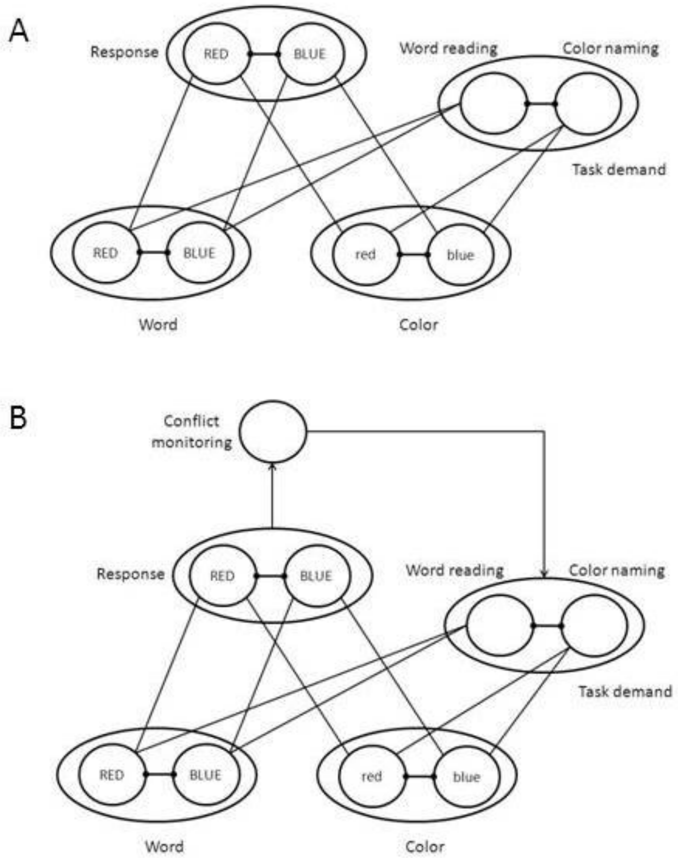


**Figure 2. A)** Stroop-task model (adopted from Cohen & Husten, 1994). The input nodes "word" and "color" are biased through the task-control unit and excite the output unit, which leads to a response. **B)** The conflict monitoring hypothesis expands the Stroop-task model by adding a conflict monitoring unit and a feedback loop to the task control unit.

A conflict monitoring unit is proposed that is directly linked to the output unit of each model. The output units are activated by excitatory signals from the input units and the activation of the output unit is fed forward to the conflict monitoring unit. Conflict arises when two incompatible input units both send excitatory signals to the output unit, thus activating two incompatible responses. Take the Stroop task model for example: When both input units, namely color naming and word reading, activate the output unit to exert the respective response (saying the ink color or saying the color word) conflict arises because both responses cannot be executed at once. According to Hopfield (1982), conflict is measured as the energy that results from the product of the energy of both excitatory signals. Take the Stroop model for example again: There are two input units that activate the output unit and each can have two states: active and inactive. In the active state an excitatory signal is passed on to the output unit while no signal (i.e., an energy value of zero) is passed on in case of the inactive state.

If both units are inactive, the product of the energy of the two input units is zero, i.e., no conflict is passed on to the conflict monitoring unit. When one input unit is active and the other unit is inactive, the product of the two signals is still zero. Again, no signal of conflict is passed on to the conflict monitoring unit. However, when both input units excite the output unit, there is a larger than zero product of the energy of both signals. This energy is passed on to the conflict monitoring unit that in turn activates the control unit to modulate task processing.

Looking back at the Stroop task model, this process would look like this: The word red is presented in blue color. According to the instruction a participant wants to respond by naming the ink color (blue). Thus, within the input unit 'color naming' the subunit 'blue' is activated and inhibits the other subunits. The unit 'color naming' sends an excitatory signal to the output unit activating the response "blue". However, due to lifelong practice, the participant cannot completely inhibit reading the word that is presented on the screen (red). Now in the unit 'word reading' the subunit 'red' is activated (and subsequently inhibits the other subunits within the unit). Now the unit 'word reading' also sends an excitatory signal to the output unit activating the response "red". Now, two incompatible responses (red and blue) compete for execution and thus, lead to conflict. As already described, the conflict is measured as the product of the energy of the two signals reaching the output unit. This energy measure is forwarded to the control unit that registers the conflict and then feeds the information back to the control unit. The control unit then modulates the task processing to best fit the task demands by varying the weight (i.e., the relevance) of the input units.

With the basic mechanism of the model clarified, two questions remain: Where is the conflict monitoring unit located in the brain? How is task processing modulated by the control unit? Several studies have addressed these questions already and I will summarize the most important results in the following section.

### 3.1.3 Where is conflict monitoring located in the brain?

Several studies have already identified brain structures that participate in cognitive control processes. Mostly the frontal brain, especially the prefrontal cortex and the dorsolateral prefrontal cortex are believed to play a major role in cognitive control (Egner & Hirsch, 2005; Garavan, Ross, Murphy, Roche, & Stein, 2002; Lau & Passingham, 2007; MacDonald, Cohen, Stenger, & Carter, 2000; Kerns et al. 2004). Evidence for this view comes also from the investigation of erroneous behavior. Of course, it is not possible to act correctly at all times. For example, in stop-signal tasks the ability to inhibit a planned response declines with an increasing stimulus onset asynchrony of target and stop signal. Also it is not always possible to inhibit the irrelevant information in a Stroop task and thus committing an error by reading the color word instead of naming the color. It is safe to say that errors are part of our behavior. They signal an incorrect or insufficient task performance (Hester, Simões-Franklin, & Garavan, 2007) and the need for cognitive control.

Error registration and processing is usually investigated using EEG recordings. So-called event-related potentials (ERPs) are measured that are variations in the brain waves reflecting data processing of any kind. Errors commonly produce the error related negativity (“$N_E$”, Falkenstein, Hohnsbein, Hoormann, & Blanke, 1991; Gehring, Goss, Coles, Meyer, & Donchin, 1993), a negativity in the ERP found in the frontal-central area of the scalp. Holroyd & Coles (2002) hypothesize that the $N_E$ is “generated by a high-level, generic, error-processing system” (p. 680) and originates in the Anterior Cingulate Cortex (ACC; Braver, Barch, Gray, Molfese, & Snyder, 2001; Carter et al., 1998; Kiehl, Liddle, & Hopfinger, 2000; Miltner, Braun, & Coles, 1997). The ACC was described by Botvinick et al. (2001) as the locus of the conflict monitoring unit. Yeung, Botvinick, and Cohen (2004) also link the $N_E$ to the ACC and the conflict monitoring hypothesis. Although the $N_E$ is linked to conflict in the brain it was suggested by Masaki, Falkenstein, Stürmer, Pinkpank, & Sommer (2007) that the amount of conflict and the size of the $N_E$ are unrelated.

The conflict monitoring hypothesis focuses mostly on conflict detection. It declares one brain structure to be mainly responsible for conflict monitoring and thus, for detecting the need for control. This structure is the ACC. Many studies have already pointed out the importance of the ACC for cognitive control (e.g., Barch et al., 2001; Botvinick et al., 2004; Botvinick, Leigh, Nystrom, Fissell, Carter, & Cohen, 1999; Carter et al., 1998; for a review see Paus, Koski, Caramanos, & Westerbury, 1998), however, although the evidence for the importance of the ACC for cognitive control is quite numerous, Botvinick's et al. (2001) model is the first to link this structure to the demand for monitoring conflict and activating control and thus, finding a common explanation for the involvement of the ACC in all studies investigating effects based on cognitive control processes. Yet, it still needs to be explained how exactly task processing is modulated after conflict has been detected.

### 3.1.4 How is stimulus processing modulated?

As mentioned before, many studies link cognitive control to frontal brain areas. So we know from where control is exerted. In this section I want to focus on the mechanism by which task processing is manipulated: There are three possible explanations for the modulation of task processing. First, it is possible that task relevant information is amplified upon the experience of conflict (amplification hypothesis). In the Stroop-task model this would mean that the control unit would distribute a stronger weight to the color naming unit than it did before conflict arose. Second, it is also possible that task irrelevant information gets inhibited upon the experience of conflict (inhibition hypothesis). In the Stroop-task model this would mean that the control unit would distribute a stronger weight to the word reading unit than it did before conflict arose. There also is the possibility that a mixture of both ideas, amplification of task relevant information and inhibition of task irrelevant information, explains the modulation of task processing (amplification-inhibition hypothesis).

Egner and Hirsch (2005) provide evidence for the amplification hypothesis. In a study using a Stroop-like task participants were presented faces of politicians and actors. On top of these pictures, names were presented. These names could either be the name of the depicted person (congruent condition) or of another person (incongruent condition). Participants performed a two-button forced choice task, discriminating actors and politicians either depending on the face (face task) or depending on the name written on top of the picture (name task). Using functional magnetic resonance imaging (fMRI), Egner and Hirsch observed a significant difference of activation between congruent and incongruent conditions in a brain area that is known to be responsible for face recognition (the fusiform face area, FFA, Kanwisher, McDermott, & Chun, 1997) and which is influenced by control processes (Summerfield, Egner, Mangels, & Hirsch, 2005; Reddy, Moradi, & Koch, 2007). This difference occurred only when faces that were presented were the relevant task information (face task) but not when the faces were distracters (name task). The activation was interpreted as cognitive control exerted to amplify the relevant information. There was no difference in FFA activation in the name task, i.e., in the condition when faces were distracters. This indicates that task-irrelevant information (i.e. the names) was not inhibited thus providing evidence against the inhibition hypothesis and the amplification-inhibition hypothesis.

There is also evidence for the inhibition hypothesis. Based on a study presented by Stoffels (1996), Stürmer, Leuthold, Soetens, Schröter, and Sommer (2002) suggest two routes of response selection in the Simon task (e.g., Simon, 1968). One of them works automatically and is driven by the spatial information (i.e., the irrelevant task information) of the target. The other route is controlled and is driven by the target identity (i.e., the relevant task information). It is suggested that the automatic route is inhibited after incongruent trials, leading to a smaller impact of the irrelevant task information. Inhibition of automatic activation can explain the so-called Gratton effect (e.g., Gratton et al., 1992) that is usually observed in conflict tasks (larger congruency effects after congruent than after incongruent trials) and is also believed to reflect cognitive control processes.

Cohen, Dunbar, and McClelland (1990) already described a computational model for the Stroop task similar to the model later promoted by Cohen and Huston (1994). Their model supports the amplification-inhibition hypothesis, as they suggest an excitatory input from the irrelevant pathway (word reading) to the output unit in congruent trials and inhibition coming from the irrelevant pathway in incongruent trials. Further evidence for the amplification-inhibition hypothesis comes from King, Korb, von Cramon, and Ullsperger (2010) who observed a “suppressed response-related activity in sensorimotor cortex” and “enhanced target processing” in the FFA (p. 12759).

Taken together, there are different ways by which control can be exerted. It is thus probable that there are different mechanisms that influence task processing and not one single mechanism that exerts cognitive control in the sense of a central executive (Baddeley, 1986).

### 3.1.5 Summary

The conflict monitoring hypothesis (Botvinick et al., 2004; Botvinick et al., 2001; Kerns et al., 2004) describes how the need for cognitive control can be registered and how task processing can be modulated. The need for control is registered in a conflict monitoring module when conflict arises during task processing. This occurs in the output modules of task processing models, when two streams of incompatible information activate incompatible responses. Upon conflict registration task processing is modulated by a feedback loop from the conflict monitoring unit to the control unit. This control unit then excites or inhibits units or subunits responsible for certain task requirements, e.g., reading the word or naming the color in a Stroop task. Thus, cognitive control describes how task processing is modulated upon conflict to be more efficient, i.e. faster or less error prone. The model builds upon models that have been found appropriate to describe processing in several different tasks, for example, the Stroop task (Cohen & Huston, 1994), the Eriksen Flanker task (Cohen, Servan-Schrieber, & McClelland, 1992), or the stem completion task (McClelland & Rumelhard, 1981). Also, many studies reported effects supposedly based on cognitive control processes that can be explained with Botvinick's et al. model, i.e., the conflict monitoring hypothesis.

The next section deals with experimental studies that investigate cognitive control processes. It is shown how and on what grounds these processes can be distinguished. I will explain these distinctions and divide the studies presented into three proposed groups.

## 3.2 Adaptation to conflict

Cognitive control processes are triggered by the experience of conflict. The model by Botvinick et al. (2001) does not differentiate between any control processes; they are ascribed to the same conflict-detection mechanism. This view, however, was recently challenged by Boy, Husain, and Sumner (2010). In a combined masked-priming and Eriksen-flanker (Eriksen & Eriksen, 1974) task they found an interaction between the negative congruency effect (NCE, e.g., Eimer & Schlaghecken, 2003) and the flanker effect. However, an interaction was absent between the NCE and the Gratton effect. These results suggest that conflict resolution in the current trial and conflict resolution based on conflict in the previous trial rely on distinct mechanisms. Additionally, Funes, Lupiañez, and Humphreys (2010) showed in a combined Simon and spatial Stroop task that different mechanisms are responsible for adjustment to conflict in the previous trial and adjustment conflict experienced over a whole block of trials (see also Purmann, Badde, & Wendt, 2009). They distinguish transient and sustained cognitive control. Transient control processes are those that act in a short timely frame, i.e. within one trial or between two trials. Sustained control processes are those that modulate stimulus processing according to conflict experience over a certain amount of time, e.g., within a block of trials.

Consequently, one can distinguish control processes according to what kind of conflict experience they are based on. First, stimulus processing can be modulated immediately when conflict is experienced within a given trial (e.g., Goschke & Dreisbach, 2008). This happens for example in Stroop tasks, where the word reading is inhibited, in the flanker tasks, where the influence of the flankers is reduced, or in priming tasks, when prime and target are incongruent. The goal of this control process is to lead to a successful execution of the current task (e.g., naming the color, not reading the word). Second, the modulation of information processing can be based on the experience of conflict in the previous trial (trial n-1), e.g., the Gratton effect (e.g., Gratton et al., 1992; Kiesel, Kunde, & Hoffmann, 2006; Kunde, 2003; Kunde & Wühr, 2006; Stürmer et al., 2002). According to Botvinick et al. (2001) this adaptation of stimulus processing between trials can be explained by an increase of attention towards the target in trial n. Third, the amount of conflict experienced over a period of time (e.g., a certain amount of trials) can influence stimulus processing in a given trial. When conflict is frequent within a block of trials, congruency effects are found to be smaller as when conflict in infrequent (Bodner, Masson, & Richard, 2006; Gratton et al., 1992; Tzelgov, Henik, & Berger, 1992).

In the following section I will describe empirical work that investigated effects that are believe to reflect cognitive control processes based on these different experiences of conflict. Due to their empirical distinction (Boy et al., 2010; Funes et al., 2010; Purmann et al., 2009), I will group them in a) within-trial control processes, b) between-trials control processes, and c) sustained control processes.

### 3.2.1 Within-trial control processes

To execute a behavior successfully it is important that control is exerted as soon as conflict arises. This has been investigated in several studies using different paradigms. For example a paradigm investigating the ability to stop the execution of a planned or an ongoing behavior when it is not appropriate anymore is the so-called stop-signal paradigm. Interrupting an ongoing behavior can be assumed to rely on a cognitive control process as it is usually a voluntary action improving the suitability of the current behavior in the environment. For an example, when you are about to cross a road and a car races around the corner without seeing you it is most suitable to stop your current behavior and stay back on the sidewalk. In an experimental paradigm this is, of course, tested differently. Usually, a go signal is presented on a computer screen upon which participants start executing a certain response. In some trials a stop signal is presented at a certain time after the go signal (e.g., between 50 and 500 ms after stimulus onset). Participants are instructed to inhibit the ongoing action as soon as they perceive the stop signal. This paradigm has been used quite often using different tasks and stimulus materials (e.g., Henry & Harrison, 1961; Lappin & Eriksen, 1966; Logan, 1981; Logan & Cowan, 1984; Logan, Cowan, & Davis, 1984; see Logan 1994 for a review). The stop-signal paradigm is a good possibility to uncover and investigate a cognitive control process, namely the inhibition of behavior. It shows that people are able to stop their actions even when they are shortly before execution. This means, not every (possibly automatic) action that is induced by perceived stimuli is also carried out. People can inhibit those actions if they are inappropriate or, more general, do not fit the current goals. This is sometimes also referred to as intentional non-actions (Kühn & Brass, 2009).

Of course, there are more paradigms that demonstrate effects that are attributed to cognitive control processes within a given trial. In the Stroop task (e.g., Egner & Hirsch, 2005) conflict arises from the word meaning, which needs to be suppressed. In the flanker task (e.g., Eriksen & Eriksen, 1974) the flankers surrounding the target need to be inhibited to respond correctly. Mattler (2003, Experiment 4) used a combination of a priming and pre-cueing paradigm to investigate another cognitive control process: the activation of task sets.

This form of control is needed when switching between tasks is necessary, i.e., when more than one task has to be performed. In each trial it is signaled which task needs to be performed. This is done by cues at the beginning of each trial. Upon this cue a task set is specified that contains possible stimuli and responses. Especially, when the task in the current trial is different from the task in the previous trial, this specification is an act of cognitive control.

Further evidence for within-trial control processes was provided by Goschke and Dreisbach (2008). They reported a decreased performance of responding to a task-irrelevant cue in conflict trials compared to conflict free trials. This is interpreted according to their “goal-shielding hypothesis” which states that upon a conflict within a trial the current action goal is enhanced while the influence of distractors is diminished. This interpretation extends the conflict monitoring hypothesis, which at first assumed that information processing is modulated after conflict arises to ensure positive task outcomes in the future. However, the control unit postulated by Botvinick et al. (2001) may also serve the purpose of modulating information processing within a conflict trial.

So there is plenty of evidence for the detection of, and adaptation to conflict within single trials. These mechanisms are very important for correct behavior outcomes. However, experience of conflict does not only elicit immediate control processes but also influences information processing afterwards. In an experiment this can be observed in the influence of conflict in one trial on information processing in the next. I labeled this phenomenon between-trials control processes and will describe some empirical evidence in the following section.

### 3.2.2 Between-trials control processes

The experience of conflict is believed to trigger cognitive control processes that modulate information processing to be more efficient and less error prone. As I just described these processes set in immediately. However, information processing is not just modulated until the conflict experience is over. Instead, it is modulated for a while to maintain successful behavior. Experimentally this becomes apparent, e.g., in behavioral data, in trials following conflict or error trials: Response times increase in trials following error trials. This post-error slowing is believed to reflect a cognitive control process

(Botvinick et al., 2001; Kerns et al., 2005; King et al., 2010; Rabbit & Rogers, 1977; but see also Notebaert et al., 2009) that leads to careful response strategies which improve performance after committed errors. In the conflict monitoring hypothesis (Botvinick et al., 2001) it is proposed that it is not specifically errors that cause this change in the processing strategy but conflict experience. This does not change but extend the predictions regarding post-error slowing. After a trial in which strong conflict is experienced (which happens in error trials) task processing takes place more carefully than after trials in which little conflict is experienced (cf. post-conflict slowing; Verguts, Notebaert, Kunde, & Wühr, 2011).

Another observation indicating between-trials control processes is the Gratton effect (Botvinick et al., 1999; Gratton et al., 1992; Kunde & Stöcker, 2002; Mordkoff, 1998; Stürmer et al., 2002). Participants in the original study (Gratton et al., 1992) performed an Eriksen Flanker task (Eriksen & Eriksen, 1974) in which they were instructed to respond to the central letter of a 5 letter string (HHHHH, SSSSS, HHSHH, SSHSS) with the left or right hand. It was found that responses to incongruent trials (HHSHH, SSHSS) were faster, if the previous trial had been incongruent as well. Responses to congruent trials were faster, if the previous trial had been congruent as well. This finding has often been interpreted in the way that attention is focused after incongruent trials to ensure improved task processing in the next trial. Possibly, after conflict experience irrelevant information is shielded more efficiently and this shielding is weaker after trials that do not induce response conflict. This is propagated by the gating account (Kunde, 2003, Kunde & Wühr, 2006). In other words, congruency effects after incongruent trials are smaller because on the one hand helpful information in congruent trials is inhibited from facilitating the response (and thus, decreasing RTs) and on the other hand detrimental information in incongruent trials is inhibited from interfering with the response. A different proposal has been brought forward in recent studies: It has been suggested that between-trials control processes are influenced by aftereffects (Goschke & Dreisbach, 2008) or the interaction (Scherbaum, Fischer, Dshemuchadse, & Goschke, in press) of within-trial control processes. Unlike in the conflict monitoring hypothesis information processing is not modulated after conflict has influenced task performance but instead is modulated online which may still be observable for a short period of time (i.e., in the next trial). The present study is not designed to differentiate between these views and also investigates sustained control processes instead of within-trial or between trials control processes. I will thus not discuss this topic in much more detail. Instead I will now turn to the fundamental processes underlying the effects of interest in the present study.

### 3.2.3 Sustained control processes

The effects ascribed to the aforementioned control mechanisms can be observed after single conflict experiences. There are also effects that are seen as evidence for control processes that influence information processing based on the experience of conflict over a certain amount of time or a certain number of conflict experiences (within a block of trials). In the following I will describe two experimental findings that are ascribed to such control processes, the conflict frequency effect and the context-specific proportion congruent effect. These are the two effects investigated in the present study.

#### 3.2.3.1 The conflict frequency effect

The conflict frequency effect describes the finding, that congruency effects are larger in experimental blocks, in which the proportion of incongruent trials is low, as compared to blocks in which the proportion of incongruent trials is high. In the latter case, the amount – or frequency – of conflict is higher, which leads the cognitive system to take the conflicting information less into account. This adaptation has been explained with a cognitive control process that is based on how predictive the irrelevant information is throughout the block. Consider the gating account mentioned before (e.g., Kunde, 2003; cf. 3.2.2), which states that more or less attention is paid to the primes depending on their usefulness.

Cheesman and Merikle (1986), as well as Jaskowski, Skalska, and Verleger (2003) reported the just described finding. However, Bodner and Dypvik (2005), who found the same result pattern, provided an explanation that does not assume cognitive control processes, but instead explains the conflict frequency effect in terms of a simple event-learning processes: this is the so-called memory-recruitment account (Bodner & Dypvik, 2005; Masson & Bodner, 2003). This account suggests that processing operations (regarding the task-irrelevant information, e.g., a prime) in a given trial are stored in a memory representation and can support future processing in trials when the same or similar processes are needed. The memory representation gets more distinct with every trial it is recruited for and the facilitation is the stronger, the more distinct the memory representation is. This means, that when a certain trial is frequent in a block of trials, it will be answered faster than less frequent trials. Now consider the experiments reporting an adaptation to conflict frequency: Two types of blocks were presented, one with mainly congruent trials and one with mainly incongruent trials. According to Bodner and Dypvik, in the former blocks the mean RT for congruent trials is decreased, which causes the overall congruency effect to increase. On the other hand, in the latter blocks the mean RT for incongruent trials is decreased, which also decreases the overall congruency effect. Thus, in experiments with blocks containing frequent congruent trials and other blocks containing frequent incongruent trials (e.g., Bodner, Masson, & Richard, 2006; Cheesman & Merikle, 1986; Gratton et al., 1992) the reported difference of congruency effects between those blocks may be explainable in terms of this just described event-learning process instead of cognitive control processes. Other explanations can be derived from different accounts (cf. Hommel, 1998; Hommel, Proctor, & Vu, 2004; Schmidt & Besner, 2008). However, since these explanations can all be dismissed by controlling for equal proportions of congruent and incongruent trials (as described above) I will focus on the account by Bodner and Dypvik (2005) in the present work.

A further alternative explanation derives from the finding of sequential effects (e.g., Gratton et al., 1992; Kunde, 2003). Congruency effects are typically larger after congruent than after incongruent trials. If the proportion of congruent trials in one block is high, more trials are preceded by congruent than by incongruent trials, which artificially boost the overall congruency effect. Vice versa, if the proportion of incongruent trials in a block is high, most trials are preceded by incongruent trials, which decrease the overall congruency effect. This might also have been the case in other experiments reporting a conflict frequency effect (e.g., Cheesman & Merikle, 1986; Bodner & Dypvik, 2005).

However, there is evidence for the assumption that a cognitive control process influences information processing based on the frequency of conflict. Take for example the Stroop task employed by Tzelgov et al. (1992). They varied the proportion of neutral trials throughout the experiment. Participants performed one experimental session consisting of 192 trials. Trials could be congruent, incongruent, or neutral. The proportion of neutral trials was 0%, 25%, 50%, or 75% (varied between participants) and the remaining trials were distributed equally between the congruent and the incongruent condition. The congruency effect varied depending on the proportion of neutral trials: The higher the proportion of neutral trials was the larger was the congruency effect. This also describes a conflict frequency effect: When neutral trials were frequent in a block, less incongruent trials were presented and thus, less conflict was experienced. Conversely, when only few neutral trials were presented, the amount of incongruent trials (and thus the amount of experienced conflict) was higher.

This experimental design rules out the first alternative explanation (event-learning mechanisms, that is, frequent trials are responded to faster) because all relevant trials (congruent and incongruent) are presented equally often within each block. However, the second proposed alternative explanation (sequential effects) cannot be ruled out. When comparing one experimental condition with few conflicts (e.g., blocks with many neutral trials) to another experimental condition with many conflicts (blocks with few neutral trials) the congruency effect in the latter condition may be artificially diminished: In these blocks with many conflicts more trials follow incongruent trials as compared to the blocks with only few conflicts. Regarding the Gratton effect, this may reduce the congruency effect in the respective block and thus produce or boost the conflict frequency effect. On the other hand, it has been shown that the Gratton effect and the conflict frequency effect are evoked by independent attentional systems (Funes et al., 2010; Purmann et al., 2009). One can thus assume that the conflict frequency effect is not a mere artifact of the Gratton effect; however, to be on the safe side this should be analyzed in all respective studies. In conclusion, both aforementioned alternative explanations need to be ruled out to conclude that a “pure” conflict frequency effect (which is brought about by a “pure” cognitive control process) is observed. This is one goal of the present study.

#### 3.2.3.2 The context-specific proportion congruent effect

The context-specific proportion congruent (CSPC) effect has been reported several times (e.g., Corballis & Gratton, 2003; Crump, Gong, & Milliken, 2006; Crump & Milliken, 2009; Lehle & Hübner, 2008; Wendt, Kluwe, & Vietze, 2008). It is based on the conflict frequency effect. However, the CSPC effect is based on a more complex statistical structure. If there are two contexts within an experimental block (with context being, for example, stimulus location) and conflict frequency varies between those contexts, the cognitive system can take the context information into account and adapt stimulus processing context specifically, even if the overall frequency of conflict throughout the whole block is 50%. Basically, the CSPC effect describes the finding of conflict frequency effects in separate contexts within one experimental block.

This is what Crump and Milliken (2009) reported. Participants responded to color patches that were preceded by a color-word prime by naming their respective color. Primes appeared centrally and color patches appeared above or below the center of the screen. Color patches that appeared at one location were mostly congruent to the prime (congruent context) and color patches at the other location were mostly incongruent to the prime (incongruent context). The target location was chosen randomly in each trial. Most importantly, Crump & Miliken used what they called context probes and transfer probes. Context probes were either congruent prime color-patch pairs that appeared frequently in the congruent context or incongruent pairs appearing frequently in the incongruent context. Transfer probes were congruent and incongruent prime color-patch pairs that appeared equally often in both contexts. The results showed that the Stroop effect was larger for trials with the target appearing at the mostly congruent location as compared to trials with the target appearing at the mostly incongruent location. By examining only transfer probes, they were able to rule out the alternative explanation that varying trial frequencies between the contexts were boosting the CSPC effect (cf. Bodner & Dypvik, 2005; memory-recruitment account). An analysis of the results regarding the congruency of trial n-1 and congruency in trial n revealed that the CSPC effect was also not brought about by RT-modulation through sequential modulation. Since both aforementioned alternative explanations (memory-recruitment account and sequential effects) can be dismissed, the results by Crump et al. can be labeled a “pure” CSPC effect. Taken together, they interpret their findings in the way that cognitive control processes can manipulate stimulus processing “on the fly”, i.e. while it happens. Also, control processes can modulate stimulus processing with regard to different contexts: Sustained cognitive control processes appear to be highly flexible and prompt.

#### 3.2.3.3 The conflict monitoring hypothesis and sustained control processes

To explain effects based on pure sustained control processes with the conflict monitoring hypothesis, an additional assumption has to be made. The hypothesis states that the amount of control applied to a task is raised after every conflict trial and lowered after trials without conflict. This can explain the conflict frequency effect in experiments in which the proportion of congruent trials is unequal within blocks (e.g., 80% congruent and 20% incongruent trials in one block and vice versa in the other block; e.g., Cheesman & Merikle, 1986; Lehle & Hübner, 2008). However, this cannot explain a conflict frequency effect, if the proportion of congruent and incongruent trials is equal within the blocks as in Tzelgov et al.'s study (1992). Even more, if conflict frequencies of two different contexts in one block are varied, the conflict monitoring hypothesis provides no explanation.

Mechanisms that could explain the effects of sustained control processes are outlined, for example, by Crump et al. (2006). These authors propose that episodes of performance are stored that include incidental context information and control settings for the processing of task-irrelevant information in specific trial instances. When a certain context is encountered later on, the control settings linked to that context are retrieved automatically. This is comparable to Spapé's (2009) hypothesis that control is closely linked to episodic retrieval and that "episodic traces also contain information regarding executive control" (p. 123).

A new proposal by Verguts and Notebaert (2008; 2009) offers a mechanism possibly underlying this automatic activation of control settings: Conflict does not lead to a modification of task settings in working memory, but instead arousal (induced by conflict) increases through noradrenalin release in the brain (via the locus coeruleus; LC) and leads to stronger binding between all cortical areas that are involved in processing of the current task. This way control settings and task-specific features (like the context) get linked quickly through Hebbian learning and their interaction is facilitated the next time they are needed. This corresponds to the episodic buffer proposed by Crump et al. (2006) and also is also in line with the episodic retrieval proposed by Spapé (2009).

## 3.3 Summary

This chapter was designed to give an introduction to cognitive control processes. These processes are assumed to optimize behavior by enabling the cognitive system to act most suitable regarding the current goal. Stimuli that require incompatible responses elicit conflict in the brain. According to the conflict monitoring hypothesis, the conflict is registered in the frontal brain and control is exerted to solve it. This can happen by means of inhibiting irrelevant information, facilitating relevant information or a combination of both. In experimental settings this can be observed in different paradigms including the Stroop task, the Eriksen flanker task, or masked priming tasks.

Control process can be divided into three groups that I have labeled within-trial-, between-trials-, and sustained control processes. This segmentation derives from the kind of conflict experience the control processes are based on in different experimental setups. Within-trial control processes act immediately after conflict has been registered to ensure a positive task outcome. Between-trials control processes act in the following trial, and represent an adaptation to just recently experienced conflict. One could describe this as a stronger focus on the task after conflicts and a laxer focus on the task after conflict free task performances. The conflict monitoring hypothesis is in line with these observations. Last, sustained control processes are based on extended conflict experience, e.g., the conflict frequency throughout a whole block of trials. Like the between-trials control processes task performance is stronger controlled when conflict is frequent and less controlled when task performance is rarely accompanied by conflict. I explained that the conflict monitoring hypothesis cannot account for some effects in this regard. Crump et al. (2006) propose an additional assumption, namely a storage mechanism for episodes of performance, which allows explaining these effects. Also a mechanism that links processing modules involved in the current task based on Hebbian learning (as proposed by Verguts and Notebaert, 2009) might be suitable to explain effects that are based on longer lasting control processes.

Two known effects that are assumed to be brought about by sustained control processes have been observed in different experimental paradigms: the conflict frequency effect and the CSPC effect. The first describes the observation that frequent conflict in a task (e.g., most trials in a Stroop task are incongruent) leads to lesser influence of the irrelevant information. The CSPC effect is a special variant of the conflict frequency effect: If in one context the frequency of conflict is high and in another context low (e.g., in a Stroop task, stimuli that appear on the left side of the screen are mostly congruent and stimuli on the right side are mostly incongruent), the cognitive system can adopt different, suitable response strategies for each context, even when the contexts are presented in a randomized order.

# 4 Unconscious processing and cognitive control processes

In the last two chapters I discussed the phenomenon of unconscious information processing as well as cognitive control processes. I described a framework on how conscious impressions might arise in the brain, how unconscious processing can be investigated and its working mechanisms. Further I reviewed the conflict monitoring hypothesis, describing how conflict is registered in the brain, and I summarized different forms of cognitive control processes. Now it is time to link these topics together by describing empirical work that tested the necessity of conscious representation of conflicting stimuli for the adaptation of behavior or information processing to conflict through cognitive control processes. To be more specific, it is tested, whether or not the conflict eliciting information needs to be (at least potentially) consciously perceivable or not for the effects that are associated with control processes to occur.

In the following you will find the same segmentation as in the last chapter: within-trial and between-trials as well as sustained control processes. Investigating the relation between cognitive control and unconscious processing may lead to deeper insights in the functions and usefulness of consciousness as well as the nature of cognitive control processes. It is often assumed, or at least implied, that higher order control functions are linked to consciousness and attention (Baars, 1988, 2002; Dehaene & Naccache, 2001; Norman and Shallice, 2000). Within this line of reasoning, one would assume that cognitive control processes will be prompted only when participants in principle can become aware of the respective conflict. Conversely, without conscious experience of the conflicting information cognitive control processes might not become active. The rationale behind the experiments in this chapter is always similar: It is tested whether effects that are known to be elicited by consciously perceived conflict information are also elicited when the conflict information is experienced unconsciously. If they are, it means that conflict adaptation is not a function that consciousness is concerned with. If they are not, one identified one function of consciousness, namely to mediate in the respective conflict situations. This might involve providing information that is relevant for a successful task performance (e.g., context information or control settings) or focusing on certain aspects of the task (e.g., relevant or irrelevant stimuli).

## 4.1 Within-trial control processes

The stop-signal paradigm investigates the inhibition of ongoing behavior. In a study by van Gaal et al. (2009) participants were instructed to stop their response upon perceiving a stop signal (a grey dot). In some trials the dot was clearly perceptible, in others it was masked in a way that it could not be consciously perceived. RTs were slower and the rate of response inhibitions was higher in stop-signal trials, even when the stop-signal was presented subliminally. This is supported by the finding that response inhibition can be unconsciously triggered in a Go/No-Go task (van Gaal, Ridderinkhof, Fahrenfort, Scholte, & Lamme, 2008). No-Go- and Stop-signals respectively increase the inhibition of responses in both studies, even if they were not consciously perceived. Also, ERPs that are typically found in the Go/No-Go paradigm for supraliminal stimulus presentation (Eimer, 1993; Falkenstein, Hoormann, & Hohnsbein, 1999; Kiefer, Marzinzik, Weisbrod, Scherg, & Spitzer, 1998) were measured in the No-Go study in masked No-Go trials, which suggests a similar influence of supraliminally and subliminally presented stimuli.

Another within-trial control process is the preparation of task sets upon a cue (Miller and Cohen, 2001; Koechlin, Ody, & Kouneiher, 2003) which can be found in task-switching paradigms, where participants usually have to perform one of two different tasks indicated by a cue at the beginning of each trial (e.g., Kiesel, Wendt, & Peters, 2007; Mattler, 2003). Against earlier assumptions it has been shown that the preparation of task sets can be elicited by unconscious stimuli (Lau & Passingham, 2007; Mattler, 2003). It thus seems that within-trial control processes do not depend on conscious representation of interfering stimuli.

## 4.2 Between-trials control processes

Since cognitive control processes have been differentiated in several studies (cf., Boy et al., 2010; Funes et al., 2010; Purmann, Badde, & Wendt, 2009) it seems obvious that all variations are tested regarding whether or not they depend on conscious representations of conflict information. I have already mentioned that the Gratton effect is considered to reflect an adaptation of stimulus processing depending on recently experienced conflict. In experimental studies this manifests in larger congruency effects after congruent than after incongruent trials. Kunde (2003) investigated the nature of the Gratton effect in a (masked) priming study: Participants responded to left or right pointing arrows by pressing left or right response keys. Target arrows were preceded by prime arrows that were meta-contrasted and thus not visible in certain trials. It was tested whether the Gratton effect would appear after trials in which the prime was visible compared to trials in which the prime was invisible.

The results suggest that between-trials adaptation to conflicts depends on the awareness of the response conflict. A Gratton effect was observed after trials with clearly visible primes. However, after trials with invisible primes, i.e., trials, in which the conflict remained unconscious, no Gratton effect was observed (see also Greenwald, Draine, & Abrams, 1996). This result was independent of the prime visibility in the current trial. Thus, between-trials control processes seem to depend on the conscious perception of recent conflict. However, they influence stimulus processing regardless of conscious perception of the current conflict.

Although challenged by van Gaal, Lamme, & Ridderinkhof (2010), the results by Kunde (2003) were recently validated by Ansorge, Fuchs, Khalid, & Kunde (in press). Further evidence comes from studies by Nieuwenhuis, Ridderinkhof, Blom, Band, and Kok (2001) and van Gaal et al. (2009). In the latter study a stop-signal paradigm was used to investigate among other questions whether or not post-error slowing would occur after unconscious conflict. Post-error slowing describes the phenomenon that RTs after erroneous trials are longer than after correct trials (King et al., 2010; Rabbit & Rogers, 1977; Rieger & Gauggel, 1999; Schachar et al., 2004). This can also be viewed as a between-trials control process that that prevents repetition of committed errors. Van Gaal et al. (2009) reported post-error slowing after erroneous stop-trials in which the stop signal was consciously perceived: When participants saw the stop signal but failed to inhibit their response, RTs in following Go-trials were slowed down. This was not the case, however, if the stop signal had not been perceived consciously in the previous trial. In conclusion, although there is one study pointing to the possibility of between-trials control processes induced by unconscious conflict, the majority of research regarding this topic suggests the contrary.

## 4.3 Sustained control processes

### 4.3.1 The conflict frequency effect

The present work is mostly concerned with effects reflecting sustained cognitive control processes and their dependence on conscious representations of conflicting stimuli. There are some studies that report findings regarding this topic. For example, as mentioned before, Cheesman und Merikle (1986) found that a high proportion of congruent trials in an experimental block leads to a larger congruency effect in that block (mostly congruent condition) compared to blocks with a low proportion of congruent trials (mostly incongruent condition). However, their results suggest that this adaptation takes place, only when the irrelevant, conflicting or facilitating information was perceived consciously. This conclusion is also suggested by the results of a study by Ansorge, Heumann, & Scharlau (2002, Experiment 3). It was shown in a cueing experiment that participants use knowledge of the predictive validity of a cue to modulate their response strategy. If cues are mostly valid, participants rely on them more than if cues are mostly invalid. However, this modulation of response strategy can only be found for unmasked cues, i.e. cues that were consciously perceivable. Similarly, Merikle and Joordens (1997) and Merikle, Joordens, and Stolz (1995, Experiment 2) found that response strategies can be applied to consciously but not to unconsciously perceived primes in a Stroop task. Taken together, these findings suggest that effects based on longer-lasting conflict experience do not emerge if the conflict inducing information is never consciously discernible.

However, one needs to keep in mind two issues: First, alternative explanations in form of event-learning mechanisms (faster responses to frequent trials) and sequential effects (larger congruency effects after congruent than after incongruent trials) can account for the presented results. It seems necessary to establish a “pure” conflict frequency effect (cf. sections 3.2.3.1 & 3.2.3.2). Second, the studies so far have only investigated whether or not behavioral effects that can be attributed to control processes arise when all conflict-inducing stimuli are perceived consciously as compared to when all conflict-inducing stimuli remain unconscious; however, no condition was investigated in which those two conditions are randomly mixed. Still, I believe that the studies discussed so far are good indicators for the role of conscious representation of conflict information for cognitive control processes. Part of the present study is designed to shed more light on the role of conscious perception of the conflicting stimuli for the conflict frequency effect. This is especially done by ruling out the alternative explanations using an experimental design in which the proportion of congruent and incongruent trials within one block was the same, so that both, congruent and incongruent trials were presented equally often in each block (cf. Tzelgov et al., 1992). Also influences of sequential effects were analyzed, and trials in which the conflicting information can be perceived consciously were randomly mixed within one experiment with trials in which this information cannot be perceived consciously.

### 4.3.2 The context-specific proportion congruent effect

To my knowledge there is no study that investigates the relation between the conscious perception of conflicting stimuli and the CSPC effect[2]. This is one of the goals of the present study. Based on the idea by Miller (1987, 1988) so-called *inducing trials* will be used. This is a similar approach like Crump and Milliken (2009) took (they call their inducing trials context probes). Analyzing trials that were presented equally often in both contexts (test trials) allows dismissing the memory-recruitment account as an alternative explanation and thus allows investigating the influence of unconscious conflict information on a "pure" CSPC effect. The possible influence of sequential modulations is investigated (and can be dismissed) using separate analyses. The method applied in the present study as well as the results will be explained and discussed in detail later on (section 6.1.1).

## 4.4 Summary and outlook on the present study

So far, I presented several studies that investigated whether or not unconscious conflict information can elicit cognitive control processes. Cognitive control processes are seen as those processes that modulate information processing to the best fit for the current

[2] Please note that part of the present study has already been published; see Heinemann, Kunde, & Kiesel (2009).

goal. Conflicting information is presented subliminally using masked priming paradigms. The primes, stimuli presented for short durations of time and masked (e.g., with pattern masking or metacontrast) are presented shortly before the target that participants respond to. If prime stimuli require a different response than the target, conflict arises, that manifests, for example, in RTs and error rates. One can notice that only those control processes that I had labeled “within-trial” are elicited by subliminally induced conflict. This is depicted in Table 1, which summarizes the studies investigating the relation of consciousness and cognitive control presented in this chapter.

**Table 1.** Summary of the studies described in this chapter that investigate the relation of conscious representation of conflict inducing stimuli and cognitive control processes. Only within-trial control processes are elicited by unconscious information. Note that van Gaal et al. (2009) report an activation of between-trial control by unconscious conflict information. However, their study relates to Kunde (2003), and his finding has recently been validated by Ansorge et al. (in press). It is thus still disputable whether between-trials control processes can be elicited by unconscious conflict information or not. In the present study I argue in favor of the majority of studies regarding this topic (namely that unconscious information does not suffice in this case).

| study by | control process | used paradigm | control process elicited by unconscious information? |
|---|---|---|---|
| van Gaal et al. (2009) | Within-trial | stop signal | ✓ |
| van Gaal et al. (2008) | | Go/NoGo | ✓ |
| Lau & Passingham (2007) | | task-switching | ✓ |
| Mattler (2003) | | | ✓ |
| Kunde (2003) | between-trials | masked priming | × |
| Ansorge et al. (in press) | | | × |
| van Gaal et al. (2010) | | | ✓ |
| Nieuwenhuis et al. (2001) | | antisaccade task | × |
| van Gaal et al. (2009) | | stop signal | × |
| Ansorge et al. (2002) | sustained | cueing | × |
| Cheesman & Merikle (1986) | | priming/Stroop | × |
| Merikle & Joordens (1997) | | | × |
| Merikle et al. (1995) | | priming/word completion | × |

However, the distinction between the three kinds of control processes is rather arbitrary and does not explain their differences in depth. So for now I would like to put this distinction aside and focus on the conditions under which unconscious conflicting information suffices to elicit control processes in experimental studies.

First, it seems that the control must be exerted quickly, i.e., within the same trial. This is given in all studies investigating what I labeled “within-trial” and “sustained control processes”. Kunde (2003) and Ansorge et al. (in press) demonstrated that the conflict in the trial n-1 needs to be consciously perceived for control processes to modulate information processing in trial n. This finding has also been briefly mentioned by van Gaal et al. (2009) and Greenwald et al. (1996). It is argued that some sort of memory trace of the conflict must remain from trial n-1 to trial n. It seems that this can only happen, if the conflict is consciously perceived. This might be explainable with studies demonstrating that brain activation through unconscious information is weaker (e.g., Dehaene et al., 2001) and decays faster (e.g., Kiefer & Spitzer, 2000) than activation through conscious information. This is in line with the framework by Crick & Koch (2003) presented earlier: For information to reach consciousness it must run through several loops and activate several related nodes.

Second, it also seems necessary that the conflict is at least sometimes consciously perceived in the experiment. One can conclude that if conflict is never induced consciously, no adaptation effects can be observed (e.g., Cheesman & Merikle, 1986). This might mean that a suitable response strategy (that reflects control processes) can only be based on conflict that is brought about by consciously presented stimuli. This seems in a way comparable to the acquisition of action triggers in the action-trigger account (Kunde et al., 2003). It is proposed that in masked priming experiments subliminal information can only activate responses if the response-eliciting stimuli are expected (which means they have been consciously experienced before). The same could also be valid for stimuli that elicit conflict. If they are not expected, or represented in the system (e.g., because they are never perceived consciously), they do not suffice to produce the respective adaptation effects. It can be argued that response strategies when they are based on conscious conflict information can also be sort of transferred to conflicts that are elicited by unconscious stimuli. This may be the case in the studies regarding within-trial control processes. Take, for example, the study by van Gaal et al. (2009): Participants were instructed to inhibit their ongoing response upon perceiving a stop signal (a grey dot). In some trials the dot was clearly perceptible, in others it was masked in a way that it could not be consciously perceived. It is conceivable that the response strategy that was elicited by the conflicting stimulus (i.e., the stop signal) was first learned in trials with perceivable stimuli and then was transferred to trials with unperceivable stimuli. – In contrast, in the studies regarding sustained control processes the conflicting information was either visible in all trials or in none.

The present work further investigates the necessity of conscious conflict experience for sustained cognitive control processes. To do so, two experimental series were conducted. First, the CSPC effect (e.g., Crump et al., 2006, Crump & Miliken, 2009) was replicated using a response-priming paradigm. It was then tested, whether this effect could also be found under conditions where the conflict inducing information was not discernible. This comparison is similar to the experiments presented by Cheesman and Merikle (1986). In a third step, it was tested, whether a response strategy based on consciously perceived conflict could also be applied to trials in which conflict could not be experienced consciously. So, two extensions to the already existing literature regarding sustained control processes are introduced: First, the alternative explanation provided by the memory-recruitment account is ruled out. This account suggests that in each trial processing episodes are stored and can support similar processing in the future. This leads to a decrease of RTs for frequently presented trials, which may facilitate the CSPC- and the conflict frequency effect.

In studies by Crump and Milliken (2009) as well as Tzelgov et al. (1992), the proportion of (analyzed) congruent and incongruent trials was equal in each context (or block) and still a behavioral effect attributed to control processes was observed; however they did not investigate the role of conscious conflict experience. Second, the transfer of response strategies based on conflict experience elicited by consciously perceivable stimuli to conflict elicited by unconsciously perceivable stimuli has not been investigated explicitly for sustained control processes.

The most important results of this first experimental series of the present study are that pure CSPC effects can be found in a response-priming paradigm when all primes (and thus the conflicts) are perceived consciously but not when all primes are presented subliminally. When mixing conscious and unconscious conflict experiences, no CSPC effect emerges at all. This finding leads to the second experimental series: Instead of the CSPC effect the conflict frequency effect was investigated. Additionally, instead of number stimuli, arrows were presented to produce a larger priming effect. The conflict frequency effect seems to base on a less complex statistical structure compared to the CSPC effect and might thus reveal the results of interest easier. However, the findings were consistent with the first experimental series: Only when all conflicts were induced by supraliminal stimuli, an effect was observed that reflected a control process modulating information processing to facilitate responses.

The overall results suggest that pure conflict adaptation effects can be observed in the paradigms employed here. However, if conflict is always elicited by heavily masked information or if trials with heavily masked and weakly masked conflict information are randomly mixed, the effects disappear, suggesting that a very high proportion, if not all conflicts need to be elicited by consciously perceivable information for these effects to occur. In this way, the present work expands former models regarding this topic, which do not take into account the need for conscious perception of conflict-inducing information.

# 5 Sustained control processes and conscious conflict experience

The following two chapters describe six experiments based on the theoretical overview I have given so far. The experiments aim to investigate whether or not “pure” sustained control processes can be elicited by task irrelevant conflicting information that is never consciously perceived. This is one goal of my work. Additionally, I studied a possible transfer of sustained control processes from situations in which conflict is induced by supraliminal information to conflicts induced by subliminal stimuli, which to my knowledge has not been investigated yet. This is done in two experimental series, one investigating the CSCP-effect (Chapter 6) and one investigating the conflict frequency effect (Chapter 7). Both series follow the same rationale. At first it is tested whether the respective effect can be elicited when the conflicting information is easily perceivable. When the effect has been established, it is tested what role awareness of this conflict inducing information plays in the activation of sustained control processes. Therefore experiments are conducted, in which such information is presented subliminally (which is similar to studies presented above, e.g., Cheesman & Merikle, 1986) or supraliminal and subliminal presentation of this information is randomly mixed, which has not been investigated before.

# 6 The context-specific proportion congruent effect and conscious conflicts

Experiments 1-3 investigate the role of conscious conflict experience for the CSPC effect. This effect has been reported several times (e.g., Corballis & Gratton, 2003; Crump, Gong, & Milliken, 2006; Crump & Milliken, 2009; Lehle & Hübner, 2008; Wendt, Kluwe, & Vietze, 2008), however it is not clear whether or not this effect relies on the conscious perception of the conflicts that evoke it.

## 6.1 Experiment 1

Experiment 1 aimed to find a CSPC effect in a masked priming paradigm. Participants categorized target digits as smaller or larger than 5. The target digit was preceded by a prime digit that required the same (i.e., congruent) or the alternative response (i.e., incongruent) as the target. Contexts were implemented using a colored rectangle that was presented in one of two possible colors as the background for all stimuli in each trial. The task differed in two respects to a ‘‘standard” masked priming procedure: First, in Experiment 1 the primes were masked rather weakly so that their identity and congruency relation to a subsequent target was consciously discernible. Second, a speed instruction was used that forced participants to respond within a certain time window. This was done to encourage participants to use all available information that might help for response selection (including the varying congruency proportions in the different contexts). In contrast to a very restricted ‘‘response window procedure” that urges participants to respond within a narrow time interval after target onset (e.g., Greenwald et al., 1996) the deadline procedure allowed participants to respond within 250 ms from target offset. With this more liberal time window, one can expect congruency effects to manifest primarily in RTs and not in accuracy data as with the strict response window procedure of Greenwald et al. (1996).

To control for event-learning effects (cf. Bodner & Dypvik, 2005), four prime digits and four target digits were used. Eight of the sixteen possible prime-target combinations were congruent and eight were incongruent. A low-interference context was implemented with 80% congruent trials and 20% incongruent trials. Accordingly, a high-interference context was implemented with 80% incongruent and 20% congruent trials. This congruency imbalance was induced by a subset of prime-target combinations, the so-called inducing trials (Miller, 1987, 1988), whereas other prime-target combinations, the test trials, occurred equally often in both contexts (cf. Table 2). In the low-interference context, four out of the eight possible congruent prime-target combinations were presented seven times per experimental block while the other four congruent combinations were presented only once per block. Likewise, in the high-interference context four out of the eight possible incongruent prime-target combinations were presented seven times while the other four incongruent prime-target combinations were presented only once per block. To measure CSPC effects that are not contaminated by frequency manipulations, the analyses were restricted to the test trials that were presented equally often in both contexts. The CSPC manipulation was implemented by the same prime and target pairings for all participants. By doing so, the same prime-target test pairs occurred in high- and low-interference contexts as test trials. Thus, different congruency effects in test trials in the high-interference and low-interference contexts cannot be ascribed to different prime-target identities.

### 6.1.1 Method

**Participants**

Sixteen undergraduate students (15 female, mean age: 22.4 years, range: 19–29) participated for course requirement or for monetary compensation. Three participants were excluded from all analyses because they performed two sessions with different S-R mappings. However, the results do not change substantially when including these participants.

**Apparatus and Stimuli**

An IBM-compatible computer with a 19" VGA display was used. Stimuli were digits presented in the center of the screen in 20 pt. Arial font. The digits 2, 3, 7, and 8 served as primes, the digits 1, 4, 6, and 9 served as targets. Masks were three symbols randomly chosen (without replacement) out of six possible symbols (%, ?, &, b, #, §). The context was set by a colored rectangle (lime or cyan), approximately 9 cm x 7 cm in width and height. It was presented in the center of the screen and served as background for all following stimuli.

**Table 2.** Frequency of prime-target combination in high-interference and low-interferences contexts. Prime-target combinations that are frequent in one of the contexts are inducing trials. Prime-target combination with equal frequency in both contexts is test trials.

| prime | target | # in low-interference context | # in high-interference context | inducing trial | test trial |
|---|---|---|---|---|---|
| 2 | 1 | 7 | 1 | X | |
| 2 | 4 | 1 | 1 | | X |
| 2 | 6 | 1 | 7 | X | |
| 2 | 9 | 1 | 1 | | X |
| 3 | 1 | 1 | 1 | | X |
| 3 | 4 | 7 | 1 | X | |
| 3 | 6 | 1 | 1 | | X |
| 3 | 9 | 1 | 7 | X | |
| 7 | 1 | 1 | 7 | X | |
| 7 | 4 | 1 | 1 | | X |
| 7 | 6 | 7 | 1 | X | |
| 7 | 9 | 1 | 1 | | X |
| 8 | 1 | 1 | 1 | | X |
| 8 | 4 | 1 | 7 | X | |
| 8 | 6 | 1 | 1 | | X |
| 8 | 9 | 7 | 1 | X | |

**Procedure**

Participants were instructed to place their index fingers on the ‘‘F” and ‘‘J” key of a standard QWERTZ keyboard. Each trial consisted of a fixation cross (presented for 700 ms), a pre-mask (70 ms), a prime (26 ms), a blank (60 ms), a post-mask (10 ms) and a target (130 ms). The target was followed by a blank (that lasted until response onset or for a maximum of 1000 ms). Simultaneously with the fixation cross, the colored rectangle that indicated the context appeared and remained on screen until the feedback was given. Each trial was followed by a 700 ms blank.

Participants were instructed to respond within 250 ms after target offset. Error feedback was given for 700 ms directly after the response. Premature responses were indicated by an error message presented for 700 ms. Late responses were indicated 1000 ms after target offset. Incorrect responses that were made during the response window were indicated by a red exclamation mark in the center of the screen.

Each block consisted of 80 trials. The overall number of trials per context was 40 and the overall proportion of congruent trials in the low-interference context was 80% and 20% in the high-interference context. Trials in each block were chosen randomly without replacement.

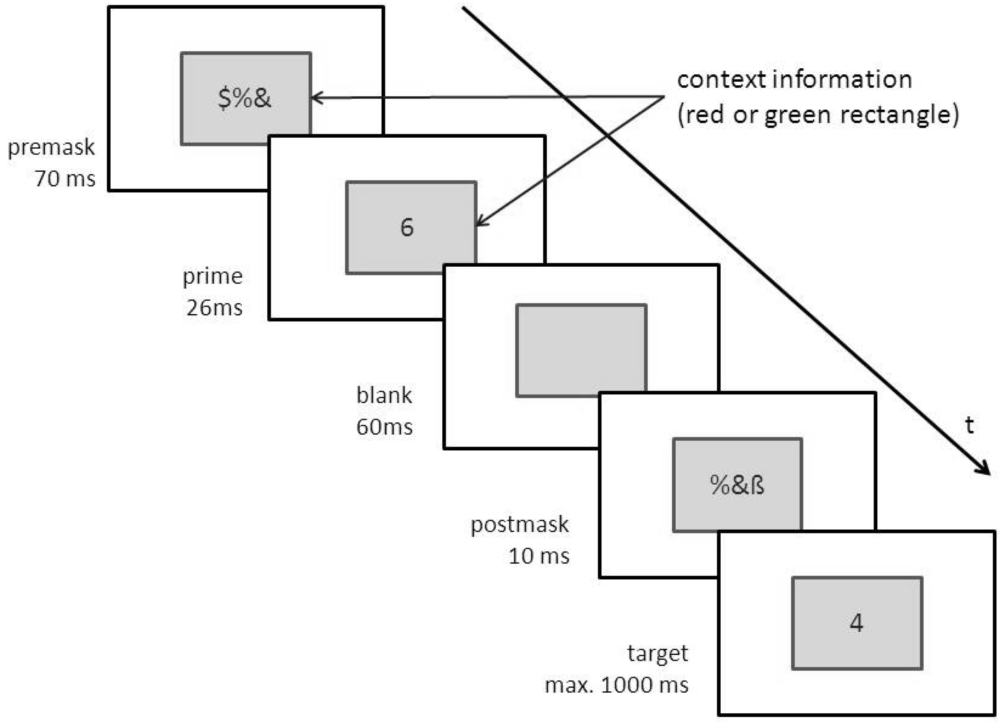


**Figure 3.** Trial procedure in Experiment 1. Participants saw a prime that was preceded by a mask and followed by a blank screen (with the context information) and a mask. The context information was a green or red rectangle. After the second mask the target digit was presented until a response was made but for a maximum of 1000 ms. Then a feedback message was presented.

The experiment consisted of two sessions that were conducted within 4 days. Session one started with two practice blocks for each context. Each of the practice blocks consisted of 80 trials that were all presented in the same context. Thus, participants conducted 2 blocks in the low-interference context (mostly congruent trials) and 2 blocks in the high-interference context (mostly incongruent trials). The order of practice blocks was counterbalanced across participants. After the practice blocks five test blocks with 80 trials each followed. Participants were encouraged to take short breaks between the blocks. Session two consisted of two practice blocks (one per context) that were followed by six test blocks. The mapping between context and proportion congruent was held consistent between sessions.

### 6.1.2 Results

The analysis was confined to the test trials because they provide an unbiased measure of the CSPC effect. Trials with RTs lower than 200 ms or higher than 1000 ms (3.9%) were excluded from the analysis. Error trials (32.9%) were not included in the RT analysis. In order to increase the trial number, correct responses that occurred after the response deadline were included in the analysis. An additional analysis revealed that the data pattern did not change substantially when excluding these responses. Mean RTs for correct responses and mean error rates (percentages of errors, PEs) were submitted to an Analysis of Variance (ANOVA) with the within-subject factors congruency (congruent vs. incongruent) and context (low-interference context vs. high-interference context). Initial analyses revealed no significant influences of the factors block or session, which is why they were not included in the following analyses.

**Response times**

The results of Experiment 1 are depicted in Figure 4. Participants responded 43 ms faster to congruent than incongruent trials (324 vs. 367 ms), $F(1,12) = 28.01$, $p < .001$, and 7 ms faster in the high-interference context than in the low-interference context (342 vs. 349 ms), $F(1,12) = 6.23$, $p < .05$. In the low-interference context RTs amounted to 322 ms for congruent trials and to 376 ms for incongruent trials. In the high-interference context RTs amounted to 326 ms for congruent trials and to 358 ms for incongruent trials. Thus, the response priming effect was larger in the low-interference context than in the high-interference context (54 vs. 32 ms), $F(1,12) = 7.12$, $p < .05$.

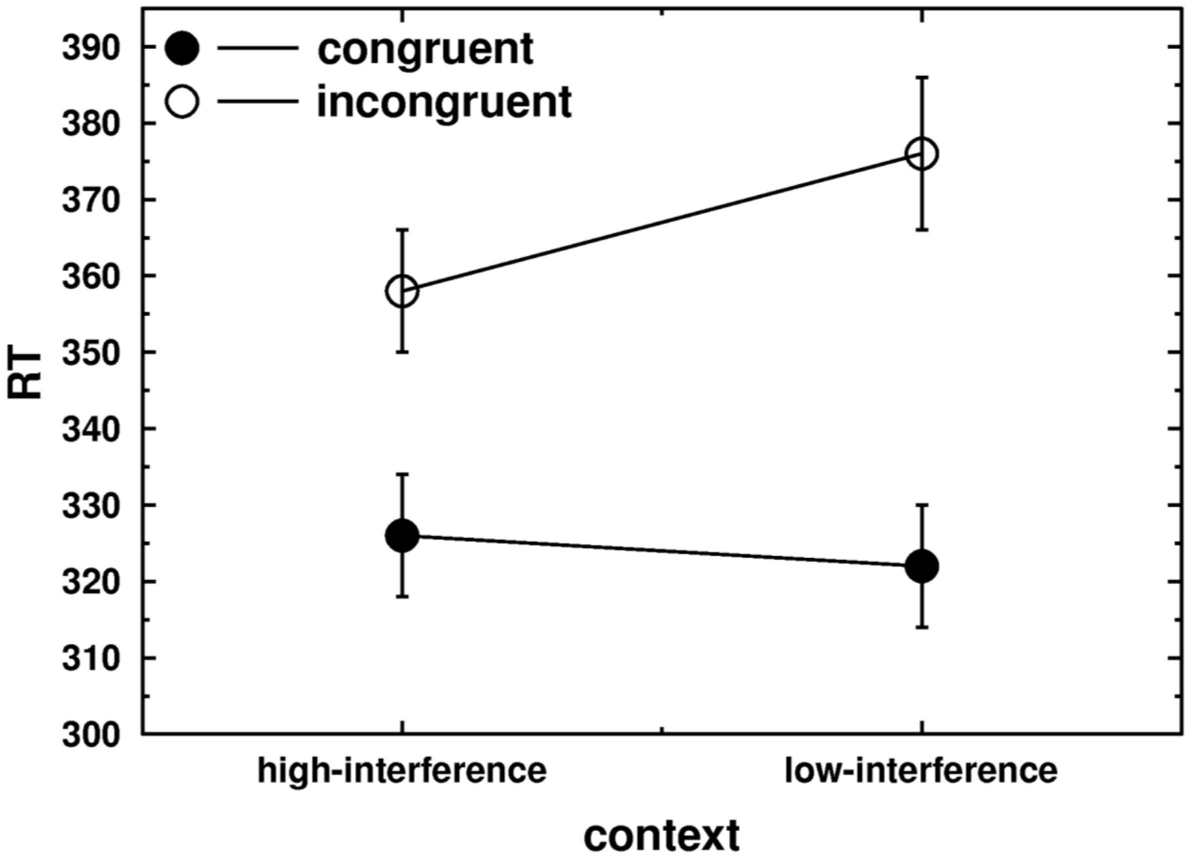


**Figure 4.** Mean RTs and standard errors in Experiment 1 for congruent and incongruent trials in the high- and low-interference contexts. The two-way interaction between the factors context and congruency was significant, representing the CSPC effect (a larger congruency effect in the low- as compared to the high-interference context).

**Errors**

Participants committed fewer errors in congruent than in incongruent trials (17.1% vs. 49.0%), $F(1,12) = 65.24$, $p < .001$. Error rates did not differ in the interference contexts ($F < 1$). In the low-interference context PEs amounted to 17.0% for congruent trials and to 50.3% for incongruent trials. In the high-interference context PEs amounted to 17.2% for congruent trials and to 47.7% for incongruent trials. Thus, the response priming effect in error rates was numerically but not statistically larger in the low-interference context than in the high-interference context (33.3% vs. 30.5%), $p > .26$.

**Prime visibility**

Although the good visibility of the primes in Experiment 1 was almost self-evident, 16 new participants performed a prime-visibility test to obtain an objective measure of prime discrimination performance. Participants were fully informed about the presentation of the primes and were asked to identify whether the prime digit presented in a trial had been smaller or larger than 5. They were told that the possibility for a smaller or larger than 5 prime-digit was exactly 50%. This binary response mode enabled us to compute the signal detection measure *d'* (Tanner & Swets, 1954) as a measure of prime visibility. If participants answered correct and the prime was indeed smaller than 5, this was considered a hit. If participants answered incorrect although the prime was smaller than 5, this was considered a false alarm. Hits or false alarms proportion of zero or one of a participant were corrected using the log-linear rule (Goodman, 1970; cited according to Hautus, 1995). The prime categorization task consisted of two blocks with 64 trials each. Each prime-target combination was presented equally often (2 times) in the visibility task. The trial structure was identical to the experimental blocks. As expected, masking was weak: The *d'*-measure amounted to 2.14 and deviated significantly from 0, $t(15) = 7.22$, $p < .001$.

### 6.1.3 Discussion

Experiment 1 tested whether CSPC effects reflect strategic[3] adaptation of information processing to the conflict setting or whether the CSPC effect merely results from frequent repetitions of specific distractor-target combinations. To explore this, a masked-priming paradigm was used. Participants categorized digits as smaller as or larger than 5 by pressing

[3] Strategic does not imply intentional in this case. I use the expression to describe different ways of information processing depending on conflict frequency in the two contexts and to distinguish the influence of control processes from mere event-learning mechanisms as described for example by Bodner and Dypvik (2005). They argue that conflict adaptation effects (like the CSPC effect) are brought about by performance facilitation of frequently presented trials. To rule out this explanation in the present study, only trials that were presented equally often in both contexts were analyzed.

a left or right response key. Two contexts were implemented by presenting stimuli either in front of a red or a green color patch. One was a high-interference context, in which conflict trials were frequent. The other context contained only few conflict trials. So-called inducing trials were used, which were specific prime-target combinations that were presented more frequently in one context and thus, changed the proportion of congruent or incongruent trials in this context. In addition, there were test trials, which are other prime-target combinations that were equally frequent in both contexts. These test trials were diagnostic for frequency-unbiased CSPC effects.

In line with recent results of Crump and Milliken (2009), a larger congruency effect was found for test trials in a context with mainly congruent trials as compared with a context with mainly incongruent trials. Although it is hard to estimate to which extent previous reports of context-specific congruency effects are mediated by other factors, such as trial frequency, it can be ruled out that such factors account for the CSPC effect in the present priming task. Therefore the idea that these effects are brought about by control processes that regulate the impact of irrelevant information context-specifically remains a viable explanation. The present results further support the recently proposed episodic account of CSPC effects by Crump et al. (2006) and are also in line with the explanation provided by Verguts and Notebaert (2008, 2009; cf. 3.2.3.3). Crump suggested that episodes of performance are stored that include information about the context as well as control settings for the processing of conflicting information. Later, when a certain context is encountered, he proposes that the control settings linked to that context are retrieved automatically.

Verguts and Notebaert suggest that binding between all cortical areas that are involved in processing of the current task occurs when conflict is encountered. This way, if conflict is encountered again, processing is facilitated, leading to better performance.

As mentioned before, the observed CSPC effect might be driven by sequential, trial-to-trial modulations of the interference effect (i.e., a reduction of congruency effects after incongruent trials; e.g., Gratton et al., 1992) rather than context-specific modulations of the interference effect. This is because there are more congruent trials in the low-interference context, leading on average to increased congruency effects in the following trials and more incongruent trials in the high-interference context leading on average to reduced congruency effects in the following trials. To check this possibility, a further analysis was conducted including the factors congruency in trial n-1, context in trial n-1, congruency in trial n, and context in trial n. There was no interaction between congruency of trial n-1 and congruency of trial n (i.e., ‘‘Gratton effect”), $F < 1$. This observation is interesting as such, since it may suggest that changing contexts destroy otherwise robust sequential effects. More importantly, it substantiates the claim that a sustained cognitive control process is responsible for the observed CSPC effect.

Although non-diagnostic for pure CSPC effects, it might nevertheless be interesting to take a look at the inducing trials, i.e., those prime-target combinations that were more frequent in one context than in the other. An inspection of the data from inducing trials revealed that the CSPC effect was not larger but if anything smaller than in test trials (in fact nonsignificantly negative). In the high-interference context, the congruency effect amounted to 47 ms whereas it amounted to 41 ms in the low-interference context. Interestingly, a similar pattern has emerged in the study by Crump and Milliken (2009, Experiment 2). These authors observed a slight positive CSPC effect in their test trials (transfer trials) and a slightly negative effect in inducing trials (context trials) in the beginning of the experiment. This data pattern suggests that the creation of associations between specific primes, contexts, and target identities did not play a big role here; otherwise the CSPC effect would be larger in the inducing trials than in the test trials. Yet, future research is certainly necessary to confirm the reliability and to investigate potential causes of this somewhat unexpected data pattern.

One also has to consider that response-related associations could be responsible for the present CSPC effect. Although the frequency manipulation of the trials does not allow the building up of associations between responses on the one hand and individual primes, targets, or contexts on the other hand (cf. Table 2), it is possible that responses became associated with certain combinations of primes and contexts irrespective of the presented target stimulus in the trial. Consider, for example, that in the low-interference context the prime number 2 appears 4 times as often in conjunction with a left response as in conjunction with a right response, and this ratio is reversed in the high-interference context. It seems therefore possible that context specific prime-response associations might contribute to the present CSPC effect. Yet, there are reasons to doubt the contribution of such links in the first place. First, such links have to be established between a response and an ensemble of context and prime. Wendt and Luna-Rodriguez (2009) explored the potential impact of frequency differences between stimulus ensembles (target and flanker identities in their case) with a negative outcome. The inefficiency of frequency differences between event ensembles might also be inferred from the analysis of the inducing trials. As noted, frequent ensembles of context, prime, and target (inducing trials, e.g., 2–1 in the low-interference context) did not generally fasten responding compared to trials with the same level of congruency but a lower frequency (e.g., 2–4). For congruent prime-target pairs RTs amounted to 324 ms with test trials and 320 ms with inducing trials. For incongruent prime-target pairs RTs amounted to 367 ms with test-trials and 368 ms with inducing trials. Second, Crump and Milliken (2009) observed CSPC effects despite equal frequencies of distractor identities in different contexts. Admittedly this does not rule out the contribution of context-specific prime-response links for the present study but it shows that CSPC effects can occur in principle even when such links are impossible. Based on this, I assume that also the effect reported in the present experiment is not influenced by such links.

Finally, a comment on error rates seems warranted. Due to the use of a response deadline, error rates were relatively high (e.g., 50.3% and 47.7% for incongruent items in the low-interference and high-interference contexts, respectively). This should not be misinterpreted that participants were guessing. In fact, it is not uncommon for interference tasks that with very fast responses error rates in incongruent trials considerably exceed the 50% guessing probability (Stins, Polderman, Boomsma, & de Geus, 2007). This simply shows that the primes exert a very strong impact on responding. If responding was entirely determined by prime information, error rate would approach 100% in incongruent trials.

To summarize, Experiment 1 revealed a CSPC effect, that is, an adaptation to different conflict frequencies in two contexts within one block. This effect was not artificially created by sequential modulations of congruency effects (e.g., Gratton et al., 1992) or response facilitation of frequently presented trials (e.g., Bodner & Dypvik, 2005). The conflicting information, i.e., the primes, was easily detectable in all trials. In the following experiments it is investigated, whether this effect can also be observed under conditions in which the primes are never or only sometimes this clearly perceptible.

## 6.2 Experiment 2

When do control processes that regulate the context-specific impact of irrelevant information become activated? As explained before, some theories link cognitive control to consciousness (Baars, 1988, 2002; Dehaene & Naccache, 2001). These theories postulate that only a conscious representation of the conflict event has the capability to elicit cognitive control processes and thereby a change of information processing. Yet, such claims can be disputed. Consider for example the model put forth by Botvinick and colleagues (2001). In this model, cognitive control regulates the impact of irrelevant information on responding as an automatic consequence of preceding response conflict. Consequently, conscious awareness of the conflict does not play any role.

To explore the role of consciousness for context-specific adaptation effects the procedure of Experiment 1 was slightly modified. The irrelevant information that was helpful or detrimental for response selection (i.e., the prime) was now masked more heavily. Numerous studies demonstrate that masked primes that are not perceived consciously influence responding nevertheless (e.g., Dehaene et al., 1998; Eimer & Schlaghecken, 2003; Kiesel, Kunde, & Hoffmann, 2007; Klotz & Neumann, 1999; Kunde, Kiesel, & Hoffmann, 2003, 2005; Vorberg, Mattler, Heinecke, Schmidt, & Schwarzbach, 2003). When the irrelevant information is not consciously represented, participants have no clue whether the irrelevant information is more helpful in one context than the other. If the control processes responsible for the CSPC effect run entirely out of consciousness the same result pattern as in Experiment 1 can be expected. If, however, the CSPC effect depends on a conscious representation of the conflict information, one would expect no context-adaptation effects.

### 6.2.1 Method

**Participants**

Sixteen undergraduate students (12 female, mean age: 24.5 years, range: 19–44 years) participated for course requirement or for monetary compensation.

**Apparatus and stimuli and procedure**

Experiment 2 differed from Experiment 1 only in one regard. The 60 ms blank that was presented after the prime in Experiment 1 was now also filled by the post-mask. Thus, the post-mask directly followed the prime and was presented for 70 ms.

### 6.2.2 Results

**Response times**

The results of Experiment 2 are depicted in Figure 5. The same outlier criterion as in Experiment 1 was used. RT outliers (3.8%) and errors (27.3%) were excluded from the analysis. As in Experiment 1, no significant influences of the factors block or session were found, which is why these factors were not included in the following analyses.

RTs and PEs from the test trials were submitted to an ANOVA with the within-subject factors congruency (incongruent vs. congruent) and context (high or low proportion of congruent trials). Participants responded 22 ms faster in congruent than in incongruent trials (335 vs. 357 ms), $F(1,15) = 18.36$, $p < .001$. Context had no effect on RTs, $F(1,15) < 1$. In the low-interference context RTs for congruent trials amounted to 337 ms and RTs for incongruent trials amounted to 358 ms. In the high-interference context RTs amounted to 333 ms for congruent trials and to 356 ms for incongruent trials. Thus, the congruency effects in both contexts did not differ, $F(1,15) < 1$.

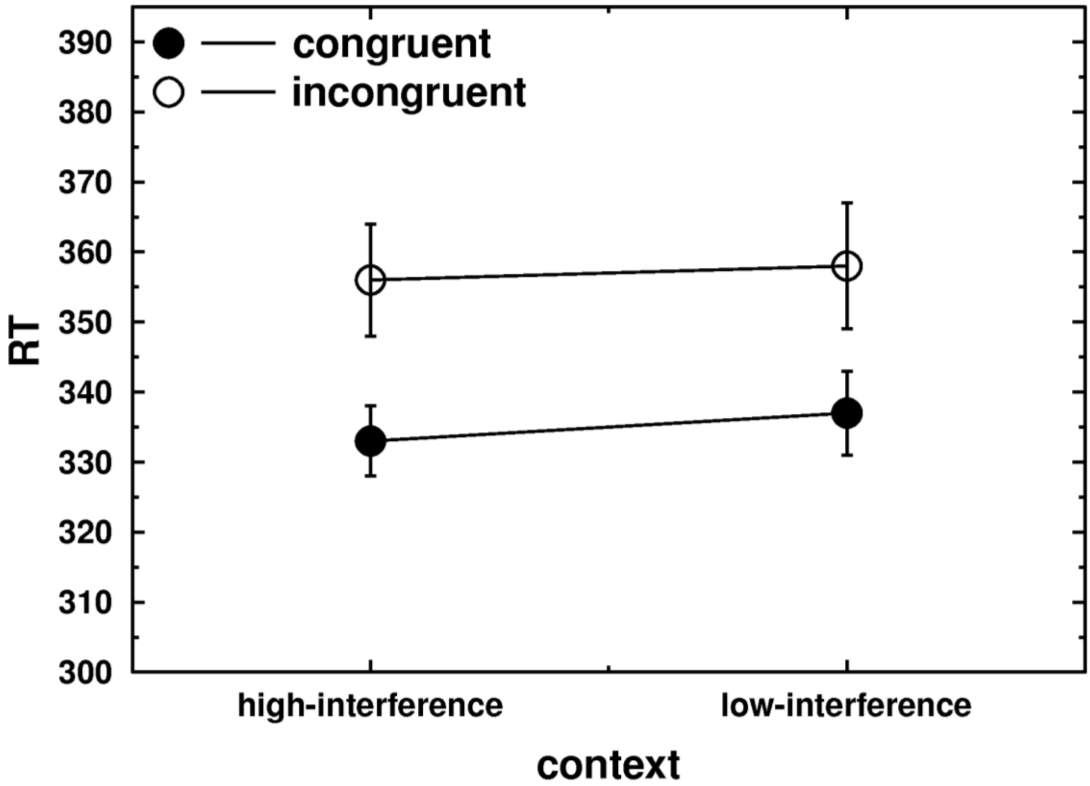


**Figure 5.** Mean RTs and standard errors of Experiment 2 for congruent and incongruent trials in the high- and low-interference contexts. The two-way interaction between the factors context and congruency that was found in Experiment 1 vanished in Experiment 2 due to heavier masking of the primes.

### Errors

Participants committed fewer errors in congruent than in incongruent trials (17.6% vs. 37.0%), $F(1,15) = 35.74$, $p < .001$. In the frequently congruent context PEs amounted to 17.4% for congruent trials and to 35.1% for incongruent trials. In the frequently incongruent context PEs amounted to 17.8% for congruent trials and to 38.9% for incongruent trials. The congruency effects did not differ between the two contexts, $F(1,15) < 1$.

### Prime visibility

In contrast to Experiment 1 the prime visibility test in Experiment 2 was conducted at the end of session 2 and not by a novel group of participants. The signal detection measure $d'$ was computed as described in Experiment 1 and amounted to $d' = 0.79$. This $d'$ was smaller than in Experiment 1 ($t(15) = 4.01$, $p < .01$ for the difference between Experiment 1 and 2) but still different from 0, $t(15) = 6.43$, $p < .001$.

To test whether the observed congruency effects were related to prime visibility, a regression analyses was conducted as proposed by Draine and Greenwald (1998) (see also Greenwald, Klinger, & Schuh, 1995; Greenwald et al., 1996). Therefore, individual *d′* values were computed as well as mean RTs for each congruency condition (congruent vs. incongruent). A congruency index was computed for each participant, with index = 100 x ((RT incongruent–RT congruent)/RT congruent). The individual congruency indices were regressed onto the individual *d′* value of each participant. It was tested, whether the intercept and the correlation between *d′* and the priming index deviated significantly from 0. An intercept larger than 0 indicates that a congruency effect also occurs with zero visibility. If the correlation does not differ from 0, this indicates that the congruency effect does not increase (or decrease) with prime visibility.

The regression of the congruency index on *d′* revealed a significant intercept of 11.89, $t(15) = 2.40$, $p < .05$. The correlation did not differ significantly from 0 ($r = .082$, $t(15) = .31$, $p > .76$). Thus, there was a congruency effect even in the range of zero prime visibility, and there was no correlation between prime visibility and congruency effect.

### 6.2.3 Discussion

Experiment 2 was conducted to test whether CSPC effects are observed when only masked primes are used, i.e., the different conflict frequencies in the contexts remain unconscious, or whether conflict events have to be consciously represented to induce context-specific adaptation of congruency effects. The same experimental set-up was used as in Experiment 1 with one modification. After the prime the post-mask was presented immediately, eliminating the blank that was presented in Experiment 1. Crucially, the stimulus-onset asynchrony, i.e., the time between prime onset and target onset was kept constant. This masking procedure was supposed to reduce, if not prevent prime visibility, thus rendering the response conflicts that arise unconscious.

Even though the masking procedure of the primes in Experiment 2 did not fully prevent prime visibility, the reduction of prime visibility compared to Experiment 1 sufficed to entirely remove the context-specific adaptation effect observed for the test trials in Experiment 1. This finding indicates that a conscious perception of the stimuli that induce response conflicts is a prerequisite for the CSPC effect. Regarding the episodic account by

Crump et al. (2006) the present results suggest that the crucial ingredients of such episodes, namely relevant target information, irrelevant prime information, and context have to be consciously accessible, or at least have to be sufficiently strong, to become stored in such an episodic buffer. Similarly, regarding the account proposed by Verguts and Notebaert (2009) the conflict might need to be sufficiently strong to get passed on and elicit binding between the areas involved in task processing (cf. section 3.2.3.3).

Comparing Experiments 1 and 2, one has to regard the amount of interference for CSPC and conflict frequency effects. Specifically, one may argue that the crucial differentiating factor between Experiments 1 and 2 was not the visibility of the irrelevant information as such, but the impact of that information on response selection. In fact, even though the prime-target stimulus-onset asynchrony, which is the main determinant of congruency effects (Vorberg et al., 2003) was identical, the prime's impact on responding in terms of the congruency effect was larger in Experiment 1 than in Experiment 2 (43 vs. 22 ms). For some reason, the system might be more willing to take into account context-specific variations of congruency the more interfering or helpful the irrelevant information is. In fact it would be a novel and interesting question whether the general impact of primes (i.e., the size of observed congruency effects) might determine the occurrence of CSPC effects.

Although the present study was not designed to disentangle the contribution of size of interference and awareness of interference for CSPC effects, I conducted a regression analysis with the combined data of Experiments 1 and 2. The dependent variable was the size of the CSPC effect in RTs (i.e., congruency effect in the low-interference context minus congruency effect in the high-interference context). The independent variables were 'experiment' (coded as 0 and 1, representing Experiment 1 and 2) and mean congruency effect of each participant.

The predictor experiment was almost significant, $\beta = .35$, $t = 1.86$, $p = .07$. This reflects the presence of a CSPC effect in Experiment 1 and the lack thereof in Experiment 2. Importantly, the mean congruency effect of each participant did not predict the size of the CSPC effect, $\beta = .21$, $t = 1.12$, $p > .27$. This lack of significance does not seem to be due to unreliability of the independent or dependent variables. To obtain an index of re-test reliability the congruency effects and the CSPC effects between sessions 1 and 2 were correlated. The congruency effects in both experiments correlated significantly between sessions (all $r > .51$, all $p < .05$), as did the CSPC effect in Experiment 1 ($r = .56$, $p < .05$).

Given the outcome of these analyses, the interpretation that the accessibility of context-related congruency frequencies rather than the overall interference level determines the size of CSPC and conflict frequency effects seems plausible. This conclusion accords with recent studies on sequential modulations of congruency effects that were also considered to reflect cognitive control processes. Like the CSPC and conflict frequency effect in the present study, sequential modulations have been obtained with visible but not with invisible conflicting information despite roughly equivalent congruency effects (Frings & Wentura, 2008; Kunde, 2003). However, it might be possible that control settings that are responsible for the CSPC effect can be activated by but not employed on conflicts induced by imperceptible stimuli. This possibility was tested in Experiment 3.

Last, an analysis of the inducing trials in Experiment 2 revealed a similar pattern as in Experiment 1. The CSPC effect was nonsignificantly reversed (27 ms vs. 17 ms in Experiment 2). This finding supports the notion that associations between specific primes, contexts, and target identities are not responsible for the CSPC effect. If this was the case one would have to expect the CSPC effect to arise in the inducing trials, even if no effect could be found in the test trials.

## 6.3 Experiment 3

The results of Experiment 2 suggest that no context-specific proportion congruent effect can be found when primes cannot be represented consciously. Two possible interpretations result from this finding: On the one hand, one can conclude that the cognitive system cannot detect the context-specific proportion congruent manipulation (and thus cannot respond to it). On the other hand, one can assume that control processes can be implicitly activated but cannot be employed on conflicts that do not gain access to consciousness. To distinguish between these two possibilities, Experiment 3 was conducted as a mixture of the first two experiments. Trials with weakly masked primes as well as trials with heavily masked primes were both presented within the same block. That way the context-specific proportion congruent manipulation can be noticed by the cognitive system in the trials with weakly masked primes. It is then testable, whether control strategies that can be activated by and applied to trials with weakly masked primes are transferred in trials with heavily masked primes.

### 6.3.1 Method

#### Participants

Thirty-two undergraduate students (23 female, mean age: 23.1 years, range: 18-32 years) participated for course requirement or for pay.

#### Apparatus and stimuli and procedure

Experiment 3 was designed as a mixture of Experiments 1 and 2. The apparatus and general procedure were the same as in Experiments 1 and 2. However, trials with heavily masked primes (as in Experiment 2) were randomly mixed with trials with weakly masked primes (as in Experiment 1). Of 112 trials in each block 32 were presented heavily masked. Weakly masked primes thus appeared in 71.4% of the trials (including inducing trials). Participants conducted two sessions. Session 1 started with two practice blocks for each context followed by four test blocks. Sessions 2 started with one practice block for each context followed by three test blocks and two blocks of the prime visibility test.

### 6.3.2 Results

#### Response times

The results of Experiment 3 are depicted in Figure 6. The same outlier criterion as in the first experiments was used. Trials with too fast or too slow responses (3%) and error trials (27.2%) were excluded from the (RT) analyses. RTs and PEs from the test trials were submitted to an ANOVA with the within-subject factors prime visibility (good vs. poor), congruency (incongruent vs. congruent) and context (high or low proportion of congruent trials).

Participants responded 10 ms faster in trials with good prime visibility as compared to trials with poor prime visibility (336 ms vs. 346 ms), $F(1,31) = 17.12$, $p < .001$. RTs did not differ between contexts, $F(1,31) < 1$. Responses to congruent trials were 32 ms faster than responses to incongruent trials (357 ms vs. 325 ms), $F(1,31) = 143.05$, $p < .001$. The congruency effect was 22 ms larger for trials with good prime visibility as compared to trials with poor prime visibility (43 ms vs. 21 ms), $F(1,31) = 24.64$, $p < .001$. The two-way interactions prime visibility x context and congruency x context, as well as the three-way interaction prime visibility x congruency x context did not reach significance, all *p > .24*.

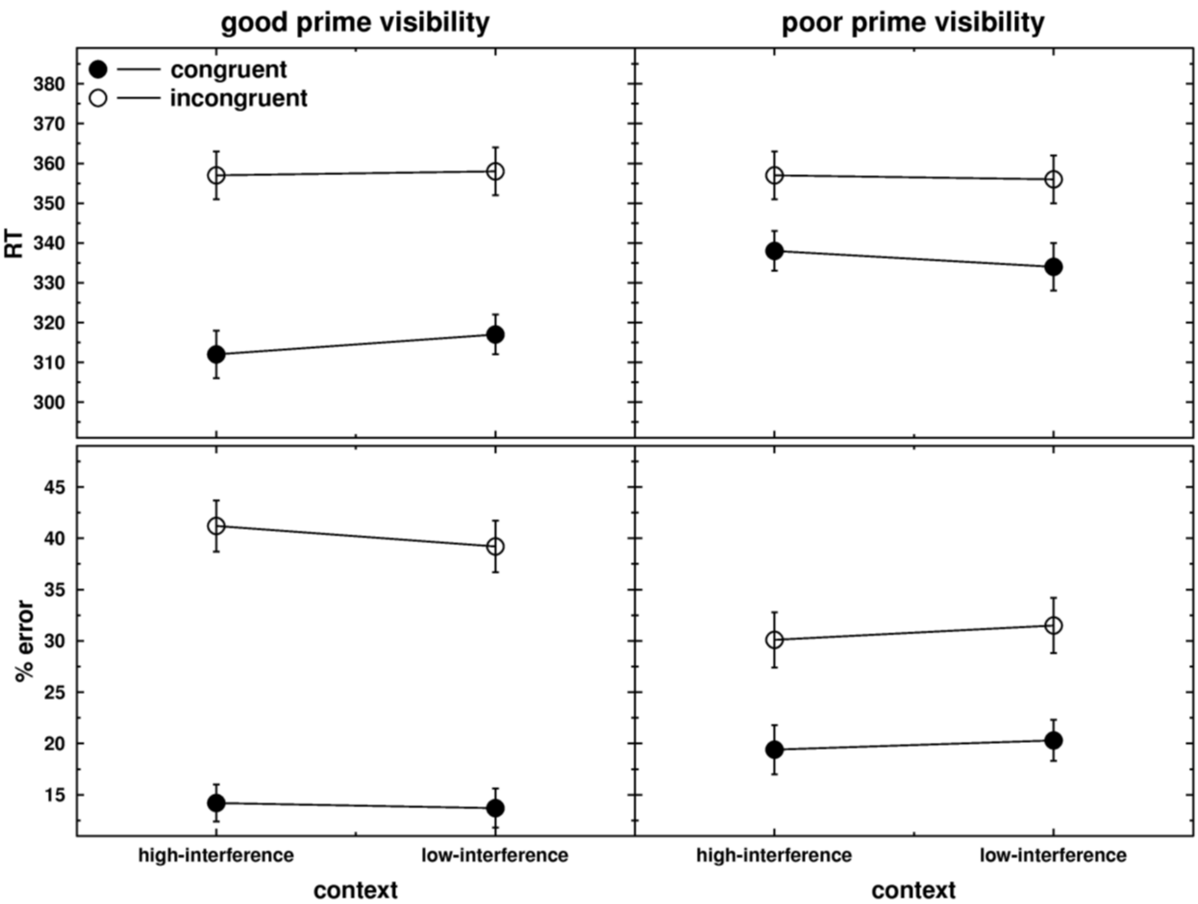


**Figure 6**. Mean RTs and error rates (with standard errors) of Experiment 3 for congruent and incongruent trials in the high- and low-interference contexts, separate for trials with good and poor prime visibility.

**Errors**

Participants committed 1.8% more errors on trials with good prime visibility as compared to trials with poor prime visibility (27.1% vs. 25.3%) and this difference was marginally significant, $F(1,31) = 3.53$, $p = .07$. Responses to congruent trials were less error prone than responses to incongruent trials (16.9% vs. 35.5%), $F(1,31) = 175.18$, $p < .001$. The congruency effect was larger for trials with good prime visibility as compared to trials with poor prime visibility (26.2% vs. 10.9%), $F(1,31) = 43.40$, $p < .001$. The congruency effect did not differ between the high- and low-interference contexts, $F < 1$, and this was not modulated by prime visibility, $F < 1$.

**Prime visibility**

The signal detection measure *d′* was computed as described in Experiment 2. Single measures were computed for heavily and weakly masked primes. For the weakly masked primes $d' = 2.76$ and differed significantly from 0, $t(31) = 17.16$, $p < .001$. For the heavily masked primes $d' = 1.21$ and also differed significantly from 0, $t(31) = 12.82$, $p < .001$. Additionally, weakly masked primes were easier to discriminate than heavily masked primes, $t(31) = 11.54$, $p < .001$.

Two regression analyses (cf. Experiment 2) with the *d′* measures (weakly and heavily masked) as the independent variables and congruency indices as the dependent variables were conducted. For the good prime visibility condition the regression of the congruency index on *d′* revealed a significant intercept of 10.82, $t(31) = 2.42$, $p < .05$. The correlation did not differ significantly from 0 ($r = .13$, $t(31) = .71$, $p > .48$). Thus, there was a congruency effect even in the range of zero prime visibility, and there was no correlation between prime visibility and congruency effect. For the poor prime visibility condition the regression of the congruency index on *d′* also revealed a significant intercept of 5.27, $t(31) = 2.27$, $p < .05$. The correlation between *d′* and congruency effect did not differ significantly from 0 ($r = .08$, $t(31) = .45$, $p = .65$).

### 6.3.3 Discussion

Experiment 3 was conducted to distinguish between two possible explanations of the combined results of Experiments 1 and 2. It is possible that CSPC effect cannot arise when the respective conflict information never accesses consciousness. Also, it is possible that the underlying control processes can be implicitly activated but cannot be employed on conflicts that do not gain access to consciousness. To test for these possibilities, Experiment 3 was conducted as a mixture of Experiments 1 and 2. Both, trials with supraliminal (as in Experiment 1) and subliminal (as in Experiment 2) primes were presented. This way it was observable whether the control processes responsible for the CSPC effect transfer from trials in which the conflict information was presented supraliminally to trials in which the information was presented subliminally. The results of Experiment 3 are surprising in the way that no CSPC effect was observed, even for trials with weakly masked primes. This result seems unexpected considering the outcome of Experiment 1. Assuming that cognitive control processes are responsible for the CSPC effect one can conclude that those processes seem not to be activated at all when the conflict information is sometimes consciously perceivable and sometimes not. Possibly this is due to the fact that the frequency of consciously perceived conflict-inducing information was lower in Experiment 3 than in Experiment 1. While in the first experiment of the present work 100% of the conflict inducing information was at least possible to perceive consciously, in Experiment 3 this proportion was reduced to 71.4% of all conflict-inducing information. It can be concluded that the proportion of conflict-inducing trials needs to be larger than this to elicit an observable CSPC effect.

## 6.4 Summary of Experiments 1-3

The present work was conducted to shed light on the nature of sustained control processes. These processes are elicited by a frequent experience of conflict and modulate stimulus processing accordingly. If conflict is frequent, information is processed “more carefully”, meaning that conflicting information is in some way prevented from influencing processing of the task relevant information. This could be achieved by focusing attention on the relevant information or withdrawing it from the irrelevant information (cf. section 3.1.4).

One interesting question is whether or not the information that elicits the conflict needs to be consciously perceived for the sustained control processes to become active. In Experiments 1-3 this question was investigated for the context-specific proportion congruent effect using a masked priming paradigm. This effect describes a modulation of the congruency effect depending on different amounts of conflict in two contexts. The congruency effect is larger in the context with low conflict frequency and smaller in the context with high conflict frequency.

In Experiment 1 all primes were presented clearly visible. A CSPC effect was observed in the response times. This effect is most likely brought about by a cognitive control process and not by lower level learning mechanisms (e.g. the event-learning as described in the memory-recruitment account by Bodner & Dypvik, 2005) as it had also been suggested before. This conclusion is suggested by analyzing only trials that were equally frequent in both contexts and were thus not susceptible to those learning mechanisms. Additionally, a further analysis revealed that sequential effects could also not account for the observed effect.

Experiment 2 was a replication of Experiment 1 with the exception that the primes were masked more heavily. Although the primes were not completely presented subliminally, the decreased visibility sufficed to eliminate the CSPC effect. This result suggests that the conflicting information responsible for the CSPC effect needs to be consciously perceivable for the effect to occur. This was further tested in Experiment 3. Heavily and weakly masked primes were presented in a random order to test whether control processes that were activated by consciously perceived conflict information (as in Experiment 1) could transfer to trials in which this information remained unconscious. Interestingly, no CSPC effect occurred at all. This may indicate that CSPC effects (or sustained control processes in general) are rather fragile. The random presentation of subliminal conflicting stimuli somehow seems to inhibit the activation of control processes in the conscious-conflict trials. Possibly, the accumulation of evidence of conflict in the respective contexts is interrupted or hindered when trials, in which the conflict inducing information is not consciously perceptible, are interspersed. This may be due to the fact that the proportion of consciously perceivable conflict information was too low in Experiments 2 and 3 (0% and 71.4% respectively) as compared to Experiment 1, in which 100% of all conflict-inducing information was consciously perceptible. Information about the conflict frequency in the contexts was probably not noticed in Experiments 2 and 3 because of the too small proportion of consciously perceived conflict-inducing information and the processing of this information was consequently not modulated.

All in all, Experiment 1 revealed the possibility that the impact of irrelevant information in a conflict paradigm can be modulated on the fly depending on the proportion of congruent trials in two randomly changing contexts. This modulation is assumed to be brought about by a cognitive control processes. However, for this control process to become active, a conscious representation of the response conflict eliciting stimulus is necessary (cf. Experiment 2). The results of Experiment 3 suggest that the activation of control is even hindered for trials in which this information can be perceived consciously when those trials are intermixed with trials in which the information is not as easily detectable.

# 7 The conflict frequency effect and conscious conflicts

As noted before, the CSPC effect is a variation of the conflict frequency effect. It basically describes two conflict frequency effects, one each for two different contexts. Thus, it appears that the statistical structure driving the CSPC effect is more complex than with the conflict frequency effect, because for the former the context has to be taken into account. This notion led to the second experimental series. Instead of the CSPC effect, the conflict frequency effect was investigated to test whether for this effect unconscious conflict information is more influential on the underlying cognitive control processes.

Again a masked priming paradigm was employed. However, instead of number stimuli participants responded to left or right pointing arrows. This change was made to gain larger congruency effects which might make the effects of interest easier observable. The primes were masked by metacontrast masks. Also, instead of using inducing- and test trials, the proportion of neutral primes was varied to manipulate the frequency of conflict. This approach is based on the study by Tzelgov et al. (1992) who reported larger congruency effects in blocks with high proportions of neutral trials as compared to blocks with low proportions of neutral trials. This can be explained by the different frequencies of conflict between the blocks. In Tzelgov et al.'s study the number of congruent and incongruent trials within one block were equal. By manipulating the frequency of neutral trials (i.e., trials in which a neutral prime was presented), the number of conflict inducing (i.e., incongruent) trials was changed as well. In blocks with frequent neutral trials there were less incongruent trials than in blocks with only few neutral trials. Thus, the congruency effect depended on the frequency of conflict within the respective blocks.

Accordingly, in this experimental series the proportion of neutral primes was varied. The proportions of congruent and incongruent trials in each block were equal so that alternative explanations regarding low-level learning mechanisms (based on different frequencies of congruent and incongruent trials as described in Experiment 1) could not account for any adaptation to conflict frequency. Primes could be left or right pointing arrows or a combination of both that served as the neutral prime (see Figure 7). It was expected that the congruency effect in an experimental block would vary depending on the proportion of neutral primes – resulting in a conflict frequency effect.

Similar to Experiments 1-3, in Experiments 4-6 it was first tested whether the conflict frequency effect would appear when all conflicts could be consciously perceived. Second, it the experiment was repeated with all primes less visible, i.e., with better masking. A third experiment combined these two conditions using the same task and both, weakly and heavily masked primes (cf. Experiment 3).

## 7.1 Experiment 4

To test whether conflict frequency effects can be found in the just described paradigm, a first experiment was conducted in which all primes were easily detectable. It was expected that a conflict frequency effect would appear that can be ascribed to a control process that modulates stimulus processing based on the frequency of conflict and not to any frequency-based learning mechanisms as described before (the memory-recruitment account by Bodner & Dypvik, 2005).

### 7.1.1 Method

**Participants**

Twenty undergraduate students (18 female, mean age: 24.5 years, range: 19-34 years) participated for course requirement or for monetary compensation.

**Apparatus and Stimuli**

The same apparatus as in Experiments 1-3 was used. Stimuli were black arrows presented in the center of the screen in front of a white background. Arrows used as primes were approximately 1.5 cm wide and .8 cm high. They could point to the left, to the right or in both directions (i.e., the left and right pointing prime arrows superimposed upon each other). Larger arrows were used as targets and were approximately 3.7 cm wide and 1.9 cm high and were either left or right pointing. Both, prime arrows and target arrows contained two white arrows superimposed upon each other, one pointing left and one pointing to the right. On the target arrows these white arrows were the same size as the black prime arrows – which lead to metacontrast masking of the primes (Figure 7).

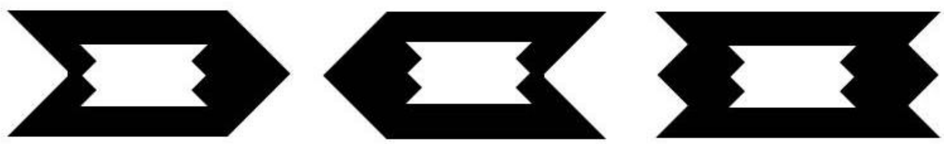

**Figure 7.** Stimuli used in Experiment 4. All three stimuli were used as primes. Targets were always left or right pointing arrows. Prime arrows were smaller than target arrows and fit in the white notch of the target arrows.

**Procedure**

Participants were instructed to place their index fingers on the ‘‘F” and ‘‘J” key of a standard QWERTZ keyboard. Each trial consisted of a fixation cross (presented for 1000 ms), followed by prime (13 ms), blank (26 ms), and target (130 ms). The target was followed by a blank, which lasted until response onset or for a maximum of 2000 ms. Correct responses were followed by a 1000 ms blank, incorrect responses were followed by a 1000 ms written error message. Participants performed four blocks with 96 trials each. Trials in each block were chosen randomly without replacement. Two blocks contained 75% trials with neutral primes, 12.5% of congruent primes and 12.5% incongruent primes (low-interference blocks). Two blocks contained 25% neutral primes, 37.5% congruent primes and 37.5% incongruent primes (high-interference blocks). The blocks were presented in an AABB or a BBAA pattern (counterbalanced across participants). At the end of the experiment participants performed a prime visibility test containing 60 trials. Participants were informed about the nature of the primes and were required to indicate the prime direction with an unspeeded response. No neutral primes were presented.

### 7.1.2 Results

The results of Experiment 4 are depicted in Figure 8. Only trials with left or right pointing prime arrows were included in the analyses. Errors were not included in the analyses (9.2%) as well as responses faster than 200 ms or slower than 1000 ms (1.5%). One participant was excluded from the analyses for committing over 40% errors which was more than two standard deviations over the overall mean. Mean RTs and mean error rates were submitted to an Analysis of Variance (ANOVA) with the within-subject factors congruency (congruent vs. incongruent) and context (low-interference blocks vs. high-interference blocks).

**Response times**

Responses to congruent trials were 103 ms faster than responses to incongruent trials (295 ms vs. 398), $F(1,18) = 476.73$, $p < .001$. Participants responded 11 ms faster in the low-interference blocks than in the high-interference blocks (341 ms vs. 352 ms), $F(1,18) = 4.94$, $p < .05$. The interaction between the two factors reached significance, $F(1,18) = 5.99$, $p < .05$. This was driven by a larger congruency effect in the low-interference blocks than in the high-interference blocks (109 ms vs. 97 ms).

**Errors**

Responses to congruent trials were less error prone than responses to incongruent trials (0.2% vs. 18.2% errors), $F(1,18) = 52.00$, $p < .001$. Participants committed more errors in the low-interference blocks than in the high-interference blocks (11.5% vs. 6.9%), $F(1,18) = 18.29$, $p < .001$. The interaction between the two factors reached significance. This was brought about by a larger congruency effect in the low-interference blocks than in the high-interference blocks (22.6% vs. 13.6%), $F(1,18) = 19.77$, $p < .001$.

**Prime visibility**

Participants performed a prime visibility test to obtain an objective measure of prime discrimination performance (the participant excluded in the abovementioned analyses was also not included in this analysis). They were told that the possibility for a left or right pointing prime arrow was exactly 50%. The task was to indicate the prime direction by pressing the left or right key used throughout the experiment.

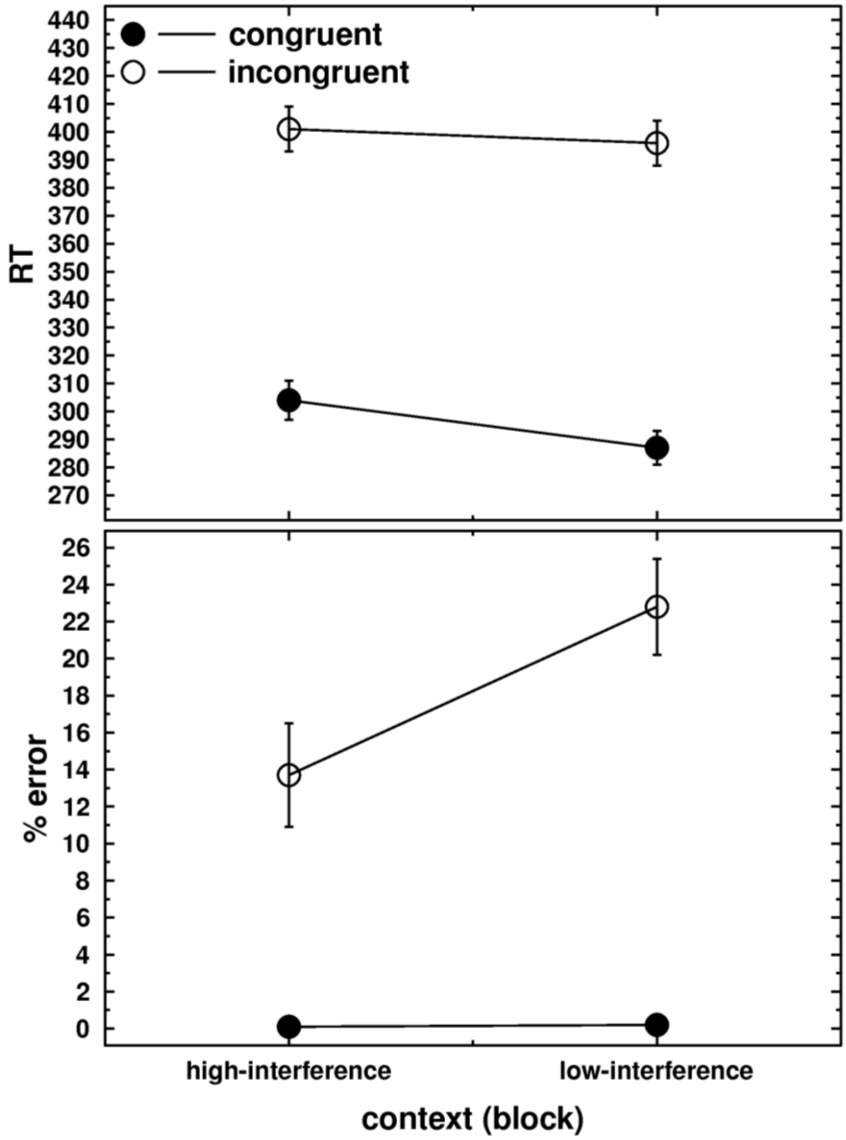


**Figure 8.** Mean RTs and error rates (with standard errors) of Experiment 4 for congruent and incongruent trials in the high- and low-interference contexts. Contexts were experimental blocks with high or low proportion of neutral primes. The conflict frequency effect appeared in both, RTs and error rates.

Using this binary response mode allows computing the signal detection measure *d'* as a measure of prime visibility (Tanner & Swets, 1954). If participants answered with a left key press and the prime arrow indeed pointed to the left, this was considered a hit. If participants answered with a left key press although the prime arrow pointed to the right, this was considered a false alarm. Hits or false alarms proportion of zero or one of a participant were corrected using the log-linear rule (Goodman, 1970; cited according to Hautus, 1995). The trial structure was identical to the experimental blocks. The primes were clearly visible as indicated by $d' = 1.50$, $t(18) = 4.21$, $p < .001$.

### 7.1.3 Discussion

Experiment 4 tested for conflict frequency effects that cannot be traced back to frequent repetitions of specific distractor-target combinations but instead reflect strategic adaptation (cf. 6.1.3) of information processing to the conflict setting. To explore this, a masked-priming paradigm was used. A high-interference context and a low-interference context were implemented by varying the amount of neutral primes (with contexts being the experimental blocks). In blocks with 75% neutral primes, only 12.5% of the primes were incongruent to the target (and 12.5% congruent); these were labeled low-interference blocks. In blocks with only 25% neutral primes, 37.5% of the remaining primes were incongruent to the target (and 37.5% congruent): high-interference blocks. Hence, the blocks differed in the number of incongruent prime-target relations that elicit response conflict.

As predicted on grounds of the study by Tzelgov et al. (1992), the congruency effect was larger in low-interference blocks than in high-interference blocks for both, response times and error rates. Since in all blocks the proportion of congruent and incongruent primes was equal, there is no possibility that differences in familiarity with congruent and incongruent trials (as described before in the memory-retrieval account by Bodner & Dypvik, 2005) can explain the results. Therefore the results indicate that these effects are brought about by control processes that modulate information processing according to conflict frequency.

However, as in Experiment 1, the observed effect in the present experiment might be driven by sequential, trial-to-trial modulations of the interference effect (i.e., a reduction of congruency effects after incongruent trials; e.g., Gratton et al., 1992) rather than context-specific modulations of the interference effect. This is, because there are more congruent trials in the low-interference context, leading on average to increased congruency effects in the following trials and more incongruent trials in the high-interference context leading on average to reduced congruency effects in the following trials. To check this possibility, a further analysis was conducted including the factors congruency in trial n-1, congruency in trial n, and context. Four participants were excluded from this analysis because in their data there was at least one design cell not containing any measurements. Note that there are only few observations in the high-interference context because most trials follow neutral trials instead of congruent or incongruent trials. Contrary to Experiment 1, a typical Gratton effect was observed, $F(1,14) = 6.35$, $p < .05$. The congruency effect was larger after congruent as compared to incongruent trials. This effect did not differ between contexts, $F < 1$. In the error rates, no Gratton effect was observed, $p = .15$, however, this analysis was also based on a small trial number (in the low-interference context). At first sight, sequential effects might be a viable explanation for the observed conflict frequency effect.

To rule out sequential effects as an alternative explanation, only trials that followed neutral trials were analyzed. If the conflict frequency effect was only driven by sequential modulations, it should not be observable in these trials. On the other hand, if the conflict frequency effect is indeed brought about by a cognitive control process, the adaptation to conflict frequency (in the respective block) should also be observable in trials following neutral trials. The congruency effect following neutral trials amounted to 97 ms in the high-interference context and to 111 ms in the low-interference context. This difference was almost significant, $F(1,18) = 4.23$, $p = .054$. I interpret this finding as evidence for a conflict frequency effect that is independent of sequential modulations. This interpretation is supported by Funes et al.'s (2010) finding that the Gratton effect and sustained control processes are mediated by two independent attentional control systems.

Another interesting question in this area is whether the processing of the relevant or the irrelevant information is modulated (Egner & Hirsch, 2005; Stürmer, Leuthold, Soetens, Schröter, & Sommer, 2002). Analyzing the neutral trials of Experiment 4 might indicate how stimulus processing is adjusted to the frequency of conflict. I assume that RTs of neutral trials are a good indicator for possible changes in the processing of relevant information (the target arrow), because the prime should not influence the response. I further suggest that if processing of the relevant information is modulated depending on the amount of conflict, RTs of neutral trials should be longer in the high-interference blocks as compared to the low-interference blocks: If conflict is frequently experienced and if this leads to reduced or inhibited processing of the target arrow, the just described RT difference should be observable. In Experiment 4 RTs for neutral trials amounted to 341 ms in the high-interference blocks and to 334 ms in the low-interference blocks and this difference did not reach significance, $p > .1$. One can conclude that the processing of the relevant information is not modulated depending on conflict frequency. This does not necessarily mean that it is the processing of irrelevant information that is modulated. However, since these two options are the favored mechanisms in the current literature (cf. 3.1.4), this analysis points to the interpretation that indeed processing of irrelevant information is modulated on the basis of conflict frequency.

A further influence of conflict on responses can be observed when analyzing only neutral trials. Recently Verguts et al. (2011) reported post-conflict slowing, which describes increased response times after conflict trials. This observation has also been made in the present experiment. Response times to neutral trials differed depending on the prime-target congruency in the previous trial, $F(2,36) = 8.62$, $p = .001$. There was no RT difference between trials that followed neutral or congruent trials, $p = .41$, but both were responded to faster than trials that followed incongruent trials, both $p < .05$. In sum, these results support the view that the conflict frequency effect is indeed based on conflict experience and not on benefits of conflict free task performance.

## 7.2 Experiment 5

To explore the role of conscious conflict perception for conflict frequency effects Experiment 4 was repeated with a slightly modified procedure. Mirroring the rationale behind Experiment 2, all prime arrows were now masked more heavily. In Experiment 2, this masking eliminated the CSPC effect and it can be assumed that if both, the CSPC effect and the conflict frequency effect are mediated by the same sustained control processes, the effect observed in Experiment 4 cannot be found in Experiment 5.

### 7.2.1 Method

#### Participants

Forty undergraduate students (37 female, mean age: 24.0 years, range: 24-40 years) participated for course requirement or for monetary compensation.

#### Apparatus and Stimuli and Procedure

Apparatus, stimuli, and procedure were the same as in Experiment 4 with the following exception: The blank following the prime was replaced by a mask. The mask was a black rectangle (approximately 1.8 cm wide and 1.1 cm high). Like the target arrows it contained two white arrows of the size of the prime arrows.

### 7.2.2 Results

Results of Experiment 5 are depicted in Figure 9. Only trials with left or right pointing prime arrows were included in the analyses. Errors were not included in the analyses (6.5%) as well as responses faster than 200 ms or slower than 1000 ms (1.1%). Two participants were excluded from the analyses for committing over 17% errors which was more than two standard deviations over the overall mean. Mean RTs and mean error rates were submitted to an Analysis of Variance (ANOVA) with the within-subject factors congruency (congruent vs. incongruent) and context (low-interference blocks vs. high-interference blocks).

**Response times**

Responses to congruent trials were 56 ms faster than responses to incongruent trials (304 ms vs. 360), $F(1,37) = 137.21$, $p < .001$. Participants responded 11 ms faster in the low-interference blocks than in the high-interference blocks, however, this difference was only marginally significant (329 ms vs. 335 ms), $F(1,37) = 3.21$, $p = .081$. The interaction between the two factors did not reach significance, the congruency effects did not differ between the contexts (60 ms vs. 52 ms), $F(1,37) = 2.33$, $p = .135$.

**Errors**

Responses to congruent trials were less error prone than responses to incongruent trials (2.1% vs. 11.0% errors), $F(1,37) = 66.25$, $p < .001$. Participants committed more errors in the low-interference blocks than in the high-interference blocks (7.2% vs. 5.8%), $F(1,37) = 4.26$, $p < .05$. The interaction between the two factors did not reach significance, the congruency effects did not differ between the contexts (9.7% vs. 8.1%), $F(1,37) = 1.20$, $p = .28$.

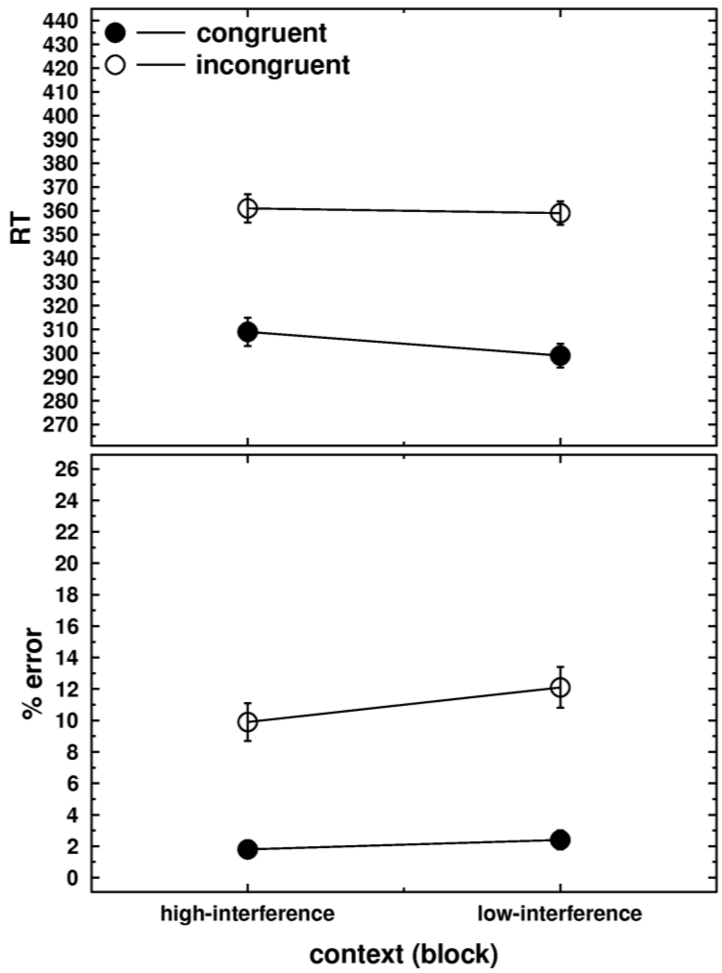


**Figure 9.** Mean RTs and error rates (with standard errors) of Experiment 5 for congruent and incongruent trials in the high- and low-interference contexts. Contexts were experimental blocks with high or low proportion of neutral primes. The conflict frequency effect observed in Experiment 5 vanished due to heavier masking of the primes.

### Prime visibility

Participants performed a prime visibility test (cf. Experiment 4) to obtain an objective measure of prime discrimination performance (the participants excluded in the abovementioned analyses were also not included in this analysis). The *d'* measure differed significantly from zero, $d' = .51$, $t(37) = 4.32$, $p < .001$, but it was also significantly smaller the *d'* measure in Experiment 6, $t(55) = 3.50$, $p < .01$, indicating a worse prime visibility in the present experiment as compared to Experiment 6.

A regression analysis (cf. Experiment 2) with the *d′* measure as the independent variable and congruency index as the dependent variable was conducted. The regression of the congruency index on *d′* revealed a significant intercept of 19.19, t(37) = 8.94, p < .001. The correlation did not differ significantly from 0 ($r$ = .03, $t$(37) = -.16, $p$ > .87). Thus, there was a congruency effect even in the range of zero prime visibility, and there was no correlation between prime visibility and congruency effect.

### 7.2.3 Discussion

Experiment 5 was conducted to test whether conflict frequency effects are observed for masked primes or whether conflict events have to be consciously represented to induce context-specific adaptation of congruency effects. Even though the masking procedure of the primes in Experiment 5 did not fully prevent prime visibility, the reduction of prime visibility compared to Experiment 4 sufficed to entirely drop the conflict frequency effect observed in Experiment 4 to a nonsignificant level. Supporting and extending the results of Experiment 2 this finding indicates that consciousness of the stimuli that induce response conflicts is a prerequisite for sustained cognitive control processes.

As mentioned before (cf. 5.1.2.3), the system might be more willing to take into account block-wise variations of conflict frequency the more interfering or helpful the irrelevant information is. Also, similar to Experiments 1 and 2 the congruency effect differed significantly between Experiments 4 and 5 (102 ms vs. 55 ms, respectively, $t$(55) = 6.37, $p$ < .001). The same regression analysis as for Experiments 1 and 2 was conducted with the data of Experiments 4 and 5 combined. The dependent variable was the size of the conflict frequency effect in RTs (i.e., congruency effect in the low-interference blocks minus congruency effect in the high-interference blocks). The independent variables were "experiment" (coded as 0 and 1, representing Experiment 4 and 5) and mean congruency effect of each participant. The predictor experiment did not reach significance, $\beta$ = .13, $t$ = .76, $p$ = .45. Also the mean congruency effect of each participant did not predict the size of the conflict frequency effect, $\beta$ = .26, $t$ = 1.50, $p$ > .13. The outcome of this analysis is ambiguous. The data suggests that there is no difference of the conflict frequency effect between the two experiments. Also, the size of the congruency effect does not predict the size of the observed conflict frequency effect. This result is in line with the comparison of

Experiments 1 and 2. One could argue, that this non-significance reflects a problem of statistical power. Despite the larger sample size in Experiment 5 compared to Experiment 4, the between-participant manipulation could prevent the difference of conflict frequency effects (i.e., the influence of the factor “experiment”) from reaching significance. To address this problem, a blockwise, within-subject manipulation of prime visibility could be the solution. However, given the data of the present experiments no substantial claim can be derived from this analysis. Concluding, I argue that the results of Experiments 4 and 5 mirror the results already shown in Experiments 1 and 2 in several ways, which can be interpreted as a slight indication that they also would show similar properties in this analysis, if statistical power was higher.

## 7.3 Experiment 6

The results of Experiments 1 and 2, namely the finding of a CSPC effect with weakly masked primes and the lack thereof with heavier masked primes were replicated in Experiments 4 and 5 for the conflict frequency effect.

The results of Experiment 5 suggest that no conflict frequency effect can be found when primes cannot be represented consciously. Following the interpretation of Experiment 2, two possible interpretations result from this finding: On the one hand, one can conclude that the cognitive system cannot detect the conflict frequency manipulation. On the other hand, one can assume that control processes can be implicitly activated but cannot be employed on stimuli that do not gain access to consciousness. To distinguish between these two possibilities, Experiment 6, following the rationale of Experiment 3, was conducted as a mixture of Experiments 4 and 5. Trials with weakly masked primes as well as trials with heavily masked primes were both presented within the same block. That way the conflict frequency manipulation can be noticed by the cognitive system in trials with weakly masked primes. It is then testable, whether control strategies that can be activated by and applied to trials with weakly masked primes are transferred to trials with heavily masked primes.

Since Experiments 4 and 5 replicated the findings of Experiments 1 and 2 one can expect that the present experiment replicates the results of Experiment 3. On the other hand it might be possible, that (given that another, less complex effect is under investigation and another paradigm is used) Experiment 6 reveals a conflict frequency effect for trials with conscious but not trials with subliminal conflict-inducing stimuli. Third, it is possible that a transfer of response strategies from trials with consciously perceivable primes to trials with subliminal primes is found. All three results would be interesting as they all point to the true nature of sustained control processes.

### 7.3.1 Method

**Participants**

Forty undergraduate students (31 female, mean age: 24.6 years, range: 18-41 years) participated for course requirement or for monetary compensation.

**Apparatus and Stimuli and Procedure**

Experiment 6 was designed as a mixture of Experiments 4 and 5. The apparatus and trial procedures were the same as in Experiments 4 and 5. However, trials with heavily masked primes (as in Experiment 5) were randomly mixed with trials with weakly masked primes (as in Experiment 4). In 75% of all trials the mask was not presented after the prime (good visibility condition). In 25% the mask was displayed after the prime (poor visibility condition). In low-interference blocks 75% of the primes were neutral; in high-interference blocks 25% of the primes were neutral. Participants completed 8 experimental blocks with 80 trials each (4 low-interference blocks and 4 high-interference blocks; order balanced across participants) followed by 2 blocks of a prime-visibility test.

### 7.3.2 Results

Results of Experiment 6 are depicted in Figure 10. Only trials with left or right pointing prime arrows were included in the analyses. Errors were not included in the analyses (7.7%) as well as responses faster than 200 ms or slower than 1000 ms (1.3%). Two participants were excluded from the analyses for committing over 22% errors which was more than two standard deviations over the overall mean. Mean RTs and mean error rates were submitted to an Analysis of Variance (ANOVA) with the within-subject factors prime visibility (good vs. poor visibility), congruency (congruent vs. incongruent) and context (low-interference blocks vs. high-interference blocks).

**Response times**

There were no RT differences between heavily and weakly masked primes (343 ms vs. 343 ms), $F < 1$. Congruent trials were responded to 72 ms faster than incongruent trials (307 ms vs. 379 ms), $F(1,37) = 674.59$, $p < .001$. There was a trend that responses to trials in the low-interference blocks were slower than responses in the high-interference blocks (346 ms vs. 340 ms), $F(1,37) = 3.53$, $p = .068$. This difference was not modulated by prime visibility, $F < 1$. The congruency effect differed between trials with good and poor prime visibility (99 ms vs. 46 ms), $F(1,37) = 144.62$, $p < .001$. The congruency effect did not differ between low-interference and high-interference blocks, $F(1,37) = 1.59$, $p = .21$ and this was not modulated by prime visibility, $F < 1$.

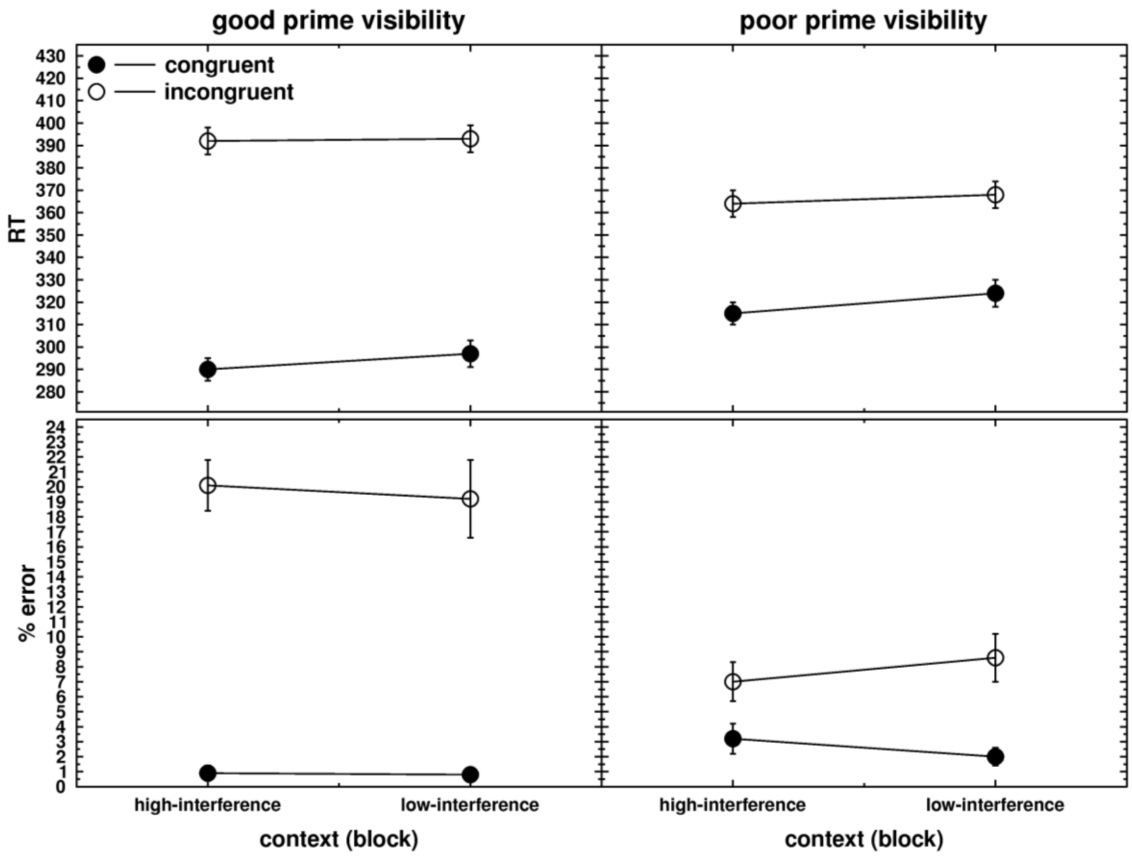


**Figure 10.** Mean RTs and error rates (with standard errors) of Experiment 6 for congruent and incongruent trials in the high- and low-interference contexts, separate for trials with good and poor prime visibility. Contexts were experimental blocks with high or low proportion of neutral primes. No conflict frequency effect was observed.

**Errors**

Participants committed more errors in trials with good prime visibility as compared to trials with poor prime visibility (10.3% vs. 5.2%), $F(1,37) = 27.15$, $p < .001$. Congruent trials were less error prone than incongruent trials (1.7% vs. 13.7%), $F(1,37) = 92.86$, $p < .001$. There was no difference between error rates for the low-interference blocks and the high-interference blocks (7.6% vs. 7.8%), $F < 1$. The influence of the context was not modulated by prime visibility, $F < 1$. The congruency effect was larger for trials with good than with poor prime visibility (18.8% vs. 5.2%), $F(1,37) = 55.98$, $p < .001$. The congruency effect did not differ between low-interference and high-interference blocks, $F < 1$. This was not modulated by prime visibility, $F(1,37) = 2.36$, $p > .13$.

**Prime visibility**

Participants performed a prime visibility test (cf. Experiments 4-5) to obtain an objective measure of prime discrimination performance. Separate *d′* measures were calculated for trials with heavily and trials with weakly masked primes. The weakly masked primes were clearly visible as indicated by $d' = .97$, $t(37) = 4.64$, $p < .001$. The *d′* for heavily masked primes also differed significantly from zero, $d' = .32$, $t(37) = 3.49$, $p < .01$, however, it was significantly lower than the *d′* for weakly masked primes, $t(37) = 4.14$, $p < .001$.

Two regression analyses (cf. Experiment 2) with the *d′* measures (weakly and heavily masked) as the independent variables and congruency indices as the dependent variables were conducted. For the good prime visibility condition the regression of the congruency index on *d′* revealed a significant intercept of 33.10, $t(37) = 18.84$, $p < .001$. The correlation did not differ significantly from 0 ($r = .18$, $t(37) = 1.07$, $p > .29$). For the poor prime visibility condition the regression revealed a significant intercept of 15.21, $t(37) = 10.29$, $p < .001$. The correlation did not differ significantly from 0 ($r = -.08$, $t(37) = -.46$, $p > .64$). Thus, in both visibility conditions, there was a congruency effect even in the range of zero prime visibility, and there was no correlation between prime visibility and congruency effect.

### 7.3.3 Discussion

The results of Experiments 4 and 5 suggest that the conflict frequency effect can only be observed when all conflict-inducing information was presented supraliminally but not when this information is always presented heavily masked. This allows generalizing the results regarding the need for conscious conflict perception found for CSPC effects to the conflict frequency effect. The outcome of Experiment 3 suggests that CSPC effects disappear even for trials with weakly masked primes when they are presented randomly mixed with trials with poor prime visibility. The goal of Experiment 6 was to replicate this finding. Therefore, trials as presented in Experiment 4 (primes were only weakly masked) were randomly mixed with trials as presented in Experiment 5 (primes were masked more heavily). Other than that, the task remained unchanged.

The results of Experiment 3 were replicated. There was no conflict frequency effect observable, even in the trials with weakly masked primes. The present experiment substantiates this finding. I have argued in the discussion of Experiment 3 that this may be brought about by a lower proportion of consciously perceptible conflict-inducing information in Experiment 3 as compared to Experiment 1. This explanation also holds for the results of Experiment 6. Here the proportion of conflict-inducing information that could be consciously perceived was 75%, while this proportion was 100% in Experiment 4. One can conclude that more than 75% of the conflict trials need to contain consciously perceptible conflict information so that the conflict frequency effect can be observed. If this proportion is to low, the conflict frequency in the respective blocks can possibly not be noticed, which prevents an observable adaptation effect.

## 7.4 Summary of Experiments 4-6

Experiments 4-6 aimed at generalizing the findings of Experiments 1-3. To do so, it was investigated whether the conflict frequency effect, as an adaptation to a simpler statistical structure than the CSPC effect (because context does not need to be accounted for), would show the same characteristics as the CSPC effect. The context frequency effect is the observation that in blocks with fewer conflict trials the congruency effect is larger, compared to blocks with frequent conflict trials. As for the CSPC effect, a sustained control process is assumed to be responsible for the conflict frequency effect, as information processing is modulated based on the frequency of conflict over a certain amount of time. A masked priming paradigm using arrow primes and targets, as well as mentacontrast masking was employed. Primes and targets were either congruent or incongruent, or the prime was neutral. The proportion of neutral primes was varied between blocks while the ratio of congruent to incongruent trials was equal in each block. This way, there were blocks with many neutral trials, i.e., with only few conflict trials (trials with incongruent primes), and blocks with few neutral trials, i.e., with frequent conflict trials.

Experiment 4 revealed a conflict frequency effect, i.e., a larger congruency effect in blocks with only few conflict trials. As in Experiment 1 all primes in Experiment 4 were clearly perceptible. Mirroring the rationale of Experiments 2, all primes in Experiment 5 were masked more heavily as compared to the preceding experiment. Again, this procedure led to the elimination of the effect of interest. This observation suggests that sustained control processes generally require conscious representation of conflict information to become activated. However, to complete the experimental series it was tested if control processes activated by conscious conflict information could be transferred to trials in which this information remained unconscious (cf. Experiment 3). The results of Experiments 3 and 6 also match. Mixing trials with conscious and unconscious conflict information (i.e., trials with weakly and heavily masked primes) prevents a conflict frequency effect from emerging. As noted before, the accumulation of evidence of conflict in the respective contexts may be interrupted or hindered when trials, in which the conflict inducing information is not consciously perceptible, are interspersed. This may be due to the fact that the proportion of consciously perceivable conflicting information was too low in Experiments 5 and 6 (0% and 75% respectively) as compared to Experiment 4, in which 100% of all conflict-inducing information was consciously perceptible. Information about the conflict frequency in the blocks was probably not noticed because of the too small proportion of consciously perceivable conflict-inducing information and the processing of this information was consequently not modulated.

Experiments 4-6 almost perfectly replicate the finding of Experiments 1-3, so that it is safe to extend the findings and conclusions regarding the CSPC effect to blockwise proportion congruent manipulations (i.e., the conflict frequency effect) and possibly to sustained control processes in general. An overview of the observations of Experiments 1-6 is given in Table 3.

In sum, the present study provides new insights in the nature of sustained control processes. First, it can be concluded that the modulation of information processing depending on the experience of conflict over a certain period of time (within a block or a context) reflects a cognitive control process. Other explanations that have been proposed for such effects, like RT facilitation in frequently presented trials or sequential modulation of congruency effects can be dismissed. Also, the effects that are based on sustained control processes only emerge when conflict is induced by clearly perceptible information in a sufficiently high proportion of conflict-inducing events.

**Table 3.** Overview of the observations of the present work. Experiments 1-3 investigated the CSPC effect. Experiments 4-6 investigated the conflict frequency effect. Both effects can be attributed to sustained control processes and are elicited only when all (or possibly a very high proportion of) conflict-inducing information is clearly perceptible.

| Experiment | effect investigated | awareness of conflict information possible? | effect observed? |
|---|---|---|---|
| 1 | CSPC | + | + |
| 2 | | - | - |
| 3 | | +/- | -/- |
| 4 | conflict frequency | + | + |
| 5 | | - | - |
| 6 | | +/- | -/- |

# 8 General discussion

## 8.1 Discussion of the conducted experiments

The present work was conducted to investigate the nature of sustained control processes. More specifically, the study pursued two main goals: First, I aimed at replicating the results of previous studies the addressed conflict frequency based modulation of stimulus processing while controlling for possible alternative explanations. Second, the study aimed to shed light on the role of conscious perception of conflicting information in activating those control processes that underlie these effects. To do so, all experiments used a masked priming paradigm to induce response conflict with a varying strength of the underlying conscious representations. Two experimental series were conducted, one investigating the CSPC effect, the second investigating the conflict frequency effect.

The conflict frequency effect describes the observation that congruency effects are larger when the proportion of incongruent trials is low, as compared to when the proportion of incongruent trials is high (cf., Tzelgov et al., 1992). That means if there are many conflicts in the context of one experimental block, the impact of the conflicting information is reduced to improve task performance. Contexts regarding the conflict frequency effect are set by an experimental block or the whole experiment. The frequency of conflict is constant over a certain amount of time and a control process is assumed to modulate information processing accordingly. However, this modulation can also occur for two contexts that change randomly, each with an “own” frequency of conflict. For example, if stimuli presented at one location frequently elicit conflict and stimuli presented at another location only rarely elicit conflict and the location of stimulus presentation is randomly chosen in each trial, both locations are processed separately, i.e. according to the frequency of conflict (e.g., Lehle & Hübner, 2008). This is called the context-specific proportion congruent (CSPC) effect (Crump et al., 2006).

### 8.1.1 The CSPC effect

In the first experimental series the CSPC effect was investigated. In Experiment 1, two contexts were established, one with frequent conflict and one with infrequent conflict. The primes were easily detectable and thus the conflict was perceived consciously throughout the whole experiment. A larger congruency effect was found for trials in a context with mainly congruent trials as compared to a context with mainly incongruent trials. Importantly, the use of inducing trials and test trials makes it possible to dismiss alternative explanations for this CSPC effect (cf. Crump & Milliken, 2009). For example, trial familiarity cannot account for the observed effect. Bodner and Dypvik (2005) have proposed that frequent trials elicit quicker responses than infrequent trials. This would artificially increase the congruency effect in a context with a higher proportion of congruent than incongruent trials and decrease the congruency effect in a context with a higher proportion of incongruent than congruent trials. In the present study the analysis was confined to the test trials, i.e., trials that were presented equally often in both contexts. This confinement rules out that more or less frequently presented trials could account for the CSPC effect. Additionally, further analyses revealed that the CSPC effect can also not be ascribed to sequential effects - the observation that congruency effects are usually reduced in trials following incongruent trials. Summarizing the results of Experiments 1-3 of the present study, one can conclude that CSPC effects reflect strategic adaptation of information processing to the conflict setting and do not just result from frequent repetitions of specific distractor-target combinations or sequential modulations of the congruency effect.

The CSPC effect might be mediated by an episodic buffer as proposed by Crump et al. (2006), in which episodes of performance are stored. These episodes include context information as well control settings for specific trials. These settings are then automatically activated when the context is encountered in later trials. More specific on how behavioral effects attributable to cognitive control processes emerge is the account proposed by Verguts and Notebaert (2009). It is suggested that binding between areas involved in the task is elicited by conflict. Thus, when a conflict trial has been processed in one context the active processing units are linked together and their combined performance is facilitated in further conflict trials in the same context.

Experiment 2 was conducted to test, whether this context specific adaptation would also occur, if the conflict was never perceived consciously. Consequently, Experiment 1 was replicated but all primes were masked more heavily. It was found, that when conflict information is never clearly perceptible, the CSPC effect vanishes. Thus, conscious representations of the stimuli that induce response conflicts seem to be a prerequisite for the CSPC effect, possibly because otherwise the cognitive system cannot detect the context-specific proportion congruent manipulation. On the other hand, control processes may also be implicitly activated by unconsciously perceived conflict information but cannot influence performance on tasks in which conflict is elicited by unconsciously perceived information.

The results of Experiment 3 suggest that the CSPC effect does not emerge easily. When trials with clearly perceptible primes and trials with subliminal primes are mixed, the effect can no longer be observed. This result leads to the conclusion that context-specific adaptation to conflict cannot depends on a frequent conflict experience including consciously perceived conflict-inducing information in a high proportion of all conflict inducing trials.

Taken together, the results support the similar findings reported by Crump and Milliken (2009). These authors employed a Stroop-like task and manipulated the conflict frequency in two contexts that were defined by target location. It seems that for the proposed mechanisms to work, two conditions have to be met. First, the system needs to represent whether a trial (in a given context) is congruent or incongruent. Second, the system has to accumulate the frequencies of such episodes over trials. Basically, consciousness might be relevant for both types of knowledge, namely ‘‘local” knowledge (or better memory instances) about the congruency in a given trial, as well as ‘‘global” knowledge about the frequency of such events depending on contexts. Masking the primes already prevents the creation of sufficiently strong representations about congruency in a given trial, and a lack of such representations eliminates the CSPC effect. In other words, a sufficiently strong and presumably conscious representation of the interfering (or helpful) prime information in a given trial and context is a necessary condition for CSPC effects to occur. This is in line with the proposal provided by Crump et al. (2006). The authors assume that context information and control settings for the processing of task-irrelevant information are stored. The control settings are activated automatically when the context is encountered later on. This way, conflict adaptation can be observed in two contexts with different conflict frequencies. One can assume that the storing of the control settings and context information occurs only when the irrelevant information can possibly be consciously perceived. In the present study this means that the prime is not heavily masked. Interestingly, it seems that the global knowledge about the frequency of congruent and incongruent events in different contexts is no pre-requisite for CSPC effects. Neither does the presence of explicit knowledge of such congruency imbalances correlate with CSPC effects, nor does providing participants with such knowledge amplify CSPC effects (Crump, Vaquero, & Milliken, 2008; Crump et al., 2006). Hence the processes that bring about CSPC effects require sufficiently strong (i.e., conscious) codes of prime, target, and context but they need not necessarily end in, or depend on, abstract explicit knowledge of frequency relations.

Basically this inference mirrors observations from the learning literature. For example, learning a covariation between a target dimension and a distractor dimension is hindered when the distractor dimension is more salient than the target dimension (Dishon-Berkovits

& Algom, 2000). Frensch and Runger (2003) have suggested that procedural learning in general does not depend on awareness of the task structure - but on attention to the to-be-learned task structure. With regard to the present findings, it seems feasible that a heavily masked prime is less salient and attracts less attention, and thus prompts less learning than a weakly masked prime.

I have argued that the accumulation of evidence of conflict in the respective contexts is hindered when the proportion of consciously perceivable conflict information is too low. In Experiments 2 and 3 this proportion is 0% and 71.4%, respectively, as compared to Experiment 1, in which 100% of all conflict-inducing information was consciously perceptible. Possibly, the (global) information about the conflict frequency in the contexts was not noticed (implicitly or explicitly) in Experiments 2 and 3, when only a small proportion of conflict-inducing information was possible to perceive consciously. If the proportion of conflict in the contexts remains unnoticed, the processing of this information can consequently not be modulated accordingly.

An important point is that the mechanisms described so far are supposed to be triggered rather quickly ("on the fly"; Crump et al., 2006), as the context becomes apparent only in the same trial in which these mechanisms shall affect performance. However, because in Experiments 1-3 the context information was presented some time before the prime, one could argue that the alleged control processes observed were not automatically triggered but instead depend on intention. Yet, given that first CSPC effects do not depend on intention (Crump et al., 2006; 2008) and second interference by irrelevant information in general can barely be intentionally controlled (Kleinsorge, 2007; Wühr & Kunde, 2008), I consider an intentional use of context information unlikely. Still, a closer examination of the time required for context information to take effect is certainly warranted, since it will help to scrutinize characteristics of the context-driven retrieval of attentional control settings.

In conclusion, Experiments 1-3 revealed two major findings: CSPC effects can be brought about by cognitive control processes that modulate information processing context specifically. The modulation is based on the frequency of conflict in each context. This finding supports the results of Crump & Milliken (2009). It has now been shown in two different paradigms (Stroop and masked priming) that CSPC effects can be accounted for by cognitive control processes and not on event-learning mechanisms as suggested before, e.g., by Bodner and Dypvik (2005). These authors argue that conflict adaptation effects can be traced back to response facilitation in frequently presented trials. If congruent trials are presented frequently in one context (as for example in the study by Lehle & Hübner, 2008) and incongruent trials are presented frequently in the other context, this artificially supports a difference in congruency effects between these two contexts.

The second major finding of Experiments 1-3 is that the control process responsible for the CSPC effect only acts when the conflict is frequently consciously represented. I have outlined above that this is possibly due to the proportion of conflict trials that include consciously perceivable conflict-inducing information. The CSPC effect of Experiment 1 (in which all conflict inducing information was presented supraliminally) vanished in Experiment 3, in which only 71.4% of conflict trials met this criterion.

Also, this finding gives insight into the nature of the relationship of control processes and conscious representation of conflict information: I have described earlier that within-trial control processes have been found to act, even when the conflict remains unconscious (e.g., van Gaal et al., 2009). They are based on current conflict (within the trials). On the other hand, between-trials control processes seem to not act upon subliminally presented conflicting stimuli (e.g., Kunde, 2003). They are based on the just previously experienced conflict (trial n-1). The CSPC effect, as a sustained control process, is based on recent conflict (over a period of time). According to Funes et al. (2010) two different control systems are responsible for these two effects. Boy et al. (2010) provided evidence that also within-trial and between-trials control processes are mediated by different control systems. The present result suggests a fundamental similarity between sustained- and between-trials control processes, possibly pointing to a common mechanism establishing them. Anyway, one can conclude that between-trials- and sustained control processes are more similar to each other than both of them are similar to within-trial control processes.

### 8.1.2 The conflict frequency effect

The second experimental series was conducted to investigate sustained control processes more deeply. Therefore three experiments tested whether the conflict frequency effect would reveal similar or different characteristics as the CSPC effect. Both are assumed to be brought about by sustained control processes and both depend on the frequency of conflict within a given context. While the CSPC effect describes adaptation to more than one context with different conflict frequencies, the conflict frequency effect describes the adaptation to conflict in a single context, i.e., an experimental block. Investigating the conflict frequency effect in addition to the CSPC effect should allow more profound assertions regarding sustained control processes in general.

The rationale behind Experiments 4-5 was the same as in Experiments 1-3. It was first tested whether a pure control effect could be established when the conflict was always clearly perceptible. Then it was tested whether this effect could be observed when the conflict was never clearly perceptible. In a third experiment trials with perceptible and imperceptible primes were mixed to find out whether the control process can act on unconscious conflict at all. The results of Experiments 4-6 generalize the findings of the previous experiments to the conflict frequency effect, not only the CSPC effect. In Experiment 4, all primes were clearly visible: A conflict frequency effect was observed. Importantly, this effect cannot be explained by event-learning mechanisms or sequential modulations, just like the CSPC effect described before. Instead a control mechanism can be assumed that modulated the influence of the prime depending on the frequency of conflict. This corresponds to the interpretation of Experiment 1.

Experiment 5 also did not provide any evidence for different control mechanisms underlying the two observed effects. The result of Experiment 4 could not be replicated when primes were always heavily masked and the conflict was never perceived consciously. This is in line with several recent findings (Cheesman & Merikle, 1986; Merikle & Joordens, 1997; Merikle, Joordens, & Stolz, 1995). If neither ‘‘local” knowledge about the congruency in a given trial, nor ‘‘global” knowledge about the frequency of such events within a block can be gained (because the relevant stimuli remain unconscious) no adaptation of information processing can take place.

Finally, in Experiment 6 trials with easily perceptible primes and trials with heavily masked primes were mixed. As in Experiment 3 this was done to investigate whether or not the control process observed trials with clearly perceptible conflicting information (i.e., the primes) could influence information processing in trials with conflicting information that is not consciously discernible. The results did not reveal a conflict frequency effect, even in trials with clearly visible primes. This may reflect a very fragile connection between the repeated experience of conflict (which leads to “global knowledge”) and the activation of the control process. Possibly, the accumulation of conscious conflict experiences is hindered when episodes containing conflicts evoked by subliminally presented information are interspersed.

I have proposed an explanation for this observation above: Adding trials with heavily masked primes in the experiments (Experiments 3 and 6) reduces the proportion of conflict trials in which this conflict is elicited by consciously perceptible information. In Experiments 1 and 4, this proportion was 100%, which was reduced to 71.4% of all conflict trials in Experiment 3 and to 75% in Experiment 6. It thus seems like conflict needs to be elicited by consciously perceptible information in more than (about) 75% of the conflict trials for conflict adaptation effects to emerge. Since both, the CSPC effect as well as the conflict frequency effect show very similar result patterns it seems possible to generally conclude that the proportion of trials in which conflict is elicited by consciously perceptible information is a significant predictor of whether or not effects reflecting sustained control processes emerge.

## 8.2 Theoretical implications of the present study: The conflict monitoring hypothesis

The conflict monitoring hypothesis (e.g., Botvinick et al., 2004; Botvinick et al., 2001; Kerns et al., 2004) describes a mechanism in the frontal brain that registers conflict and upon that modulates information processing accordingly. Numerous studies support this hypothesis (e.g., Akçay & Hazeltine, 2007; Botvinick et al., 1999; Carter et al., 1998; Gratton et al., 1992; Kunde & Stöcker, 2002; Stürmer et al., 2002; Tzelgov et al., 1992). However, it cannot account fully account for the results of the present study. According to the conflict monitoring hypothesis control on task performance is increased after conflict trials and decreased after conflict-free trials. When the proportion of congruent trials is unequal within blocks or contexts (e.g., 80% congruent and 20% incongruent trials in one block and vice versa in the other block; e.g., Cheesman & Merikle, 1986; Lehle & Hübner, 2008) this mechanism predicts the observed results. However, if the proportion of congruent and incongruent trials is equal within the blocks as in Experiments 4-6, this mechanism provides no satisfying explanation. Even more, if two or more contexts with separate conflict frequencies need to be taken into account, the conflict monitoring hypothesis cannot explain the observed results.

An extension of this account by Crump et al. (2006) assumes that context information is stored together with control settings for the processing of task-irrelevant information (here: the primes) in specific trial instances. When a certain context is encountered later on, the control settings linked to that context are retrieved automatically. Such an additional mechanism would extend the conflict monitoring hypothesis to satisfyingly predict the results observed in the present work as well as in previous studies (e.g., Crump & Milliken, 2009).

Verguts and Notebaert (2009) propose a mechanism that, instead of storing context information and control settings (as proposed by Crump et al., 2006), elicits arousal upon conflict experience, which enforces binding between all cortical areas that are involved in processing of the current task. This way control settings and task-specific features (like the context) get linked more closely and can interact more easily the next time they are involved in task processing. While the proposal by Crump can be integrated in the conflict monitoring hypothesis by adding a storage space for trial-specific information (like the context and control strategies), the account by Verguts and Notebaert can be seen as an alternative explanation for the empirically observed effects.

The present study was not designed to speak in favor of either one of the two proposals. The results are explainable by both accounts. However, the present study has shown that any comprehensive explanation of effects that are attributed to sustained control processes should take into account that a high proportion of conflict experiences needs to be elicited by consciously perceivable information for these effects to occur.

## 8.3 Prime visibility

The present study was designed to investigate the influence of unconscious conflict information on sustained control processes. I have described earlier how stimuli are presented subliminally and how it can be determined whether the stimulus is consciously perceived or not: To prevent stimuli from reaching consciousness they are presented only shortly and masked afterwards. To determine if stimuli are consciously perceived or not it is tested whether participants can discriminate them better than chance. In the present study participants were to categorize either digits (after Experiments 1-3) as smaller or larger than 5, or arrows as pointing left or right (Experiments 4-6). Afterwards, *d'* was computed; a *d'* value that does not differ significantly from 0 suggests that primes were presented subliminally.

All primes that were supposed to be clearly visible were easily discriminable (Experiments 1, 3, 4, & 6). On the other hand, not all primes that were supposed to be invisible were indiscriminable: The *d'* values for all heavily masked primes were significantly above 0 (Experiments 2, 3, 5, & 6). Although this is commonly seen as an indicator that stimuli are perceived consciously, this does not devaluate the results of the present study. As indicated before, the heavier masking of the primes already sufficed to eliminate the CSPC effect, as well as the conflict frequency effect. It is hard to imagine that a further reduction of prime visibility would lead to a re-emergence of these effects. Additionally, the regression analyses showed that congruency effects would have been observable, even at zero prime visibility, leading to the conclusion that the observed results would not change substantially, if primes would have been perfectly masked.

## 8.4 A final summary and an outlook

The relationship of consciousness and cognitive control is a current and interesting field of research. Several studies provided insights in the nature of control processes with regard to their dependence on conscious representations of conflict-inducing information. The present study expanded our understanding of this relationship through the investigation of sustained control processes.

I pursued two main goals with the present study: The first was to find pure conflict adaptation effects that could be traced back to sustained cognitive control processes in the masked priming paradigm. The second goal was to investigate whether the control processes responsible for these effects rely on conscious perception of conflict information. The results suggest that pure conflict adaptation effects (those that can be attributed to sustained control processes) can be observed, even when possible event-learning mechanisms, as proposed by the memory-recruitment account (Bodner & Dypvik, 2005) cannot occur. This confirms results regarding both, the CSPC effect (Crump & Milliken, 2009) and the conflict frequency effect (Tzelgov et al., 1992). One important contribution of the present work is thus the expansion of the findings to the masked priming paradigm. Even more important and genuinely new is the finding that pure sustained control processes appear to rely strongly on the possibility of conscious perception conflicting stimuli. The present results suggest that effects attributed to sustained control processes emerge only when conflicts are induced by a high proportion of consciously perceivable conflicting information. In Experiments 1 and 4 of the present study this proportion was 100% and reducing it to about 75% in Experiments 3 and 6 sufficed to eliminate the investigated effects. To my knowledge this is the first study regarding the CSPC effect and its relation to consciousness, as well as the first study to test whether the influence of control processes can transfer from consciously to unconsciously induced conflicts.

While this study has answered some questions, of course, other questions have arisen: For one, it would be interesting to find out, why exactly the investigated effects vanish in Experiments 3 and 6 (or in other words, why the activation of control processes is hindered). I have argued that the proportion of trials that do not elicit conflict through consciously perceivable information influences whether or not the investigated effects arise. It would be worthwhile to investigate further in this direction and possibly identify the proportion of trials including consciously perceivable conflicting information that suffices to produce these effects. It also would be very interesting to investigate the effect (or the lack thereof) in the inducing trials. One might have expected that the CSPC effect (there were no inducing trials in Experiments 4-6) would emerge even more strongly in those trials as compared to the test trials. However, no CPSC effect (in fact in 2 of 3 cases a numerically reversed effect) was observed. At this point I cannot provide any satisfying explanation, but future research might follow this direction. Further, one could seek more direct evidence for the mechanism of the modulation of information processing. In the discussion of Experiment 4, I argued that processing of the relevant information is not modulated and that it was thus acceptable to assume that processing of irrelevant information is modulated. This is a question that would illuminate the nature of sustained control processes even more and may inspire future Experiments.

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# Appendices

## A Detailed RT and %error results

*Table A.1:* Mean response times and (standard errors) from Experiment 1 in milliseconds as a function of context and congruency. Congruency effect is RT(congruent) – RT(incongruent).

| | | incongruent | congruent | congruency effect |
|---|---|---|---|---|
| context | high-interference | 358 (8) | 326 (8) | 32 |
| | low-interference | 376 (10) | 322 (8) | 54 |

Table A.2: Mean percentage of errors and (standard errors) from Experiment 1 as a function of context and congruency. Congruency effect is %error(congruent) – %error(incongruent).

| | | incongruent | congruent | congruency effect |
|---|---|---|---|---|
| context | high-interference | 47.7 (2.9) | 17.2 (3.4) | 30.5 |
| | low-interference | 50.3 (2.9) | 17.0 (3.5) | 33.3 |

*Table A.3:* Mean response times and (standard errors) from Experiment 2 in milliseconds as a function of context and congruency. Congruency effect is RT(congruent) – RT(incongruent).

| | | incongruent | congruent | congruency effect |
|---|---|---|---|---|
| context | high-interference | 356 (8) | 333 (5) | 23 |
| | low-interference | 358 (9) | 337 (6) | 21 |

*Table A.4:* Mean percentage of errors and (standard errors) from Experiment 2 as a function of context and congruency. Congruency effect is %error(congruent) – %error(incongruent).

| | | incongruent | congruent | congruency effect |
|---|---|---|---|---|
| context | high-interference | 38.9 (4.0) | 17.8 (2.0) | 21.1 |
| | low-interference | 35.1 (3.8) | 17.4 (2.5) | 17.7 |

*Table A.5:* Mean response times and (standard errors) from Experiment 3 in milliseconds as a function of prime visibility context, and congruency. Congruency effect is RT(congruent) – RT(incongruent).

| | | | incongruent | congruent | congruency effect |
|---|---|---|---|---|---|
| Good prime visibility | context | high-interference | 357 (6.5) | 312 (5.7) | 45 |
| | | low-interference | 358 (6.0) | 317 (4.7) | 41 |
| Poor prime visibility | | high-interference | 357 (6.4) | 338 (5.5) | 19 |
| | | low-interference | 356 (5.6) | 334 (5.5) | 22 |

*Table A.6:* Mean percentage of errors and (standard errors) from Experiment 3 as a function of prime visibility context, and congruency. Congruency effect is %error(congruent) – %error(incongruent).

| | | | incongruent | congruent | congruency effect |
|---|---|---|---|---|---|
| Good prime visibility | context | high-interference | 41.2 (2.5) | 14.2 (1.8) | 27.0 |
| | | low-interference | 39.2 (2.5) | 13.7 (1.9) | 25.5 |
| Poor prime visibility | | high-interference | 30.1 (2.7) | 19.4 (2.4) | 10.7 |
| | | low-interference | 31.5 (2.7) | 20.3 (2.0) | 10.2 |

*Table A.7:* Mean response times and (standard errors) from Experiment 4 as a function of context and congruency. Congruency effect is RT(congruent) – RT(incongruent).

| | | incongruent | congruent | congruency effect |
|---|---|---|---|---|
| context | high-interference | 401 (8) | 304 (7) | 97 |
| | low-interference | 396 (8) | 287 (6) | 109 |

*Table A.8:* Mean percentage of errors and (standard errors) from Experiment 4 as a function of context and congruency. Congruency effect is %error(congruent) – %error(incongruent).

| | | incongruent | congruent | congruency effect |
|---|---|---|---|---|
| context | high-interference | 13.7 (2.8) | .1 (.1) | 13.6 |
| | low-interference | 22.8 (2.6) | .2 (.2) | 22.6 |

*Table A.9:* Mean response times and (standard errors) from Experiment 5 in milliseconds as a function of context and congruency. Congruency effect is RT(congruent) – RT(incongruent).

| | | incongruent | congruent | congruency effect |
|---|---|---|---|---|
| context | high-interference | 361 (6) | 309 (6) | 52 |
| | low-interference | 359 (5) | 299 (5) | 60 |

*Table A.10:* Mean percentage of errors and (standard errors) from Experiment 5 as a function of context and congruency. Congruency effect is %error(congruent) – %error(incongruent).

| | | incongruent | congruent | congruency effect |
|---|---|---|---|---|
| context | high-interference | 9.9 (1.2) | 1.8 (.4) | 8.1 |
| | low-interference | 12.1 (1.3) | 2.4 (.6) | 9.7 |

*Table A.11:* Mean response times and (standard errors) from Experiment 6 in milliseconds as a function of prime visibility context, and congruency. Congruency effect is RT(congruent) – RT(incongruent).

| | | | incongruent | congruent | congruency effect |
|---|---|---|---|---|---|
| Good prime visibility | context | high-interference | 392 (6) | 290 (5) | 102 |
| | | low-interference | 393 (6) | 297 (6) | 96 |
| Poor prime visibility | | high-interference | 364 (6) | 315 (5) | 49 |
| | | low-interference | 368 (6) | 324 (6) | 44 |

*Table A.12:* Mean percentage of errors and (standard errors) from Experiment 6 as a function of prime visibility context, and congruency. Congruency effect is%error(congruent) – %error(incongruent).

| | | | incongruent | congruent | congruency effect |
|---|---|---|---|---|---|
| Good prime visibility | context | high-interference | 20.1 (1.7) | .9 (.5) | 19.2 |
| | | low-interference | 19.2 (2.6) | .8 (.3) | 18.4 |
| Poor prime visibility | | high-interference | 7 (1.3) | 3.2 (1.0) | 3.8 |
| | | low-interference | 8.6 (1.6) | 2.0 (.6) | 6.6 |

## B Declaration of authorship

I certify that the work presented here is, to the best of my knowledge and belief, original and the result of my own investigations, except as acknowledged, and has not been submitted, either in part or whole, for a degree at this or any other University.

Eidesstattliche Erklärung

Ich versichere an Eides statt, dass ich die von mir vorgelegte Dissertation selbstständig angefertigt habe und alle benutzten Quellen und Hilfsmittel vollständig angegeben habe. Eine Anmeldung der Promotionsabsicht habe ich an keiner anderen Fakultät oder Hochschule beantragt.

Teile dieser Arbeit wurden vorab publiziert (genehmigt vom Promotionsausschuss der Fakultät 14 der Technischen Universität Dortmund) als:

Heinemann, A., Kunde, W., & Kiesel, A. (2009). Context-specific prime-congruency effects: On the role of conscious stimulus representations for cognitive control. *Consciousness and Cognition, 18*, 966-976. doi: 10.1016/j.concog.2009.08.009.

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