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# Unconscious Conflicts in Unconscious Contexts: The Role of Awareness and Timing in Flexible Conflict Adaptation

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Humans adapt to context-specific frequencies of response conflicts. Typically, the impact of conflict-inducing information is reduced in contexts with high compared to low frequency of conflict. We investigated how such context-specific conflict adaptation depends on awareness and timing of conflict-eliciting stimuli and conflict-signaling contexts. In a priming paradigm, we varied the visibility of the prime and whether the context is a feature of either prime or target. Concretely, the context was represented by the format of either prime (Experiment 1) or target (Experiment 2), which means that primes or targets of a particular format were associated with a high or low probability of conflict (i.e., prime–target incongruity). In both experiments, we found a context-specific modulation of congruency effects, both with masked and visible primes. To control for mechanisms of event learning in Experiments 3 and 4, context-specific conflict frequency was realized by inducing trials, while stimuli in test trials were associated with equal conflict frequency. We again found a context-specific congruency modulation when the prime represented the context, most interestingly also with masked primes within test trials. When the target represented the context, however, such a modulation occurred with visible primes, but not with masked primes. These results provide a compelling case for the unconscious exertion of a very flexible form of cognitive control. Context-specific conflict adaptation processes can basically operate independently of both conflict awareness and context awareness, but they depend on close temporal proximity of context and conflict information.

*Keywords:* unconscious processing, conflict adaptation, cognitive control

Cognitive psychology has intensively investigated how humans control behavior in a way that is adaptive to changing environments (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Verguts & Notebaert, 2008). A frequently studied expression of cognitive control is the adaptation to response conflict. Conflict typically occurs when relevant information interferes with certain task-irrelevant information. For example, in the priming paradigm, participants have to respond as fast as possible to a target stimulus while ignoring a prime stimulus that is presented shortly before. Responding is delayed and more error prone when prime and target are associated with different responses (i.e., an incongruent trial) than when they are associated with the same response (i.e., a congruent trial).

The experience of previous conflict helps to overcome subsequent conflict, which is reflected in a sequential modulation of the congruency effect. Typically, congruency effects are reduced following incongruent trials (e.g., Gratton, Coles, & Donchin, 1992; Hommel, 1994; Kiesel, Kunde, & Hoffmann, 2006; Wendt & Luna-Rodriguez, 2009). Conceivably, this observation reflects a recruitment of cognitive control following a conflict-laden trial (Botvinick et al., 2001). By either inhibiting the prime or focusing more on the target (Egner & Hirsch, 2005; Stürmer, Leuthold, Soetens, Schröter, & Sommer, 2002), the detrimental influence of the prime can be reduced.

Besides this adaptation to recent conflict, cognitive control allows us to flexibly adapt our behavior according to the overall frequency of conflict in the environment (Cohen & Servan-Schreiber, 1992; Logan & Zbrodoff, 1979; Tzelgov, Henik, & Berger, 1992). For example, in an environment with a high frequency of potential conflict, we might proactively adapt our behavior based on this context information (e.g., Jaśkowski, Skalska, & Verleger, 2003) and suppress the processing of conflicting information to increase task performance. In the priming paradigm, one way to create different conflict-laden contexts is to manipulate the proportion of congruent versus incongruent trials between blocks. In a block with mainly incongruent trials, a good strategy is to reduce the influence of the interfering primes, because these primes mostly induce conflict and interfere with the

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participants' goal. On the contrary, in a block with mainly congruent trials, the prime triggers the correct response on almost all trials and thus enhances performance, so a good strategy is to use the information of the prime in order to speed up responding to the target. Such strategic adaptations are reflected by larger congruency effects in blocks with mainly congruent trials and reduced congruency effects in blocks with mainly incongruent trials (Logan & Zbrodoff, 1979; Tzelgov et al., 1992). This block-wise adaptation to the conflict frequency provides an example of how the cognitive system adapts itself to contextual information to improve task performance.

### Context-Specific Conflict Adaptation

While this exertion of cognitive control according to the degree of interference in the environment seems a rather basic and not very fine grained way to deal with potential conflict, it has been shown to be extremely flexible when required. In the previously described experiments, contexts were always designed by creating blocks with mainly incongruent trials and blocks with mainly congruent trials. Due to the blocked design, participants knew beforehand in which context the next trials would be, and there was no need to adjust the cognitive control settings during a single block. However, participants can flexibly allocate cognitive control and adapt their behavior according to a context that randomly changes between trials. For example, Crump, Gong, and Milliken (2006) used a priming task in which targets were presented either above or below the midline. The critical contextual manipulation was that targets presented above the midline were mostly preceded by congruent primes (75%), whereas targets presented below the midline were mostly preceded by incongruent primes (25%). Crucially, because the location of the target varied randomly from trial to trial, the overall probability of encountering a congruent or incongruent trial was exactly at chance level. The authors observed larger congruency effects in the highly congruent context compared to the highly incongruent context (for similar findings, see Corballis & Gratton, 2003; Crump & Milliken, 2009; Heinemann, Kunde, & Kiesel, 2009; Wendt & Kiesel, 2011). This context-specific conflict adaptation effect is an intriguing demonstration of the potential flexibility of the human cognitive system to adapt in order to exert more efficient behavior.

### Awareness as a Principal Prerequisite of Cognitive Control?

In the current study, our main focus was to examine the specific contribution of consciousness in the exertion of cognitive control in context-specific conflict adaptation. More specifically, we investigated the role of awareness of both the conflicting stimulus (e.g., the prime) and the context information. Over the years, an overwhelming amount of studies have shown that many processes do not require consciousness in order to be executed. For example, it was shown that stimuli that are never consciously perceived are nevertheless able to prime motor responses (Eimer & Schlaghecken, 1998), activate the motor cortex (e.g., Dehaene, Kerszberg, & Changeux, 1998; Dehaene, Naccache, et al., 1998), facilitate responding to semantically related targets (e.g., Dehaene, Naccache, et al., 1998; for a review, see Van den Bussche, Van den Noortgate, & Reynvoet, 2009), and exogenously

capture attention (e.g., Scharlau & Ansorge, 2003), showing the redundancy of consciousness in these processes.

Because accumulating evidence has suggested that consciousness does not play a crucial role in many bottom-up cognitive processes, researchers started to wonder whether there are some areas that might be exclusively reversed for consciousness (e.g., Dehaene & Naccache, 2001; Jack & Shallice, 2001; Lau, 2009; Norman & Shallice, 1986; Umiltà, 1988). According to Dehaene and Naccache (2001), unconscious processing is restricted to bottom-up processing. Both fully visible and heavily masked primes can produce the same behavioral consequences. Although the effects of heavily masked primes tend to be smaller than clearly visible primes, probably reflecting a lack of neural amplification (Dehaene, Changeux, Naccache, Sackur, & Sergent, 2006; Haynes, Driver, & Rees, 2005), the effects are typically qualitatively similar. Dehaene and Naccache (2001) explained this qualitative similarity by assuming that stimuli can potentially be processed up to a high semantic level by specialized modular systems. According to their global neuronal workspace (GNW) model, these modular systems operate on a completely unconscious level. Thus, both conscious and unconscious primes are processed up to the same level, as long as this is restricted to a purely bottom process.

According to the GNW model, information can also be used in a top-down fashion in order to strategically initiate or modify behavior, but only via interactions between different modular systems. However, these interactions cause global ignition in the workspace, which is the main determinant of consciousness in the GNW model. These modular systems are assumed to be distributed neurons with long-distance connectivity, and a feeling of awareness arises when they interconnect (Dehaene, Naccache, et al., 1998). Thus, the process required for stimuli to exert top-down strategic influences is also the main determinant of conscious processing. Consequently, a crucial prediction of this theory is that only consciously perceived stimuli can be used in a strategic top-down manner. Stimuli that remain unconscious can potentially be processed up to high semantic levels, but they should be unable to induce top-down control.

### The Role of Awareness in Conflict Adaptation

Based on the idea that only conscious events can induce top-down adaptation, GNW predicts that participants should only adapt to response conflict when that conflict itself is consciously experienced. Conversely, when the conflict remains unconscious, this bottom-up conflict information should not be able to trigger a strategic adaptation. Confirming this prediction with regard to conflict adaptation on a trial-by-trial basis, several studies showed that adaptation to recent conflict is crucially linked to consciousness (e.g., Ansorge, Fuchs, Khalid, & Kunde, 2011; Frings & Wentura, 2008; Greenwald, Draine, & Abrams, 1996; Kunde, 2003). A sequential modulation of the congruency effect was only found when the primes were presented nonmasked. However, this consensus was recently put into doubt by studies that found conflict adaptation following unconscious conflict (Desender, Van Lierde, & Van den Bussche, 2013; van Gaal, Lamme, & Ridderinkhof, 2010). These authors suggested that awareness of the conflict is no crucial precondition to trigger top-down cognitive control. However, it remains debated whether this truly reflects

unconsciously triggered conflict adaptation or whether it is caused by some conscious by-product (Desender & Van den Bussche, 2012; Desender, Van Opstal, & Van den Bussche, 2014).

As outlined before, another way to deal with conflicting information is to proactively use the overall degree of conflict in the environment to adapt the processing system to upcoming conflict. Again, according to the GNW, this should only be possible when participants are consciously aware that there is a particular degree of conflict. If the information that a particular block of trials is highly conflict-laden remains unconscious, this information should not be able to trigger strategic adaptation. However, several studies showed that even with perfectly masked primes, congruency effects were sharply reduced when the overall probability of conflict was very high (e.g., Bodner & Dypvik, 2005; Bodner & Masson, 2001, 2004; Jaśkowski et al., 2003; Jiang, van Gaal, Bailey, Chen, & Zhang, 2013; Klapp, 2007). To explain these results within the framework of the GNW, one would have to follow an alternative explanation: When manipulating the probability of conflict, participants might become aware of this manipulation at a metacognitive level. For example, it could be the case that participants noticed (consciously or unconsciously) that blocks with mainly incongruent trials are very difficult (Kinoshita, Forster, & Mozer, 2008) or highly error prone (Jaśkowski et al., 2003). In this case, participants might adapt their behavior based on this metacognitive information, without knowing the origin of it, instead of adapting their behavior due to the accumulation of unconscious conflict information.

### Unconscious Context-Specific Conflict Adaptation

An elegant way to overcome this metacognitive interpretation of reduced congruency effects in high-interference blocks (e.g., Jaśkowski et al., 2003; Kinoshita et al., 2008) is the context-specific conflict adaptation paradigm explained before. In this paradigm, the overall conflict frequency between the blocks does not change when each context is presented equally often in each block. More specific, if context A consists of 80% incongruent trials and context B of 20% incongruent trials, the overall probability of encountering an incongruent trial, independent of the context, will be at chance level. If participants are completely unaware of the fact that different contexts associated with different degrees of conflict occur in the experiment, conscious by-products of the unconscious manipulation cannot be the source of strategic adaptation to the different contexts. Therefore, this paradigm is perfectly suited to examine whether participants can strategically cope with conflicting information without consciousness being involved.

Because conscious processing is in general much stronger than unconscious processing (Haynes et al., 2005), we expected the context-dependent exertion of unconscious cognitive control to be heavily dependent upon several crucial preconditions. In order to examine the borders of flexible unconscious adaptation processes, we varied several characteristics that might be crucial for associating conflict information with context information and then use the context information to improve responding.

A first crucial precondition to be able to associate conflict frequency with the corresponding context might be that context cues must be presented in a way so that they are mandatorily processed. For example, in the study of Crump et al. (2006),

attention was allocated to the targets, so the location of these targets was inherently processed. Contrary to this, in the study of Heinemann et al. (2009), two contexts were created by presenting two colored rectangles indicative of the particular context at the onset of every trial. Because these rectangles were irrelevant for the task at hand, we might assume that the cognitive system has more difficulties learning the covariation of context and conflict information. Therefore, in the current article, one goal was to investigate whether a presentation of the context information that is implemented within the task relevant stimuli enables a context-specific congruency modulation without awareness. To create different contexts in the priming paradigm, we will use the format in which stimuli are presented as a context cue. If stimuli are presented in two formats, the particular format of a stimulus is very likely to be processed automatically, because linking these particular stimuli to their appropriate response might help to improve task performance.

A second crucial precondition to associate conflict frequency with context information might be the timing when particular information becomes available. To recognize a regular covariation between conflict and context information, their temporal relation is obviously crucial. In many previous studies using this design, both sources of information were presented simultaneously, providing, so to say, optimal conditions to recognize their connection. For example, in the priming paradigm, information about whether or not a conflict is at hand is only available at the time the target is presented, because beforehand it cannot be known whether prime and target are conflicting. If target location is used as context cue (Crump et al., 2006), context information becomes available at the same time as the participant can determine whether conflict is at hand. On the other hand, when context information is presented early in time (e.g., Heinemann et al., 2009), conflict information is not yet available. To be able to associate the context with the conflict information, the context representation thus has to be held active for a longer time duration. To examine whether the timing of context and conflict information plays an important role in the association between both sources of information, in the current series of experiments we varied whether the context information is presented as a feature of the prime or as a feature of the target stimulus.

Interestingly, although simultaneity might facilitate the formation of associations between context and conflict information, the situation is rather reversed when it comes to using these associations to facilitate responding. Now if context information becomes only available at the time the conflict is experienced (i.e., with presentation of the target), the cognitive system does not have much time to reconfigure itself for this particular context to still be able to impact on the presumably already ongoing processing of the prime stimulus. On the contrary, when context information is presented temporally close to the conflicting stimulus (i.e., shortly before or together with the prime), the cognitive system has sufficient time to alter its processing pathways in order to effectively deal with the upcoming conflict. Thus, although it might be advantageous for the system to learn the regularities between context and conflict when both sources of information are presented together in time, when this information has to be used to improve responding, it seems preferable to present context information slightly before the conflicting stimulus.

## The Current Study

In the current study, we systematically investigated whether consciousness plays a crucial role in the flexible, context-dependent exertion of cognitive control. We used a priming paradigm with two contexts, one with low and the other with high conflict frequency. With this paradigm, we examined the role of awareness in the adaptation to conflict based on context information and the role of awareness with regard to the timing between these two sources of information.

Our first goal was to examine whether awareness of the conflict is a crucial precondition to associate conflict with context information. To examine this, we presented primes either clearly visible or heavily masked. Observing context-specific conflict adaptation effects only when primes are always presented clearly visible would suggest that awareness of the conflict is a crucial precondition. Our second goal was to examine whether awareness of the context information is a crucial precondition in order to learn its contingency with the conflict information. This can be examined by presenting the context information as a feature of the prime and presenting primes either clearly visible or heavily masked. Note that in the latter condition, both context and conflict information are presented unconsciously. Our third goal was to examine the necessity of presenting context information together in time with conflict information. We manipulated the timing between both sources of information by presenting the context either as a feature of the prime or as a feature of the target.

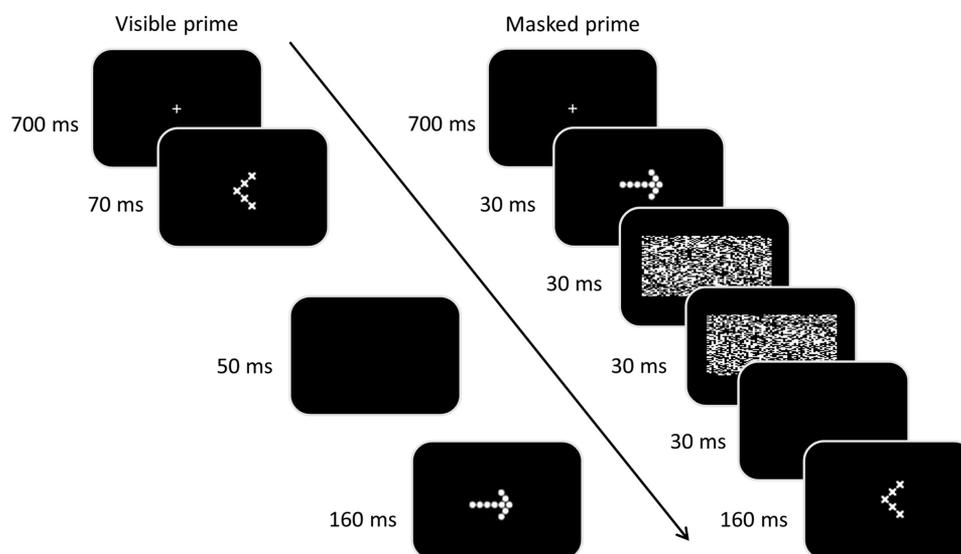
In Experiments 1 and 2, we used arrows as stimuli, and the format of the arrows (composed of dots vs. composed of crosses; see Figure 1) represented different contexts. Prime arrows were presented either clearly visible or heavily masked, and the context was conveyed by either the prime format (Experiment 1) or the target format (Experiment 2). In Experiments 3 and 4, we used

numbers as stimuli, and again used a format manipulation (i.e., Arabic digits vs. number words) to create different contexts. Primes were presented either clearly visible or heavily masked, and the critical context was again conveyed by either prime format (Experiment 3) or target format (Experiment 4). Experiments 1 and 3 are thus suitable to investigate the role of both conflict awareness and context awareness in a temporal frame when context and the conflicting stimulus are presented simultaneously. Experiments 2 and 4 are suitable to investigate the role of conflict awareness while context information is always presented consciously as a feature of the target. Here the context information is presented only after the conflicting stimulus, but together with the target, at the point in time when the presence or absence of a conflict in this trial can be determined.

## Experiment 1

### Method

**Participants.** Thirty-five participants (29 female) participated either in fulfillment of course requirements or in return for payment. Eighteen participants participated in the conscious condition, 17 in the unconscious condition. This sample size was determined beforehand based on our experience with priming studies: With arrow stimuli, congruency effects are very stable and comparatively large (e.g., Kiesel, Berner, & Kunde, 2008, Experiment 2 control condition vs. Experiment 4). As we aimed at investigating a modulation of the congruency effect, we chose a sample size that, based on our experience, allows for congruency effects to occur, so that potential modulations of this congruency effect can emerge. With arrow cues, this can be achieved with a comparably smaller sample size (compared to



*Figure 1.* Sequence of stimuli in trials of Experiments 1 and 2. On the left, a trial featuring a visible prime is depicted. The prime is not masked, but directly followed by a blank screen and the target. On the right, a trial featuring a prime that is masked by two random pixel backward masks is depicted. In both types of trials, the prime–target stimulus onset asynchrony is 120 ms. The context was indicated by either the format of the prime arrow (Experiment 1) or the format of the target arrow (Experiment 2).

Experiments 3 and 4, in which number stimuli are used and the sample sizes are larger). Mean age of the sample was 23 years (range: 18–30). All participants reported normal or corrected-to-normal vision and were naive with respect to the hypothesis.

**Apparatus and stimuli.** Stimuli were presented on an IBM compatible computer with a 17-in. (43.18-cm) VGA display, using the software package E-Prime (Psychology Software Tools, <http://www.pstnet.com>). Stimulus presentation was synchronized with the refresh rate of a 100-Hz monitor. Responses were executed with the index fingers of both hands and collected with external response keys. All stimuli were presented in white on a black background. The stimuli used were left and right pointing arrows, which were presented in two formats (see Figure 1).

**Design.** Primes presented in one format were followed by a congruent target in 80% of all trials. Primes presented in the other format were followed by a congruent target in 20% of all trials. For example, an arrow prime consisting of dots was congruent with the target in 80% of trials and incongruent in 20% of trials. Likewise, an arrow prime consisting of crosses was incongruent with the target in 80% of trials and congruent in 20% of trials. In this example, the dot format of the prime represents a context of low conflict, whereas the cross format of the prime represents a context of high conflict. It was counter-balanced across participants which prime format represented which context. The format of the prime varied randomly from trial to trial. Importantly, the format of the target varied independently from the prime format.

**Procedure.** Each trial started with the presentation of a centrally displayed fixation cross, lasting 700 ms (see Figure 1). Subsequently, participants in the conscious condition were presented with a prime arrow for 70 ms, followed by a blank for 50 ms. Participants in the unconscious condition were presented with a prime arrow for 30 ms, followed by two random pixel masks for 30 ms each (resulting in a total masking time of 60 ms) and a blank for 30 ms. This results in the same prime–target stimulus onset asynchrony (SOA) of 120 ms for both the conscious and the unconscious condition. After this, a target was presented for 160 ms. Participants' responses were recorded in a time window of maximal 3,000 ms. After response onset, the next trial started after an intertrial interval of 1,000 ms. If participants made an error, the message "FEHLER" (German for *ERROR*) appeared on-screen during the intertrial interval. Each participant performed 20 blocks of 40 trials (no training blocks). Participants were instructed to respond as fast as possible to the target arrow, while making as few errors as possible.

**Prime visibility.** After the main experiment, participants were presented with the same trials as during the main experiment, but this time they had to consecutively indicate the direction of the prime and then prime format. To preclude unconscious influences of the prime on this measure (e.g., Kiesel et al., 2006; Schlaghecken & Eimer, 2004), responses could only be given 500 ms after target presentation (for a similar procedure see Vorberg, Mattler, Heinecke, Schmidt, & Schwarzbach, 2003). Participants in the conscious condition were presented with 48 trials, and participants in the unconscious condition were presented with 160 trials.

## Results

Reaction times (RTs) faster or slower than 2.5 standard deviations from their condition mean (1.6%), the first trial of every block (2.4%), and trials following an error (7.5%) were excluded from the analysis. Mean RTs for correct responses and mean error rates were then submitted to an analysis of variance (ANOVA) with congruency (congruent vs. incongruent) and context (high-interference context vs. low-interference context) as within-subject factors and masking (masked vs. nonmasked) as between-subjects factor.

Targets were responded to 63 ms faster when they were congruent compared to incongruent,  $F(1, 33) = 154.15, p < .001, \eta^2 = .82$ . The size of the congruency effect did not differ between the nonmasked (63 ms) and the masked condition (63 ms;  $F < 1$ ). This main effect of congruency was modulated by context,  $F(1, 33) = 14.13, p < .001, \eta^2 = .30$ . The congruency effect was 16 ms larger in the low-interference (71 ms) compared to the high-interference context (55 ms). Importantly, this interaction was not modulated by the visibility of the prime ( $F < 1$ ). Planned comparisons revealed that the modulation of the congruency effect by the context occurred in both the conscious,  $F(1, 17) = 4.61, p = .046, \eta^2 = .21$ , and the unconscious condition,  $F(1, 16) = 17.76, p < .001, \eta^2 = .53$ .

In the error analysis, a main effect of congruency was found,  $F(1, 33) = 82.89, p < .001, \eta^2 = .72$ . The error rate was 12.5% lower on congruent compared to incongruent trials. This congruency effect was smaller in the conscious (9%) compared to the unconscious condition (16%),  $F(1, 33) = 6.77, p = .014, \eta^2 = .17$ . There was also a main effect of context,  $F(1, 33) = 4.53, p = .041, \eta^2 = .12$ , with more errors in the low-interference context, as well as an interaction between context and congruency,  $F(1, 33) = 12.64, p < .001, \eta^2 = .28$ . The congruency effect was 4.6% larger in the low-interference (14.8%) compared to the high-interference context (10.2%). This interaction was not modulated by the visibility of the prime,  $F(1, 33) = 2.40, p = .13, \eta^2 = .068$ . Planned comparisons revealed that the modulation of the congruency effect by context was apparent in the unconscious condition (6.7%),  $F(1, 16) = 10.51, p = .005, \eta^2 = .40$ , and that there was an accordant trend in the conscious condition (2.6%),  $F(1, 16) = 2.58, p = .128, \eta^2 = .14$ .

**Prime visibility.** To ensure that primes were truly invisible, we used the data from the detection task to calculate a signal detection  $d'$  (Tanner & Swets, 1954). Right pointing arrows were treated as signal, left pointing arrows as noise. To compute this measure for the format of the prime, we considered one format as signal, the other as noise. A  $d'$  of 0 shows that participants were not able to differentiate between signal and noise. Individual values (hits and false alarms) of 0 and 1 were corrected by 0.05 (see Hautus, 1995). In the conscious condition, the primes were clearly visible. Responses to both the direction ( $d' = 3.46$ ),  $t(17) = 9.67, p < .001$ , and the format of the primes ( $d' = 3.40$ ),  $t(17) = 11.23, p < .001$ , differed significantly from chance level. The same analysis confirmed that primes in the unconscious condition were not visible. Responses to both the direction ( $d' = 0.12$ ),  $t(16) = 1.97, p = .066$ , and the format of the primes ( $d' = 0.06$ ),  $t(16) = 2.011, p = .062$ , did not differ significantly from chance level. To further ensure that our results are not caused by prime visibility, we regressed the congruency effects onto our  $d'$  measure (Draine &

Greenwald, 1998). Each participant's congruency effect was regressed onto this participant's  $d'$  value. With this method, one is able to assess two values that indicate a dissociation of conscious from unconscious processing (Greenwald, Klinger, & Schuh, 1995): the correlation between individual prime visibility and the congruency effect, and the intercept of the regression line with the  $y$ -axis. A nonsignificant correlation indicates that congruency effects emerged independently from prime visibility. The intercept represents the size of a congruency effect at a theoretical level of absolutely zero visibility, predicted from the data. There was no correlation between the congruency effect and the visibility of the prime direction ( $r = .18$ ),  $t(16) = 0.73$ ,  $p = .48$ , and there was a positive intercept ( $b = 66.71$ ),  $t(16) = 8.47$ ,  $p < .001$ , showing priming at zero visibility. Because prime format is predictive of the context, it was tested whether the visibility of the format was related to the modulation of the congruency effect by the context. This was not the case ( $r = .15$ ),  $t(16) = 0.58$ ,  $p = .57$ , and the positive intercept ( $b = 15.18$ ),  $t(16) = 3.38$ ,  $p = .004$ , showed a context-specific modulation of the congruency effect at zero visibility.

## Discussion

The results of Experiment 1 show that context information that is contained in the primes can be used to adapt stimulus processing strategically even when the primes were masked. To determine how the timing of conflict information and context information plays a role in this kind of conflict adaptation, we conducted Experiment 2, in which the context was not represented by the format of the prime, but by the format of the target, hence later than the potentially conflict-inducing event itself.

## Experiment 2

### Method

**Participants.** Thirty-three participants (26 female) participated either in fulfillment of course requirements or in return for payment. Seventeen participants participated in the conscious condition, 16 in the unconscious condition. As in Experiment 1, this sample size was determined beforehand based on comparably large and stable congruency effects that are observable with arrow stimuli. Mean age of the sample was 21 years (range: 18–41). All participants reported normal or corrected-to-normal vision and were naive with respect to the hypothesis.

**Apparatus, stimuli, procedure, and design.** Experiment 2 resembled Experiment 1 except for the following changes.

In Experiment 2, the format of the target represented a context of high or low interference. A target arrow of a particular format was preceded by an incongruent prime in 80% and preceded by a congruent prime in 20% of all trials. Target arrows of the other format were preceded by a congruent prime in 80% and preceded by an incongruent prime in 20% of all trials. As both target formats were presented equally often, the overall proportion of congruent to incongruent primes was 50%. In contrast to Experiment 1, the prime format was not associated with a particular conflict frequency. As prime and target format were varied independently from each other, the prime format was nonpredictive for either the target format or the congruency of prime and target. Participants were instructed to respond as fast as possible with a key press

accordant to the direction of the target arrow. The format of the target arrow was irrelevant for the task.

Each participant first performed four training blocks containing 20 trials each, followed by 20 blocks of 40 trials. In the training blocks, the target format was only varied between the blocks, but not within the blocks, so that only one format was presented during a single block (with formats alternating between the blocks). In the experimental blocks, the target format was varied randomly on a trial-by-trial basis.

After the main experiment, participants were asked to indicate the direction of the prime arrow in 40 trials (unmasked condition) or 160 trials (masked condition).

## Results and Discussion

RTs deviating more than 2.5 standard deviations from their condition mean (1.5%), trials from practice blocks, the first trial of every block (2.4%), and trials following an error (8.3%) were excluded from the analysis. Mean RTs for correct responses and mean error rates were then submitted to an ANOVA with congruency (congruent vs. incongruent) and context (low-interference context vs. high-interference context) as within-subject factors and masking (masked vs. nonmasked) as between-subjects factor.

Targets were responded to 65 ms faster when they were congruent compared to incongruent,  $F(1, 31) = 211.58$ ,  $p < .001$ ,  $\eta^2 = .87$ . The interaction of congruency and masking was significant,  $F(1, 31) = 4.83$ ,  $p = .036$ ,  $\eta^2 = .14$ , which is due to a larger congruency effect of 74 ms in the conscious condition compared to the smaller congruency effect of 54 ms in the unconscious condition. The main effect of congruency was modulated by the context,  $F(1, 31) = 8.66$ ,  $p = .006$ ,  $\eta^2 = .22$ . The congruency effect was 9 ms larger in the low-interference context (69 ms) compared to the high-interference context (60 ms). Importantly, this interaction was not modulated by the visibility of the prime ( $F < 1$ ). Planned comparisons of the effects of congruency and context in the conscious and unconscious conditions revealed that the modulation of the congruency effect by the context was apparent in both the conscious condition,  $F(1, 16) = 4.89$ ,  $p = .042$ ,  $\eta^2 = .23$ , with a 11-ms larger congruency effect in the low-interference context compared to the high-interference context, and the unconscious condition,  $F(1, 15) = 5.03$ ,  $p = .040$ ,  $\eta^2 = .25$ , in which the congruency effect was 6 ms larger in the low-interference context compared to the high-interference context.

In the error analysis, a main effect of congruency was found,  $F(1, 31) = 78.99$ ,  $p < .001$ ,  $\eta^2 = .72$ . The error rate was 13% lower on congruent trials compared to incongruent trials. This congruency effect was significantly modulated by the context,  $F(1, 31) = 6.35$ ,  $p < .017$ ,  $\eta^2 = .17$ . The congruency effect was 2.8% larger in the low-interference (14.4%) compared to the high-interference context (11.6%). Importantly, this interaction was not modulated by the visibility of the prime,  $F(1, 31) = 0.298$ ,  $p = .589$ ,  $\eta^2 = .01$ . Planned comparisons revealed that the modulation of the congruency effect by the context was apparent in the conscious condition,  $F(1, 16) = 10.32$ ,  $p = .005$ ,  $\eta^2 = .39$ , with a 3% larger congruency effect in the low-interference context. In the unconscious condition, the congruency effect was 2.3% larger in the low-interference context, but this interaction was not significant,  $F(1, 15) = 1.207$ ,  $p = .289$ ,  $\eta^2 = .074$ .

**Prime visibility.** In the conscious condition, primes were clearly visible. Responses to both the direction ( $d' = 3.19$ ),  $t(16) = 14.30$ ,  $p < .001$ , and the format ( $d' = 2.65$ ),  $t(16) = 13.84$ ,  $p < .001$ , of the primes differed significantly from chance level.

The analysis of prime visibility also confirmed that primes in the unconscious condition were not visible, with a  $d'$  value of 0.004 that did not differ from chance level,  $t(15) = 0.067$ ,  $p = .95$ .

In conclusion, Experiment 2 revealed a modulation of the congruency effect that was based on a context conveyed by visible target features. This context-specific adaptation happened regardless of the visibility of the primes themselves. The impact of both masked primes and visible primes was modulated by the context.

### Interim Discussion of Experiments 1 and 2

In Experiments 1 and 2, we examined the role of conscious stimulus representations and timing in context-specific conflict adaptation. We investigated whether two randomly changing contexts that are associated with a high or low frequency of conflict can be used to improve responding, depending on awareness of the context, awareness of the conflict, and the timing of context and conflict. The results of Experiments 1 and 2 were straightforward, showing that independent of conflict awareness, independent of context awareness, and independent of the timing between both sources of information, participants were able to link conflict to context information and use the latter to improve responding. In both experiments, congruency effects were found to be reduced in the high-interference context compared to the low-interference context.

However, before drawing conclusions from these data, an alternative interpretation of the results must be considered. Due to the implementation of the congruency imbalance between the two contexts in Experiments 1 and 2, particular combinations of primes and targets were more frequent than others. In Experiment 1, prime arrows associated with low interference were more frequently combined with target arrows pointing in the same direction than with target arrows pointing in the other direction (and vice versa with prime arrows associated with high interference). This confound makes it difficult to decide whether the observed interaction between context and congruency was the consequence of participants associating conflict frequencies with contexts, and thus of actual conflict adaptation, or was instead caused by item-specific low-level learning (e.g., Hommel, 2004; Hommel, Proctor, & Vu, 2004; Mayr, Awh, & Laurey, 2003; Risko, Blais, Stolz, & Besner, 2008a, 2008b; Schmidt, 2013a, 2013b; Schmidt & Besner, 2008; Schmidt, Crump, Cheesman, & Besner, 2007). According to these accounts, reduced congruency effects in the highly incongruent context can potentially be explained by assuming that participants only acquired the relation between specific primes and their associated response (i.e., contingency learning), rather than the association between context and conflict. For example, when the dotted arrow format represented a high-conflict context in Experiment 1, it is possible that participants learned that a left-pointing dotted arrow prime is associated with a right response. Also, RTs tend to be faster on stimuli that are encountered more frequently (Logan, 1988). In the low-interference context, where congruent trials are very frequent, responses to these congruent stimulus combinations are faster, which results in a larger congruency effect. In the high-interference context, where incongruent trials are very fre-

quent, responses to these incongruent stimulus combinations are faster, which accordingly results in a smaller congruency effect. Thus, in Experiments 1 and 2, it cannot be ruled out that the observed pattern of results was caused by low-level learning mechanisms, without any involvement of cognitive control mechanisms.

To investigate whether we are examining a flexible context-dependent form of cognitive control, Experiments 3 and 4 were carried out to further explore the underlying mechanisms of the results of Experiments 1 and 2. In Experiments 3 and 4, some stimuli were presented equally often in both contexts throughout the experiment, so that an interaction of context and congruency with these stimuli cannot be explained by low-level learning (e.g., Crump & Milliken, 2009). We used numbers as prime and target stimuli in a larger-or-smaller-than-5 task (Dehaene, Naccache, et al., 1998), and again used prime or target format (i.e., Arabic number vs. spelled-out number word) as context cue. Half the stimuli were used as *inducing trials*. In these trials, the prime format (Experiment 3) or the target format (Experiment 4) was associated with high or low probability of conflict (completely analogous to Experiments 1 and 2), and thus these inducing trials served to induce the congruency frequencies for each context. The other stimuli were *test trials*. In test trials, as mentioned above, the prime format or target format was not associated with a higher frequency of either incongruent or congruent prime-target pairs, and each combination of test stimuli was presented equally often throughout the experiment. Therefore, effects of the context on the congruency effect in test trials show that the association of conflict frequency with context, which is only implemented by the inducing trials, generalizes to other stimuli that contain context features and thus provide us with an unbiased measure of conflict adaptation that cannot be explained by event learning. In fact, as Schmidt (2013b) noted, this form of contextual conflict adaptation might be the only real demonstration of a conflict adaptation mechanism. Apart from these changes, both experiments follow the same logic as Experiments 1 and 2.

### Experiment 3

#### Method

**Participants.** A new sample of 64 participants (49 female) participated either in fulfillment of course requirements or in return for payment. Half the participants participated in the conscious condition, the other half in the unconscious condition. The sample size was increased compared to Experiments 1 and 2. This was done to have sufficient power to detect even subtle variations of congruency effects, which according to our experience are generally smaller with number stimuli than with arrow stimuli (e.g., Kiesel et al., 2008, Experiment 2 control condition vs. Experiment 4). One participant was removed because his mean RT was more than 2.5 standard deviations above the group mean. Mean age of the sample was 23.9 years (range: 18–36). All participants reported normal or corrected-to-normal vision and were naive with respect to the hypothesis.

**Apparatus and stimuli.** The same apparatus as in the first experiment was used. Stimuli used in this experiment were the Arabic digits 1, 2, 3, 4, 6, 7, 8, 9, and their corresponding German number words *eins*, *zwei*, *drei*, *vier*, *sechs*, *sieben*, *acht*, and *neun*.

Half the numbers (either 1, 4, 6, and 9 or 2, 3, 7, and 8, counterbalanced over participants) were utilized as inducing stimuli, and the other numbers were utilized as test stimuli. Prime stimuli were flanked by the signs “\$” and “\$” on both sides until the total number of characters equaled 7 (e.g., \$\$\$7\$\$\$) or 8 (e.g., \$sieben\$). Masks consisted of an array of hash marks (#####), followed by an array of at signs (@@@@@@).

**Design.** Inducing primes presented in one format were followed by a congruent target in 87.5% of all trials. Inducing primes presented in the other format were followed by a congruent target in 12.5% of all trials. Test primes were followed by a congruent target in 50% of all trials, regardless of their format. Because inducing primes appeared 4 times as often as test primes, the overall frequency of congruent trials was 80% in the low-interference context and 20% in the high-interference context. It was counterbalanced across participants which prime format represented which context. The format of the prime and the format of the target varied randomly and independently from trial to trial. On every trial, both prime and target were either test or inducing stimuli.

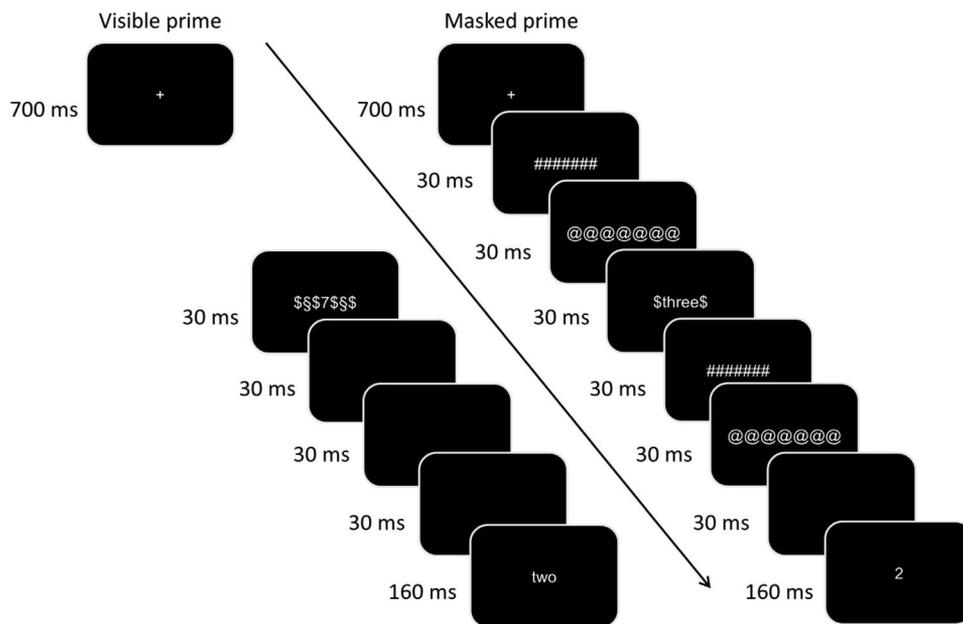
**Procedure.** Each trial started with the presentation of a centrally displayed fixation cross for 700 ms (see Figure 2). Subsequently, participants in the conscious condition were presented with a prime for 30 ms, followed by a 90-ms blank. Participants in the unconscious condition were presented with an array of hash marks for 30 ms, followed by an array of at signs for 30 ms, both functioning as forward masks. After this, a prime appeared for 30 ms, followed again by the same two masks for 30 ms each (60 ms total) and a blank for 30 ms. This results in the same prime–target

SOA of 120 ms for both the conscious and unconscious condition (and also the same SOA as in Experiments 1 and 2). Afterward, both groups were presented with a target lasting 160 ms. Participants had to decide within a response window of 3,000 ms as fast as possible whether the target number was larger or smaller than 5 by pressing a left or right response key (mapping counterbalanced over participants). The next trial started 1,000 ms after response onset. If participants made an error, the message “FEHLER” (German for *ERROR*) appeared during this interval. Each participant performed 12 blocks of 80 trials. Participants were instructed to respond as fast as possible to the target, while making as few errors as possible.

**Prime visibility.** After the main experiment, participants were presented with the same trials as in the main experiment, this time responding to the prime rather than to the target. Responses to the primes, which were masked in 50% of the trials, could be given only at least 640 ms after target presentation. In the first 128 trials, participants were asked to respond to the magnitude of the primes. In the following 128 trials, participants responded to the format of the prime.

## Results

RTs deviating more than 2.5 standard deviations from their condition mean (2.1%), the first trial of every block (1.2%), and trials following an error (5.5%) were excluded from the analysis. Mean RTs from correct responses and mean error rates were then submitted to an ANOVA with congruency (congruent vs. incongruent) and context (high-interference context vs. low-interference



*Figure 2.* Sequence of stimuli in trials of Experiments 3 and 4. On the left, a trial featuring a visible prime is depicted. The prime is not masked by forward masks and backward masks. To account for the missing backward masks, the blank screen before target onset is extended so that the prime–target stimulus onset asynchrony is 120 ms in both types of trials. On the right, a trial featuring a prime that is masked by forward and backward pattern masks is depicted. The context was indicated by either the format of the prime number/word (Experiment 3) or the format of the target number/word (Experiment 4).

context) as within-subject factors and masking (masked vs. non-masked) as between-subjects factor. Analyses were conducted separately for inducing trials and test trials. Results are illustrated in Figure 3.

First, we present the results of the inducing trials. Targets were responded to 30 ms faster when they were congruent compared to incongruent,  $F(1, 61) = 232.86, p < .001, \eta^2 = .79$ . This effect was larger in the conscious (43 ms) compared to the unconscious condition (16 ms),  $F(1, 61) = 44.95, p < .001, \eta^2 = .42$ . The congruency effect was modulated by the context,  $F(1, 61) = 17.79, p < .001, \eta^2 = .23$ . Congruency effects were found to be 11 ms larger in the low-interference (35 ms) compared to the high-interference context (24 ms). This interaction was not modulated by the visibility of the prime,  $F(1, 61) = 1.75, p = .19, \eta^2 = .028$ . Planned comparisons revealed that the modulation of the congruency effect by the context was apparent in both the conscious condition (12 ms),  $t(31) = 2.98, p = .006$ , and the unconscious condition (8ms),  $t(30) = 2.64, p = .013$ .

Errors made on inducing trials mimicked these results. Error rates were 3.8% lower on congruent compared to incongruent trials,  $F(1, 61) = 42.33, p < .001, \eta^2 = .41$ . This effect was larger in the conscious condition (5.4%) compared to the unconscious condition (2.3%),  $F(1, 61) = 6.91, p = .011, \eta^2 = .10$ . The congruency effect was modulated by the context,  $F(1, 61) = 6.86, p = .011, \eta^2 = .10$ . Congruency effects were found to be 2.0% larger in the low-interference (4.8%) compared to the high-interference context (2.8%). This interaction was not modulated by the visibility of the prime,  $F(1, 61) = 2.11, p = .15, \eta^2 = .033$ . Planned comparisons revealed that the modulation of the congruency effect by the context was apparent in the conscious condition (3.2%),  $t(31) = 2.49, p = .018$ , but it failed to reach significance in the unconscious condition (0.9%),  $t(30) = 1.09, p = .28$ .

Next, we present the results of the test trials. Targets were responded to 33 ms faster when they were congruent compared to incongruent,  $F(1, 61) = 104.78, p < .001, \eta^2 = .63$ . This effect was 24 ms larger in the conscious (45 ms) compared to the

unconscious condition (21 ms),  $F(1, 61) = 17.98, p < .001, \eta^2 = .23$ . Although there was only a trend for an interaction between congruency and context,  $F(1, 61) = 2.87, p = .095, \eta^2 = .045$ , this interaction was modulated by the visibility of the prime,  $F(1, 61) = 3.83, p = .05, \eta^2 = .06$ . Planned comparisons revealed that the modulation of the congruency effect by the context was absent in the conscious condition (0 ms;  $t < 0.008, p = .99$ ). Strikingly, however, the congruency effect was modulated by the context in the unconscious condition (11 ms),  $t(30) = 2.14, p = .041$ .

Errors made on test trials mimicked these results. Error rates were 4.3% lower on congruent compared to incongruent trials,  $F(1, 61) = 33.84, p < .001$ . This effect was only marginally larger in the conscious (5.5%) compared to the unconscious condition (3.0%),  $F(1, 61) = 3.16, p = .08, \eta^2 = .049$ . The congruency effect was modulated by the context,  $F(1, 61) = 7.27, p = .009, \eta^2 = .11$ . Congruency effects were found to be 3.27% larger in the low-interference (5.96%) compared to the high-interference context (2.69%). This interaction was not modulated by the visibility of the prime ( $F < 1$ ). Planned comparisons revealed that the modulation of the congruency effect by context was absent in the conscious condition (2.5%),  $t(31) = 1.47, p = .153$ , and apparent in the unconscious condition (4.2%),  $t(30) = 2.42, p = .022$ .

As the observed modulation of the congruency effect by the context in the test trials of the unconscious condition is a crucial result for the overall interpretation of our data, we aimed at providing stronger evidence for this effect. To this end, we replicated Experiment 3 with a completely new sample of 32 participants. All participants were presented with masked primes only. As only the test trials yield unambiguous evidence for conflict adaptation processes, the results for the test trials are presented in the following.

RTs deviating more than 2.5 standard deviations from their condition mean (2.0%), the first trial of every block (1.2%), and trials following an error (5.8%) were excluded from the analysis. Mean RTs from correct responses in test trials and mean error rates in test trials were then submitted to an ANOVA with congruency

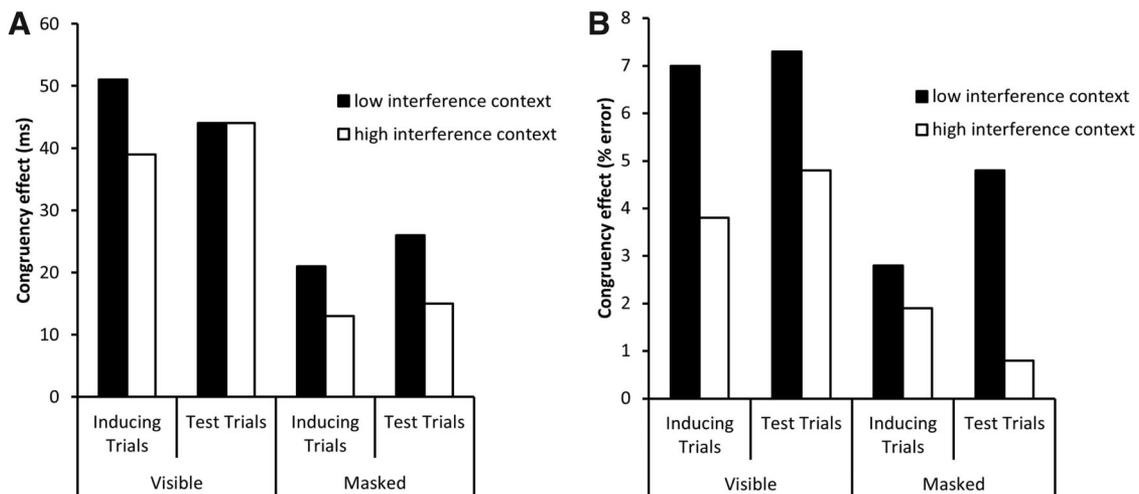


Figure 3. Results of Experiment 3. Figure 3A shows congruency effects in reaction time as a function of prime visibility (visible vs. masked), trial type (inducing vs. test trial), and context (low interference vs. high interference). Figure 3B shows the same for error rates.

(congruent vs. incongruent) and context (high-interference context vs. low-interference context) as within-subject factors (as stated, primes were always masked, so the factor masking is not applicable).

Participants responded 19 ms faster after congruent compared to incongruent primes,  $F(1, 31) = 32.35$ ,  $p < .001$ ,  $\eta^2 = .51$ . Crucially, the main effect of congruency was modulated by a significant interaction with the context,  $F(1, 31) = 4.85$ ,  $p = .035$ ,  $\eta^2 = .14$ . This interaction was characterized by a smaller congruency effect in the high-interference context than in the low-interference context. In the high-interference context, the congruency effect was 13 ms, while in the low-interference context, the congruency effect amounted to 25 ms.

With error rates, we also found a significant congruency effect of 1.8%,  $F(1, 31) = 5.20$ ,  $p = .03$ ,  $\eta^2 = .14$ . However, no interaction of congruency and context was found ( $F < 1$ ).

Additionally, these 32 participants were tested for their conflict awareness (and context-specific conflict awareness). To this end, after the main experiment, they performed 240 trials in which they again responded to the target. Importantly, they had to indicate after each trial whether they thought prime and target were conflicting. First, we found that they were able to indicate correctly above chance (i.e., in 58% of trials) whether the trial was conflicting,  $t(31) = 6.93$ ,  $p < .001$ . This result is in line with current findings that show that conflict awareness might occur (in form of a subjective conflict experience) even when there is no awareness of the prime itself (Desender et al., 2014). However, one should also keep in mind that in contrast to the main experiment, participants knew that they would be asked after each trial to indicate conflict or no conflict, so that their awareness of these concepts was presumably increased by the measurement itself. Second, we tested for awareness of the context meaning, that is, whether participants consciously associated a particular context with conflict. If this would be the case, participants should be biased to report conflict in the high-conflict context and likewise be biased to report no conflict in the low-conflict context. The analysis revealed, however, that participants were equally biased to judge a trial as conflict free when it featured the high-conflict context (62% judgment “congruent”) and when it featured the low-conflict context (61% judgment “congruent”),  $t(31) = 0.575$ ,  $p = .569$ . Thus, taken together, it seems that while participants potentially had some awareness of conflict, they had no awareness of the relation between conflict and context.

**Prime visibility.** In the conscious condition, primes were clearly visible. Responses to both the magnitude ( $d' = 2.60$ ),  $t(31) = 13.90$ ,  $p < .001$ , and the format ( $d' = 2.55$ ),  $t(31) = 13.46$ ,  $p < .001$ , of the primes differed significantly from chance level.

In the unconscious condition,  $d'$  deviated significantly from 0 in both the magnitude task ( $d' = 0.35$ ),  $t(30) = 3.62$ ,  $p < .001$ , and the format task ( $d' = 0.24$ ),  $t(30) = 4.73$ ,  $p < .001$ . We again regressed individual prime magnitude visibility on individual congruency effects. The congruency effect correlated with the visibility of prime magnitude ( $r = 11.72$ ),  $t(30) = 2.56$ ,  $p = .016$ , but there was also a positive intercept ( $b = 14.55$ ),  $t(30) = 5.009$ ,  $p < .001$ , showing congruency effects at zero visibility. To analyze the relation of awareness of the context feature and a context-specific congruency effect, we regressed individual prime format visibility onto individual context-specific congruency effect (i.e., the difference in congruency effects between both contexts for each partic-

ipant). The modulation of the congruency effect by the context was not related to the visibility of the prime format ( $r = -10.62$ ),  $t(30) = 0.92$ ,  $p = .36$ , and the intercept was positive ( $b = 12.78$ ),  $t(30) = 2.99$ ,  $p = .006$ , implying a context-specific modulation of the congruency effect at zero context visibility.

## Discussion

In summary, Experiment 3 revealed adaptation effects that were based on a context that was signaled by a prime feature. This adaptation occurred even when the primes were masked, thus when both the conflict inducing stimulus and the context itself were unconscious. Moreover, this adaptation occurred in test trials, in which the possible impact of low-level learning processes that may have contaminated the adaptation effects in Experiments 1 and 2 were ruled out. A replication of the masked portion of Experiment 3 helped solidify the evidence that a context-specific modulation of the congruency effect that can unambiguously be attributed to conflict adaptation processes (and not low-level event learning mechanisms) is possible even when both the conflicting stimulus and the context are presented masked. Remarkably, such adaptation was not observed with visible primes, where the conditions for adaptation can usually be considered even more favorable. We will come back to this result in the General Discussion section.

## Experiment 4

### Method

**Participants.** A new sample of 63 participants (41 female) participated either in fulfillment of course requirements or in return for payment. Thirty-two participated in the conscious condition, 31 in the unconscious condition. The sample size was determined beforehand on the same basis as in Experiment 3. Mean age of the sample was 23 years (range: 18–33). All participants reported normal or corrected-to-normal vision and were naive with respect to the hypothesis.

**Apparatus, stimuli, procedure, and design.** Experiment 4 resembled Experiment 3 except for the following. Now the format of the target, not the format of the prime, functioned as a context feature and was associated with a particular probability of congruent or incongruent prime–target pairs. As prime and target format were varied independently from each other, the prime format was nonpredictive for either the target format or the congruency of prime and target. Inducing targets presented in one format were preceded by a congruent prime in 87.5% of all trials. Inducing targets presented in the other format were preceded by a congruent prime in 12.5% of all trials. Regardless of their format, test targets were preceded by a congruent prime in 50% of all trials. Because inducing targets appeared 4 times as often as test targets, the overall frequency of congruent trials was thus 80% in the low-interference context and 20% in the high-interference context. It was counterbalanced across participants which target format represented which context.

### Results

RTs deviating more than 2.5 standard deviations from their condition mean (2.2%), the first trial of every block (1.2%), and

trials following an error (4.1%) were excluded from the analysis. Mean RTs for correct responses and mean error rates were then submitted to an ANOVA with congruency (congruent vs. incongruent) and context (high-interference context vs. low-interference context) as within-subject factors and masking (masked vs. non-masked) as between-subjects factor. Analyses were conducted separately for inducing trials and test trials. Results are illustrated in Figure 4.

First, we present the results of the inducing trials. Targets were responded to 26 ms faster when they were congruent compared to incongruent,  $F(1, 61) = 205.89, p < .001, \eta^2 = .77$ . This effect was larger in the conscious (43 ms) compared to the unconscious condition (15 ms),  $F(1, 61) = 54.20, p < .001, \eta^2 = .47$ . The congruency effect was modulated by the context,  $F(1, 61) = 6.02, p = .017, \eta^2 = .09$ . Congruency effects were found to be 7 ms larger in the low-interference (32 ms) compared to the high-interference context (25 ms). This interaction was not modulated by the visibility of the prime,  $F(1, 61) = 1.21, p = .275$ . Planned comparisons between the conscious and unconscious condition, however, revealed that the modulation of the congruency effect by the context was only apparent in the conscious condition,  $F(1, 31) = 5.34, p = .028, \eta^2 = .15$ . Here we found a congruency effect of 48 ms in the low-interference context and a smaller congruency effect of 38 ms in the high-interference context. When the primes were masked, the interaction of congruency and context was not significant,  $F(1, 30) = 1.14, p = .294, \eta^2 = .035$ .

Error rates were 4.4% lower on congruent compared to incongruent trials,  $F(1, 61) = 67.38, p < .001, \eta^2 = .52$ . This effect was larger in the conscious (6.6%) compared to the unconscious condition (2.1%),  $F(1, 61) = 18.03, p < .001, \eta^2 = .23$ . The congruency effect was not modulated by the context,  $F(1, 61) = 1.70, p = .20$ , and there was no three-way interaction with the visibility of the primes ( $F < 1$ ).

Next, we present the results of the test trials. Targets were responded to 33 ms faster when they were congruent compared to incongruent,  $F(1, 61) = 293.26, p < .001, \eta^2 = .83$ . The congru-

ency effect was larger in the conscious (47 ms) compared to the unconscious condition (20 ms),  $F(1, 61) = 51.71, p < .001, \eta^2 = .46$ . The congruency effect was also modulated by the context,  $F(1, 61) = 6.14, p = .016, \eta^2 = .09$ , with a 38-ms congruency effect in the high-interference context compared to a 29-ms congruency effect in the low-interference context. This interaction was not significantly modulated by the visibility of the prime,  $F(1, 61) = 2.43, p = .125, \eta^2 = .038$ . Planned comparisons between the conscious and unconscious condition, however, revealed that the modulation of the congruency effect by context was indeed found only in the conscious condition,  $F(1, 31) = 9.89, p = .004, \eta^2 = .24$ , with a congruency effect that was 14 ms larger in the low-interference than in the high-interference context. In the unconscious condition, the congruency effect did not interact with the context ( $F < 1$ ).

Error rates were 4.4% lower on congruent compared to incongruent trials,  $F(1, 61) = 43.49, p < .001, \eta^2 = .42$ . This congruency effect depended on the visibility of the prime,  $F(1, 61) = 20.75, p < .001, \eta^2 = .25$ , with a congruency effect of 7.4% in the conscious condition compared to a congruency effect of 1.0% in the unconscious condition. The congruency effect was also modulated by the context,  $F(1, 61) = 4.12, p = .047, \eta^2 = .063$ . Congruency effects were larger in the low-interference (5.3%) compared to the high-interference context (3.5%). This interaction was not modulated by the visibility of the prime,  $F(1, 61) = 1.92, p = .171$ . Planned comparisons between the conscious and unconscious condition revealed, however, that the modulation of the congruency effect by the context was apparent in the conscious condition,  $F(1, 31) = 4.84, p = .035, \eta^2 = .14$ , but completely absent in the unconscious condition ( $F < 1$ ).

**Prime visibility.** In the conscious condition, primes were clearly visible. Responses to both the magnitude ( $d' = 2.36$ ),  $t(31) = 12.19, p < .001$ , and the format ( $d' = 2.75$ ),  $t(31) = 38.21, p < .001$ , of the primes differed significantly from chance level.

In the unconscious condition,  $d'$  deviated significantly from 0 in the magnitude task ( $d' = 0.22$ ),  $t(30) = 3.50, p = .001$ . Consid-

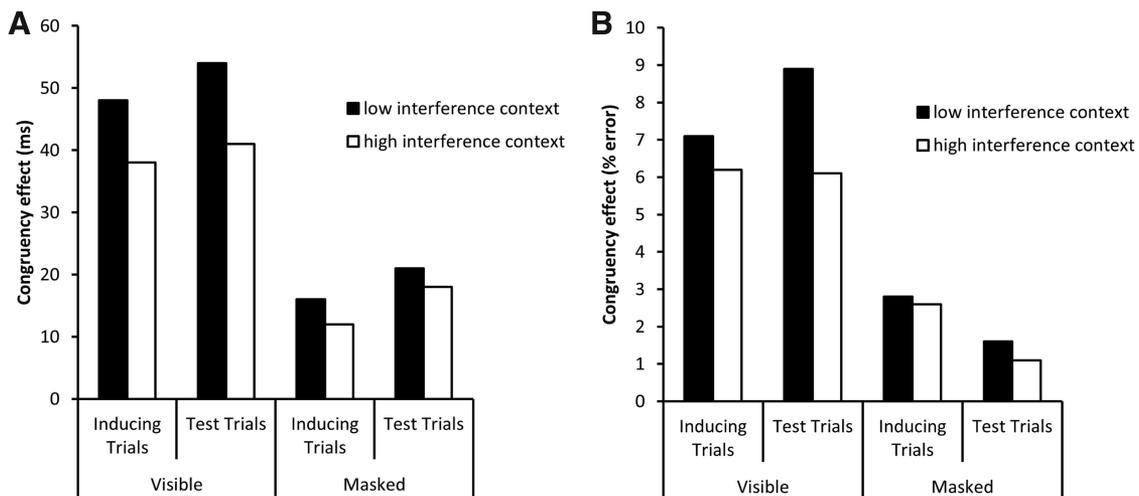


Figure 4. Results of Experiment 4. Figure 4A shows congruency effects in reaction time as a function of prime visibility (visible vs. masked), trial type (inducing vs. test trial), and context (low interference vs. high interference). Figure 4B shows the same for error rates.

ering the identification of the prime format (which was nonpredictive in Experiment 4),  $d'$  did not differ significantly from 0 ( $d' = 0.38$ ),  $t(30) = 1.52$ ,  $p = .14$ .

## Discussion

In summary, Experiment 4 revealed adaptation effects that were based on a context that was signaled by a visible target feature. This occurred when the conflict-inducing primes were visible, but in keen contrast to Experiment 3, not when they were invisible. This restriction to visible primes was evident in inducing trials, where low-level learning processes may have taken place, and replicated in test trials in which low-level learning mechanisms could not take effect.

The difference to Experiment 3 was that the context information was featured in the target. This leads to two critical implications: First, the conflicting stimulus (the prime) and the context information were now presented temporally apart; that is, the context information was only available after the prime was presented. Second, context information was now always consciously presented, independent of prime visibility. As a conscious presentation of the context should usually facilitate determining when conflict adaptation processes are necessary, the absence of adaptation effects in both inducing trials and test trials seems to be attributable to the now changed timing of context and conflict. So, while a conscious context representation seems to play no major role for the emergence of context-specific conflict adaptation (as seen with the presence of such an effect in Experiment 3, where the context was masked), the timing of context and (unconscious) conflict is critical.

## General Discussion

The present study examined the interplay of awareness and cognitive control. Specifically, we investigated whether context-specific conflict adaptation is restricted to instances in which we are aware of conflicts and contexts, or whether and under which circumstances conflict adaptation can operate independent of context and conflict awareness. In a priming paradigm, two randomly changing contexts were associated with either high or low interference. In Experiments 1 and 3, the different contexts were signaled by the format of the prime, which was presented either masked or nonmasked. Because the prime also functions as the potentially conflicting stimulus, the visibility of the prime determined both the awareness of the conflict and the awareness of the context. In Experiments 2 and 4, the format of the target signaled the different contexts. Thus, context information was always presented visibly, while awareness of the conflict again varied with prime visibility. Additionally, the representation of the context in either the prime or the target also entails that context information is available rather “early” when the prime is presented or rather “late,” not before the target appears. With this design we focused on three questions. First, can context information be linked to unconscious conflict? Second, can unconscious context information be linked to conflict and used for conflict adaptation? And third, what is the role of timing of conflict and context for context-specific adaptation processes?

The results of Experiments 1 and 2 suggest that neither awareness of the context information nor awareness of the conflict

information is necessary to use context information for conflict adaptation. In Experiment 1, context information was included in the prime, so that both the conflicting stimulus and the context information were presented unconsciously when the prime was masked. Still, congruency effects were reduced when the prime signaled a context of high instead of low interference regardless of prime visibility. Additionally, the timing of conflict information and context information played no crucial role in Experiments 1 and 2. Context-specific adaptation occurred independent of whether context information was provided with the prime or later with the target.

However, the results of Experiments 1 and 2 are not unambiguous, as the experimental design did not preclude alternative explanations of the results that are not based on conflict adaptation. First, particular combinations of stimuli were more frequent than other combinations of stimuli. This allows for an alternative explanation in terms of event learning, which means that responses to particular stimulus combinations (which are integrated into events) are faster the more frequent the event is (Hommel, 1998; Logan & Zbrodoff, 1979). Second, in recent years it was theorized that certain phenomena that were seen as instances of conflict adaptation do not in fact reflect conflict adaptation, but other processes like contingency learning and temporal learning (Schmidt, 2013a, 2013b; Schmidt & De Houwer, 2011, 2012). Contingency learning means that when particular stimuli are associated with a particular response, this contingency is the mechanism that leads to specific effects. Items associated with the congruent response facilitate the congruent response, thus increasing the congruency effect. Items associated with the incongruent response facilitate the incongruent response, thus decreasing the congruency effect. Accordingly, as the four primes in Experiment 1 were each associated (with a probability of 80%) with a particular response, a contingency learning mechanism could explain the found results. As Schmidt (2013b) pointed out, the contingency account is unable to explain context-specific modulations of the congruency effect when inducing and test trials (as in Experiments 3 and 4) are used. Temporal learning means that participants learn when (or, in other words, how fast) to respond. For example, in a block with high proportion of congruent trials, participants learn that they are able to respond fast, and as these fast responses are mainly for congruent trials (as it is a block with mainly congruent trials), the congruency effect is increased. Accordingly, the congruency effect is decreased in a block with mainly incongruent trials. With a context-specific conflict manipulation, however, temporal learning is more problematic. One would have to assume that temporal expectancy can vary from trial to trial (instead of being task-wide), for which there is no evidence (Schmidt, 2013b). Thus, when the context varies randomly trial by trial, and contingency learning is precluded by the usage of test and inducing trials, which was the case in both Experiments 3 and 4, “conflict adaptation may be the only viable account that remains” to explain context-specific effects (Schmidt, 2013b, p. 621).<sup>1</sup>

<sup>1</sup> A speculative possibility that remains would be that the likely response to the context feature in combination with the prime category (i.e., larger or smaller than 5) is learned. However, this would assume that only the prime category, but not the prime identity, is extracted in addition to the context, or otherwise there should be no effect with test stimuli (as for a test stimulus, the participant would learn that both responses are equally probable in both contexts). We thank one of the reviewers for this suggestion.

To disentangle the contribution of unconscious cognitive control and low-level learning, we carried out Experiments 3 and 4. In these experiments, low-level learning was controlled by the use of inducing trials and test trials. The results of Experiment 3 (as well as the results of a separate replication) confirmed that even when low-level learning was ruled out, participants were able to associate the different contexts with their according conflict frequencies and use this to improve responding, even when both the conflicting stimulus and the context information were presented unconsciously. This implies that participants were able to detect conflict even when the prime was masked and to accumulate this conflict information to determine the conflict frequency for each context separately.

At least in part, the subjective experience of conflict might have played a role in this mechanism. Recently, it was found that the subjective experience of conflict, which can occur independent of the identification of the conflicting stimulus, is important for the adaptation to recent conflict (Desender et al., 2014). In a replication of Experiment 3, we observed that participants indeed had some awareness of whether or not a conflict was present in a trial. However, they showed no awareness that different contexts are associated with different conflict frequencies. This indicates that in context-specific conflict adaptation, subjective conflict experience might play a role when at first the conflict frequency has to be associated with the context information. The actual adaptation process, which is the modulation of prime processing based on the context information, however, seems not to be driven by subjective conflict experience, as the context itself seems not to elicit such conflict experience. To determine the exact role of conflict experience in (unconscious) context-specific conflict adaptation, further research is warranted.

Context-specific conflict adaptation was not found when primes were masked in Experiment 4. The crucial difference to Experiment 3 was that the context was only available at the time the target was presented. With visible primes, we still found context-specific conflict adaptation. This demonstrates the remarkable swiftness with which our conflict adaptation system operates, given that the context information has to be used instantly to be able to still modulate the already ongoing processing of the conflicting stimulus. When the primes were masked, however, no context-specific conflict adaptation was found. As the relative timing of conflicting stimulus and context was the crucial difference to Experiment 3, this suggests that in this case, the context information was in fact available too late in relation to the conflicting stimulus to still influence its processing.

The relation between consciousness and cognitive control received increasing attention in recent years. In many prominent theories of consciousness, cognitive control receives an important status with respect to conscious processing. For example, according to the GNW theory (Dehaene & Naccache, 2001), unconscious stimuli can potentially reach very high semantic processing levels, but these stimuli should be unable to trigger top-down cognitive control. Unconscious stimuli remain within unconscious processing modules and hence are not able to trigger the workspace (i.e., become conscious) and to trigger top-down behavior. However, several studies investigating different instances of cognitive control, like inhibition (Hughes, Velmans, & de Fockert, 2009; van Gaal, Ridderinkhof, Fahrenfort, Scholte, & Lamme, 2008; van Gaal, Ridderinkhof, van den Wildenberg, & Lamme, 2009), task

set activation (Lau & Passingham, 2007; Mattler, 2006; Reuss, Kiesel, Kunde, & Hommel, 2011), and endogenous orienting of attention (Reuss, Kiesel, Kunde, & Wühr, 2012; Reuss, Pohl, Kiesel, & Kunde 2011), have demonstrated that unconscious information is able to induce cognitive control processes, casting doubt on a functional role of consciousness in control processes (Hommel, 2013). For example, Reuss, Kiesel, et al. (2011) used a task switching paradigm in which an explicit task cue instructed the participant to do one of two tasks. When the cue was masked, participants were free to choose the task. Importantly, they chose the unconsciously cued task more often than the noncued task, and responded faster when they chose the cued task compared to when they chose the other task. Likewise, in the studies by van Gaal and colleagues (van Gaal et al., 2008, 2009), participants inhibited their response when they encountered a stop signal or a no-go signal, even when this signal was presented unconsciously. What all these observations have in common is that they show that a process that is meant to be carried out on the basis of conscious stimuli (e.g., a task cue) can also be performed on the basis of unconscious stimuli (e.g., Van Opstal, Gevers, Osman, & Verguts, 2010). Although recent studies have suggested ways to overcome interpretations in term of stimulus–response associations (Wolke, van Gaal, Scholte, Ridderinkhof, & Lamme, 2011), it seemed to be a crucial precondition for cognitive control functions triggered by unconscious external stimuli, that participants are also confronted with conscious instances of the stimuli (e.g., Chiu & Aron, 2014). On the basis of this literature, Kunde, Reuss, and Kiesel (2012) contrasted cognitive control processes that are initiated due to explicit information (like the aforementioned stop signal, task cue, or spatial cue) with cognitive control processes that are initiated due to implicit information (like conflict adaptation, as information has to be integrated to determine conflict in the first place). They argued that when an explicit cue asks for a particular cognitive control process, this is possible even when the cue is masked. When implicit information calls for cognitive control, however, this information has to be available consciously to trigger cognitive control processes.

The results of the current study, however, suggest that the exertion of unconscious cognitive control is not limited to explicit information directly triggering control. Under specific conditions, cognitive control can be exerted unconsciously in a flexible context-dependent manner, even without any conscious practice. Because we varied the visibility of the prime between subjects, conflict and context information were never presented consciously in the masked priming condition. Therefore, the found adaptation effects cannot be attributed to a conscious experience of context and conflict that was then also applied to masked stimuli. On the contrary, in the masked condition of our experiments, participants were largely unaware of conflict information and context information, and thus of the systematic covariation between conflict frequency and context information. As such, they were unaware of the possibility to use the context information strategically to reduce the impact of conflicting stimuli. Thus, our findings substantially extend the current literature by showing that cognitive control processes can be induced purely by stimuli that are never consciously perceived at all. Instances of unconsciously triggered cognitive control processes therefore are not restricted to cases in which a consciously learned explicit cue calls for control. On the contrary, the cognitive system seems to be capable of detecting

very subtle manipulations and using them to improve responding. This is not only true for cognitive control processes, but also for other processes like decision making. In a study by Pessiglione et al. (2008), participants had to decide on each trial whether or not to press a button, which was then followed by a positive or negative outcome. This decision was preceded by a heavily masked cue that was associated with either a rewarding or a punishing outcome. Strikingly, although the cues were in principle irrelevant for the task, participants were able to learn the cue–outcome associations and modify their decision making accordingly.

Our findings are in line with theories of cognitive control that assume an implicit, rather than explicit, learning of particular regularities in the environment (Blais, 2010; Blais, Robidoux, Risko, & Besner, 2007; Blais & Verguts, 2012; King, Korb, & Eegner, 2012; Verguts & Notebaert, 2008). For example, the modulation of the size of the Stroop effect (Stroop, 1935) depending on a block-wise manipulation has long been considered an example of voluntary processing strategies or strategic modulation of attention (Cheesman & Merikle, 1986; Lindsay & Jacoby, 1994; Lowe & Mitterer, 1982). However, it was shown that such a modulation of the Stroop effect is in fact independent of the participants' explicit knowledge of block-wise congruency proportions (Blais, Harris, Guerrero, & Bunge, 2012). Subjective awareness of the proportion of congruent trials (which was measured by questionnaire after each block) had no impact on the adaptation to these congruency proportions. Blais et al. (2012) thus reasoned that "participants are subconsciously adapting to their environment" (p. 275). King et al. (2012) analyzed functional magnetic resonance imaging (fMRI) data to investigate whether top-down control settings can be induced or retrieved in an implicit way. To this end, they used a flanker task in combination with implicit contextual cues (thus not unlike the masked context in Experiments 1 and 3 at hand); that is, presentation in the left or right hemifield was associated with congruent or incongruent flanker stimuli. Despite participants not being aware of the contextual manipulation (again measured by questionnaire), both the behavioral data and the fMRI data show context-specific cognitive control that operates "on the fly." The results of King et al. are also intriguing, as they used trial-unique stimuli to eliminate event learning and stimulus–response links as an alternative explanation for their results. They concluded that contextual conflict control can occur despite a lack of awareness of the contextual manipulation, which again calls into question the notion that controlled processing is inherently volitional. Overall, our results complement these findings by showing that regularities in the environment can be adapted to even when they are represented truly unconsciously (and not only "implicitly" but per se clearly recognizable).

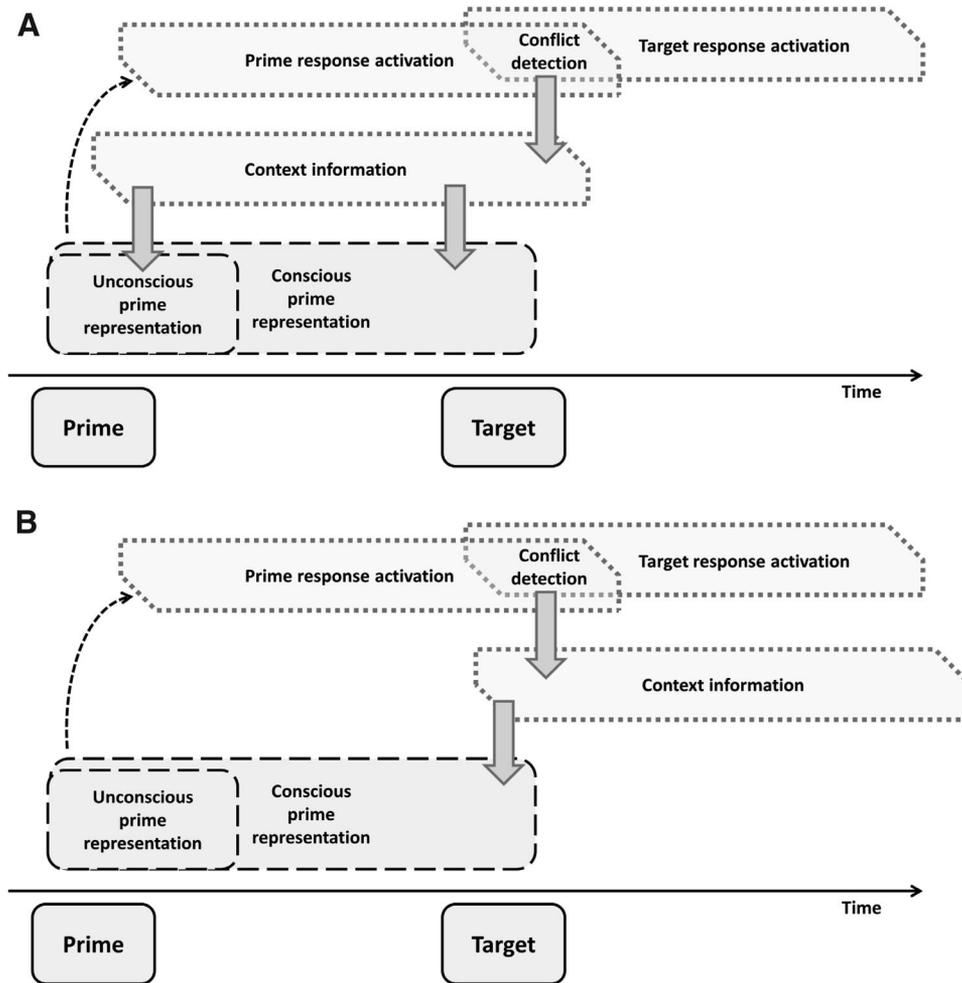
Blais and Verguts (2012; see also Verguts & Notebaert, 2008) argued that especially when cognitive control has to act fast (for which rapidly changing contexts are a prime example), an account of slow and deliberate cognitive control is insufficient. In their model, they assume that cognitive control operates through associative learning. Specifically, the model posits that any feature in the environment that is correlated with conflict (e.g., context feature) can be associated with current task representations. This leads to increased top-down activation when such a feature is encountered again. Applied directly to our experiments, this model would thus predict that the high-conflicting context (as an envi-

ronmental feature correlated with conflict) strengthens top-down control. While the authors do not explicitly talk about stimulus awareness, Blais and Verguts specifically note that this learning process "can be fast and, in principle, proceed without much effort" (p. 138), and awareness should thus at least be no necessary prerequisite for the implementation of cognitive control, which is corroborated by our findings.

Together with the recent stream of observations showing unconscious cognitive control, the current results pose a serious challenge for theories assuming a close link between consciousness and cognitive control. For example, our results contradict the prediction of the GNW that unconscious stimuli that remain within a modular system should not be able to trigger control functions. However, more than a mere extension of the potentially far-reaching capabilities of unconscious processing, our results also sketch a framework of boundaries to which this flexible conflict adaptation is restricted. Although the results of Experiments 1 and 3 nicely illustrated that the potential of stimuli to alter the system's processing pathways is certainly not restricted to consciously perceived stimuli, the results of Experiment 4 clearly show the boundaries of this flexible unconscious adaptation. When context information is only presented late in time, processing pathways of unconsciously presented primes remain unaltered. Following the observation that unconscious representations decay very rapidly in time (Haynes et al., 2005), lasting no more than approximately 1 s, this temporal framework in which context and conflict information was presented seemed to be very crucial. As noted in the introduction, the design of Experiment 4 seems to be more appropriate to easily learn how the different contexts are associated with conflict frequency, because here context and conflict information are presented together in time. In Experiment 3, context information is presented some time before conflict can be determined. However, once the association between both sources of information is learned, the early availability of context information in Experiment 3 seems more convenient when the context is used to initiate conflict adaptation. With context information available early, the cognitive system has more time to reconfigure itself according to the conflict frequency that is signaled by the context. Experiments 3 and 4 revealed adaptation to unconscious primes and unconscious contexts only when the context was a feature of the prime, but not when it was a feature of the target and hence temporally more separated from the prime. Consequently, the system is capable of adapting the processing pathways of unconscious representations only when the context information is provided soon enough in time.

In sum, it seems that that the control-invoking event (the context feature) and the process to be controlled (prime processing) need to possess a high spatial–temporal contiguity. In view of the present results, we conjecture that the lack of a sufficient spatial contiguity of invisible prime and visible context is a likely reason for the failure to observe adaptation effects in a previous study, in which the context was conveyed by background color rather than being an inherent feature of the prime (Heinemann et al., 2009).

In Figures 5A and 5B, we illustrate the potential interplay of the processes that are involved with context-specific conflict adaptation that can explain this current pattern of results. Figure 5A depicts the processes when the prime contains the context information. We assume that when the prime is presented, a prime representation that is stronger and longer lasting with nonmasked



*Figure 5.* Illustration of temporal overlaps between potential underlying processes of context-specific conflict adaptation. The dashed arrow on the left represents how the response activation is driven by the prime representation. The upper gray arrow represents how conflict is associated with the context information. The lower gray arrows represent the modulation of the prime representation by the context. In Figure 5A, the context is represented in the prime stimulus. When the prime is presented consciously, the large temporal overlap of context information and prime representation allows for a contextual modulation of the prime representation (lower right arrow) that in turn modulates the congruency effect. When the prime is presented unconsciously, the prime representation is more short-lived, but as the context information is available early, there still exists enough temporal overlap of context information and prime representation for a contextual modulation of the prime representation (lower left arrow). In Figure 5B, the context is represented in the target stimulus. Here the context is available too late to still be able to impact on the short-lived unconscious prime representation, so that no contextual conflict adaptation is observable with masked primes. The context is, however, still able to impact on the more long-lasting conscious prime representation.

primes than with masked primes is formed. From this prime representation, both the context information and the response activation are extracted, whereby response activation is stronger the longer the prime representation persists. When the target is presented, it activates its corresponding response. Now, by comparing the response activation that stems from the prime to the response activation of the target, one can determine whether or not there is a conflict.

To use context information as an indicator of the probability of conflict, one first has to learn the relation of a context with a

particular conflict frequency. To this end, the absence or presence of a conflict that has been determined once the target was presented has to be linked to the context information over a series of trials. This is possible even with masked primes because both the response activation of the prime (otherwise no congruency effect would emerge at all) and the context information persist at least until target presentation. When each context has been associated with a particular conflict frequency, the context information can then be used strategically once it is available in each trial to modulate the processing of the conflicting stimulus. As the context

information is already available early together with the prime, it can impact on the prime representation even when the prime was masked and the prime representation persists only for a short time (see the temporal overlap of context information and unconscious prime representation in Figure 5A). As the prime representation powers the response activation as long as it persists, this context-specific modulation of the prime representation accordingly modulates how strong the response activation of the prime is and consequently the size of the congruency effect.

Now consider what happens when the target contains the context information (see Figure 5B). All the basic processes are the same, but context information is only available when the target is presented. Again, participants first have to learn the systematic covariation of conflict probability and context. As the absence or presence of a conflict can only be determined after the target has been presented, and the context information is now available exactly at this moment as well, this learning process should be favored here. Then again, once the contexts have successfully been associated with particular conflict frequencies, the context information can be used strategically once it is available in each trial to modulate processing of the potentially conflicting stimulus. With nonmasked primes, the prime representation persists quite long due to the visibility of the prime. Possibly, masked primes that bear an overlearned meaning, like the arrow stimuli in Experiment 1, also persist longer due to their preexperimentally existing connection to behavioral relevance. As the prime representation is still active when the context information is presented, the latter can be used to modulate the prime representation and thus in turn modulate the primes' response activation. When the prime is masked, however, the prime representation persists only for a short time. Now, once context information is available, it cannot be effectively used to modulate the prime processing, as the prime representation already ceased to exist and thus cannot be modulated any more (note the missing overlap of context information and unconscious prime representation in Figure 5B). Thus, the spatial-temporal characteristics of the model provide a straightforward explanation of the presence of a contextual modulation of the congruency effect in Experiment 3 and the absence of such a modulation in Experiment 4.

There is one observation in Experiment 3 that requires some discussion. While we did observe adaptation to a prime-related context feature in test trials when the prime and thus the context feature were masked, we did not observe such adaptation in test trials when both were unmasked. At first glance, this suggests that there was no context-specific adaptation, although the conditions for such adaptation with a visible and prime-inherent context feature were almost ideal. Actually, we believe that the missing transfer from inducing to test trials does not reflect the lack of, but in fact a more *selective* level of context-specific adaptation. When interfering stimuli (primes) and context (prime format) are both visible, the conflict-context association might include both the format and the identity of the conflict-inducing primes, rather than spreading unselectively to all primes in a certain format. In other words, the system might learn that conflict is likely when one of the inducing primes occurs (e.g., 1 in Arabic format), whereas conflict is no more likely when an Arabic test prime (e.g., 3 in Arabic format) or a prime in another format (e.g., *one* as number word) occurs. Of course this would be a reinterpretation of the test and inducing trials logic that requires further elaboration.

To conclude, we have shown here for the first time that information processing adapts to unconsciously triggered conflict signaled by unconscious stimulus features. At the same time, the present study suggests strong limitations of such adaptation. Only with high spatial-temporal contiguity of conflict inducing and conflict signaling stimulation did we observe such adaptation.

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