

Functional characteristics of control adaptation in intermodal sensory processing



Tobias Melcher^{a,b,*}, Roland Pfister^c, Mareike Busmann^{b,d}, Michael-Christian Schlüter^a, Thomas Leyhe^a, Oliver Gruber^b

^a Center of Old Age Psychiatry, Psychiatric University Hospital, Basel, Switzerland

^b Centre for Translational Research in Systems Neuroscience and Clinical Psychiatry, Department of Psychiatry and Psychotherapy, Georg-August-University, Goettingen, Germany

^c Department of Cognitive Psychology, University of Wuerzburg, Germany

^d Department of Psychosomatic Medicine and Psychotherapy, Curtius Hospital Luebeck, Germany

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ABSTRACT

The present work investigated functional characteristics of control adjustments in intermodal sensory processing. Subjects performed an interference task that involved simultaneously presented visual and auditory stimuli which were either congruent or incongruent with respect to their response mappings. In two experiments, trial-by-trial sequential congruency effects were analysed for specific conditions that allowed ruling out “non-executive” contributions of stimulus or response priming to the respective RT fluctuations. In Experiment 1, conflict adaptation was observed in an oddball condition in which interference emanates from a task-irrelevant and response-neutral low-frequency stimulus. This finding characterizes intermodal control adjustments to be based – at least partly – on increased sensory selectivity, which is able to improve performance in any kind of interference condition which shares the same or overlapping attentional requirements. In order to further specify this attentional mechanism, Experiment 2 defined analogous conflict adaptation effects in non-interference unimodal trials in which just one of the two stimulus modalities was presented. Conflict adaptation effects in unimodal trials exclusively occurred for unimodal task-switch trials but not for otherwise equivalent task repetition trials, which suggests that the observed conflict-triggered control adjustments mainly consist of increased distractor inhibition (i.e., down-regulation of task-irrelevant information), while attributing a negligible role to target amplification (i.e., enhancement of task-relevant information) in this setup. This behavioral study yields a promising operational basis for subsequent neuroimaging investigations to define brain activations and connectivities which underlie the adaptive control of attentional selection.

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1. General introduction

1.1. Top-down attentional control: scope and experimental investigation

Top-down attentional control (TAC), i.e., the purposeful selection of relevant over irrelevant sensory information, is an essential prerequisite of goal-directed action and hence a main instance of executive control. Accordingly, TAC has been intensively investigated in both cognitive psychology and non-clinical cognitive neuroscience (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Gruber

& Goschke, 2004; Kiesel et al., 2010; Maunsell & Treue, 2006; Treue, 2001). Moreover, deficits in this domain may represent a direct expression of neuropathophysiological processes, which renders TAC an important issue for clinical neuroscience, too (e.g., Melcher, Falkai, & Gruber, 2008). In the latter context, attentional dysfunctions are among the most promising candidate *endophenotypic markers* (Gottesman & Gould, 2003) for psychiatric disorders such as schizophrenia (Cornblatt & Malhotra, 2001; Pinkham, Gur, & Gur, 2007; Snitz, MacDonald, & Carter, 2006; Turetsky et al., 2007) and bipolar disorder (Clark & Goodwin, 2004; Kurtz & Gerraty, 2009; Langenecker, Saunders, Kade, Ransom, & McInnis, 2010; Pattanayak, Sagar, & Mehta, 2011).

The functioning and neural implementation of TAC can be investigated by means of two basic groups of task paradigms: Attentional cueing tasks on the one hand and conflict or interference tasks on the other hand. In *attentional cueing tasks*, subjects

* Corresponding author at: Center of Old Age Psychiatry, Psychiatric University Hospital, Wilhelm Klein-Strasse 27, CH-4012 Basel, Switzerland. Fax: +41 (0)61 325 55 85.

E-mail address: tobias.melcher@upkbs.ch (T. Melcher).

are explicitly instructed by a *cue* stimulus to orient attention to a specific location, sensory dimension or modality prior to the appearance of the target stimulus proper (Corbetta & Shulman, 2002; Posner, Walker, Friedrich, & Rafal, 1984). Cueing paradigms allow investigating behavioral benefits and costs in target processing after valid cues and invalid cues, respectively. Moreover, measuring brain responses to attentional cues provides a straightforward strategy to investigate neural implementations of TAC and has led to the description of *frontoparietal attention networks* (for review see Corbetta & Shulman, 2002).

By contrast, *conflict* or *interference tasks* like the Stroop task (Stroop, 1935), the Simon task (Simon, 1969), the Flanker task (Eriksen & Eriksen, 1974), and the task-switching paradigm (Kiesel et al., 2010; Monsell, 2003), subjects are presented with multivalent stimuli. The different stimulus aspects may be mapped to different competing responses at times (incongruent stimuli) and thereby induce competition requiring increased top-down control to select the relevant over the irrelevant aspects. Accordingly, brain activations related to competition trials are widely interpreted as neural substrate of attentional control (Kerns et al., 2004). This interpretation, however, is restricted by the fact that contrast analyses between competition conditions and non-competition baseline conditions intermingle at least two processes: the occurrence or detection of competition on the one hand and remediate executive efforts on the other. This functional dissociation is a central postulate of the prominent *conflict monitoring account* (Botvinick et al., 2001), wherein activation in the anterior cingulate cortex is construed as neural substrate of conflict monitoring (i.e., the detection of conflict or competition) and subsequent activation in the dorsolateral prefrontal cortex is construed as the neural substrate of implemented selective control. This neurofunctional distinction of complementary evaluative (i.e., monitoring) and executive sub-processes provides a plausible conceptualization of cognitive control, not as singular instance but rather as a continuous, dynamic and adaptive process (Scherbaum, Dshemuchadse, Fischer, & Goschke, 2010). At the same time, this conceptualization stresses that the investigation of attentional control in interference processing may undesirably confound genuine executive processes with other evaluative processes. The *conflict adaptation principle* – a direct derivative of conflict monitoring theory – yields an experimental strategy to circumvent the described confound.

1.2. The conflict adaptation principle (and its challenges)

The conflict adaptation principle basically yields that top-down control is strengthened after the occurrence of conflict (Botvinick et al., 2001; Kerns, 2006; Kerns et al., 2004; Rabbitt, 1966; Rabbitt, 1968; Ullsperger, Bylisma, & Botvinick, 2005). The basic experimental demonstration of conflict adaptation is the so-called Gratton-effect (Gratton, Coles, & Donchin, 1992), which describes decreased or even absent behavioral conflict effects after conflict trials as compared to when trials without conflict precede. This sequential effect (Egner & Hirsch, 2005; Kerns et al., 2004) is statistically described as interaction between current and preceding congruency of relevant and irrelevant information and has been observed in a variety of different tasks (e.g., Egner, Ely, & Grinband, 2010; Kunde & Wühr, 2006; Notebaert, Gevers, Verbruggen, & Liefvooghe, 2006; Pfister, Schroeder, & Kunde, 2013; Ullsperger et al., 2005). Most importantly, the interpretation of sequential effects as reflecting “control exertion” is challenged by different alternative explanations which describe the Gratton effect as emanating from “passive” sensory priming rather than (pro-)active control adaptation (see Egner, 2007, for a review). First, conflict reduction after incongruent trials may reflect repetition priming in some settings due to stimulus-response repetitions

which facilitate responding (Mayr, Awh, & Laurey, 2003). For this reason, prior studies have adjusted their data for stimulus repetitions (cf. Egner & Hirsch, 2005; Kerns et al., 2004), which, however, partly leads to an undesirable imbalance regarding response repetitions between the compared sequence conditions (cf. Nieuwenhuis et al., 2006). Another challenge of the control adaptation principle is yielded by Feature Integration Theory (Hommel, Proctor, & Vu, 2004), which explains performance decrements for trial sequences with congruency switches between trials (congruent following incongruent, IC, and vice versa, CI) by incompatible response priming when stimulus features of the preceding trial are repeated in one stimulus dimension and changed in another. Stimuli including a repetition of just one stimulus feature, according to the theory, provoke ‘partial repetition costs’ because they prime both a response repetition and a response alternation simultaneously. Trial sequences with congruency repetitions (II and CC trials), on the other hand, include either complete stimulus repetitions which necessarily imply a response repetition (leading to repetition priming) or complete stimulus alternations that typically also call for a response alternation so that in either case both stimulus dimensions prime the required response.

1.3. Goals and scope of the present investigations

To date, a considerable number of studies using a wide range of tasks and stimuli have demonstrated conflict adaptation effects (i.e., interference reduction after interference trials) occurring independent of sensory priming processes (e.g., Kim & Cho, 2014; Notebaert & Verguts, 2007; Schmidt & Weissman, 2014). Therefore, there is substantial evidence that control efforts are indeed adapted (i.e., increased) after interference or conflict trials, at least when certain experimental preconditions are met (cf. Freitas & Clark, 2014; Weissman, Jiang, & Egner, 2014; but see Cho, Orr, Cohen, & Carter, 2009; Puccioni & Vallesi, 2012; Schmidt, 2013; Schmidt & De Houwer, 2011). This basically opens the possibility to adopt interference task paradigms in functional neuroimaging to define control-related brain activations by the analyses of sequential effects (cf. Egner & Hirsch, 2005). However, the specific functional characteristics of control adaptation after interference processing are still not sufficiently understood. In the present work, we therefore wanted to demonstrate Gratton-like sequential effects in an intermodal interference paradigm which cannot be explained by priming effects and therefore most probably reflect control adaptation. On this basis, we sought to elucidate the functional characteristics of control adaptation in a multimodal setting to answer the following two questions:

- (1) *How general is intermodal control adaptation?* More specifically, are control increases following conflict processing suited to improve performance in interference conditions different from the specific condition that triggered control adaptation. Prior studies exclusively observed adaptation effects between equivalent conflict or interference conditions within the same task (e.g., Hommel et al., 2004; Schmidt & Weissman, 2014) or between analogous conflict conditions of different task paradigms (e.g., Egner, Delano, & Hirsch, 2007; Freitas & Clark, 2014). If control adaptation indeed leads to a strengthening of attentional selectivity, this should also improve performance in different interference conditions which share the same or overlapping attentional requirements.
- (2) *How specific is intermodal control adaptation?* Generally, one can distinguish two basic sub-processes to exert top-down attentional control: the amplification of task-relevant information and the inhibition of task-irrelevant information. In this context, the question suggests itself as to whether

increased attentional selectivity following conflict processing consists of increased information amplification or increased information inhibition, or both simultaneously. So far, only few studies have addressed this important issue. Egner and Hirsch (2005), for instance, conducted an fMRI investigation in which they found evidence that conflict adaptation mainly (or even exclusively) is based on amplification of information selection (see also Notebaert & Verguts, 2008). On the other hand, however, behavioral studies showed inhibition of task-irrelevant information to be involved in interference resolution (Fanini, Nobre, & Chelazzi, 2006; Nobre, Rao, & Chelazzi, 2006). The present work sought to build upon this preliminary empirical basis.

In this context, we were specifically interested in the neurocognitive mechanisms to control cross- or intermodal sensory processing, i.e., when stimuli from different sensory modalities interfere or compete with each other. Important to note, functional characteristics of control mechanisms in intermodal sensory processing possibly (or even probably) significantly differ from analogous intramodal mechanisms, so that conclusions drawn in one area cannot be simply transferred to the other. Moreover, the extent and the specific characteristics of interference – which naturally determine the remediate control efforts – critically depend on the sensory modalities of the respective competing stimuli, too. This was nicely demonstrated, for instance, in a recent study on intermodal interference effects between visual and tactile stimuli (Mast, Frings, & Spence, 2014). This setting yielded strong interference from visual stimuli on tactile processing (in terms of incompatible response priming), whereas tactile stimuli on the other hand exerted no interference on visual processing. Such modality-dependent differences or asymmetries in the emergence of stimulus interference strongly suggest that control mechanisms of interference resolution likewise crucially depend on the modalities of the competing stimuli and, moreover, their specific roles as either task-relevant or task-irrelevant information. In the present study, we specifically investigated intermodal control adaptations during the processing of competitively presented visual and auditory stimuli which alternated in their roles as task-relevant and task-irrelevant information. The specific experimental design of the respective interference task allowed us to define Gratton-like sequential effects, which cannot be accounted for by priming explanations and, thus, most probably reflect proper control adaptation. With regard to the two above-mentioned questions, we expected conflict adaptation to consist of a strengthening of attentional selectivity and, therefore, to occur in interference situations different from the one in which the system has been adapted, too. Second, we expected to find evidence for both increased amplification of task-relevant information and increased inhibition of task-irrelevant information to be involved in conflict adaptation. These two hypotheses were tested in separate experiments.

2. Experiment 1: Oddball

2.1. Introduction

Experiment 1 was designed to investigate the generalizability or transferability of control adaptation effects. More specifically, we wanted to test whether adaptive control increases are specific to the original source of attentional competition or whether they improve the processing of other types of attentional competition in following trials of the same task, as well.

The question of whether or not conflict adaptation for one type of conflict also propagates on other types of conflict reminds of studies on conflict adaptation across different tasks. For instance,

Notebaert and Verguts (2008) demonstrated conflict adaptation (i.e., Gratton effects) to occur across different tasks, which, crucially, was bound to the fact that both tasks used the same kind of relevant information. In the same vein, many other studies failed to observe conflict adaptation when the investigated sequenced conflict conditions required different attentional foci (cf. Egner et al., 2007; Funes et al., 2010a; Funes et al., 2010b; Schmidt & De Houwer, 2011; Wendt, Kluwe, & Peters, 2006). This strongly suggests that across-task adaptation effects are ultimately based on, how Notebaert and Verguts (2008) call it, “locally” increased sensory selection rather than increased motor selection (i.e., the shielding of the/an required motor response against competing response tendencies), even though the applied tasks in their study included competition between motor responses (i.e., motor-based conflict) based on stimulus–response overlap (Egner et al., 2007; Kornblum, 1992; Melcher et al., 2013; for a recent exception in terms of transfer from adaptation to emotional interrupts to the processing of Simon interference, see Wirth, Pfister, & Kunde, 2015).

In the present study, we extended the approach of previous work on between-task transferability of control adaptation by adopting the reverse perspective: we investigated transferability of control adaptation across different kinds of competition of the same task, rather than transferability across different tasks including the same kind of competition. Moreover, we translated the concept of control adaptation to a multimodal setting in which competition occurred between stimuli of different sensory modalities rather than within the same sensory domain. In line with the notion of control adjustments acting “locally”, we expected that increasing attentional requirements in one trial facilitates performance in following different competition trials if they share the same attentional requirements.

In order to address this issue, we created a multimodal task-switching paradigm including two distinct types of attentional competition between visual and auditory information. First, during incongruent trials, simultaneously presented auditory and visual stimuli were mapped to different (i.e., opposite) motor responses, leading to a standard conflict or incongruity condition. Second, we included oddball trials during which the irrelevant stimulus modality was not associated to any response, while the according stimulus value occurred rarely compared to the prevalent response-related visual and auditory stimulus values. Over the past two decades, an extensive literature on the oddball effect has accumulated. In the respective studies, subjects are occasionally presented with infrequent task-irrelevant information, the oddball, which saliently deviates from a standard as defined by the otherwise equivalent prevalent stimuli (e.g., Berti & Schröger, 2001; Melcher & Gruber, 2006; Milham & Banich, 2005). Oddballs of this kind are robustly related to substantial impairments of task-relevant processing, evident in delayed responses to target stimuli. This behavioral interference effect is generally explained in terms of an attentional capture or interruption which requires subjects to increase or reinstate control efforts for task-relevant processing (Berti & Schröger, 2001; Downar, Crawley, Mikulis, & Davis, 2000; Escera, Alho, Winkler, & Näätänen, 1998; Parmentier, 2008). Beyond behavioral impairments, however, attentional capture by oddballs can be considered as part of a highly adaptive background monitoring mechanism which enables agents to recognize potentially important events, particularly threats, outside their current focus of attention. A comprehensive series of neuroimaging studies suggests that the bilateral temporo-parietal junction (TPJ) represents a major neural instance of this mechanism (Bledowski, Prvulovic, Goebel, Zanella, & Linden, 2004; Downar, Crawley, Mikulis, & Davis, 2001; Downar et al., 2000). The extent of the bottom-up orienting response to an oddball (indicated by the extent of the behavioral losses) can be taken as indicator for the cognitive

system's adaptive calibration and thereby to mirror fluctuations in control strength: relatively low orienting responses to oddballs indicate relatively high control levels for task-relevant processing, and inversely. Importantly, oddball effects occur independently of the response-mapping of the respective deviant stimulus feature, and in this sense have been shown for both incongruent/congruent stimuli (Gruber et al., 2009) and neutral stimuli (Melcher & Gruber, 2006; Milham, Banich, & Barad, 2003). Oddball interference has been investigated in comparison with interference by incongruent stimuli (representing proper cognitive or motor conflict), which has led to informative descriptions of their differential neural signatures (cf. Melcher & Gruber, 2006; Milham et al., 2003). At the same time and beyond obvious conceptual and neurofunctional differences, incongruity interference and oddball interference can be plausibly conceived to involve substantial procedural overlap as both comprise competition between task-relevant and task-irrelevant information for priority in cognitive processing (Melcher, Born, & Gruber, 2011; Milham et al., 2003). This assumed procedural overlap basically gives reason for the present investigation of control adaptation effects between conflict and oddball conditions. More specifically, Experiment 1 was designed to test whether interference by oddballs is reduced after the processing of incongruity conflict and, accordingly, whether conflict adaptation involves general control increases (in terms of increases of sensory selectivity) which enable to resolve other kinds of attentional competition, too.

2.2. Methods

2.2.1. Participants and apparatus

Eighteen right-handed participants (4 males; mean age: 23.78 ± 2.88 (SD)) participated after they had given written informed consent and received monetary compensation. All participants reported normal or corrected-to-normal vision and hearing, had no history of major psychiatric or neurological disorder and were naive concerning the hypotheses of the study. The experimental procedure was approved by the local ethics committee.

Participants performed in two different tasks – a color task and a tone task. The current task was indicated by target-inherent cuing (“x” or “+” in the background of the display; see Fig. 1). Visual stimuli – blue, yellow, and red¹ color patches – appeared on a 17" computer monitor whereas tones – C, C' (one octave above C), and F# (lying exactly in the middle of the other tones) in a piano timbre – were played via headphones. In the color task, participants responded with their left index finger to blue color patches and with their right index finger to yellow color patches. Red color patches never appeared as targets in the color task and were not mapped to any response. In the tone task, participants responded with their left index finger to the low tone (C) and with their right index finger to the high tone (C'). The remaining tone (F#) never appeared as target in the tone task and was not mapped to any response. Color-key and, importantly, tone-key mapping were not counterbalanced across participants to ensure a SMARC-compatible mapping for all participants in order to avoid interference effects based on the spatial mapping of tone heights (see Keller & Koch, 2006; Lidji, Kolinsky, Lochy, & Morais, 2007; Rusconi, Kwan, Giordano, Umiltà, & Butterworth, 2006).

2.2.2. Procedure

Trials started with a preparation period of 1000 ms (blank screen). Then, the target appeared for 600 ms and informed the

participants about the task at hand. The program waited for up to 1500 ms for this response and started the next trial afterwards. Errors or response omissions were not fed back to the participants to allow for a constant pacing of stimuli.

After a training part of 80 unanalyzed practice trials, participants performed three experimental blocks of 270, 272, and 270 trials, respectively (812 trials in total). Crucially, 20% of the trials featured an oddball on the irrelevant dimension, i.e., a red color patch in the tone task and the deviant tone (F#) in the color task. Participants were informed about this procedure but were instructed to ignore these irrelevant attributes of the target stimuli. A pre-defined order of trials structured the experiments in mini-runs of 4–7 consecutive trials of the same task. This sequence ensured that all possible combinations of current trial type (congruent, incongruent, oddball) and preceding trial type appeared equally often for each task, except that oddball trials did not appear in task-switch trials and were never followed directly by another oddball trial.

2.3. Results

2.3.1. Data treatment and analyses

After testing for basic oddball and congruency effects for both tasks, we focused the analyses on task-repetition trials to cover control processes that extended to oddball trials and can thus not be explained in terms of simple feature integration mechanisms. For RT analysis we excluded trials with wrong responses (4.93%) or response omissions (2.48%), and all trials following such errors. We then conducted two separate analyses. The main analysis targeted oddball trials that were analyzed as a function of task (tone vs. color) and preceding trial type (incongruent vs. congruent). Additionally, we conducted a validation analysis to probe for similar adaptation effects as are frequently reported in the literature (Gratton et al., 1992). To this end, we analyzed congruent and incongruent trials as a function of task (tone vs. color) and preceding trial type (incongruent vs. congruent vs. oddball). To avoid violations of sphericity, we used the multivariate approach to repeated-measures ANOVAs for all reported tests.

2.3.2. Basic oddball and congruency effects

As expected, RTs were higher in the incongruent and the oddball condition as compared with the congruent condition (Fig. 1). A 2×3 ANOVA with the factors task and congruency showed both, the main effect of task, $F(1,17) = 7.03$, $p = .017$, $\eta_p^2 = .29$, and the main effect of congruency to be significant, $F(2,16) = 30.34$, $p < .001$, $\eta_p^2 = .79$. The interaction of task and congruency also approached significance, $F(2,16) = 2.96$, $p = .081$, $\eta_p^2 = .27$, and was driven by a stronger oddball effect in the color task than in the tone task. Crucially contrast analyses revealed that both, the oddball effect (oddball vs. congruent) and the congruency effect (incongruent vs. congruent) were significant for both tasks (all p values $< .001$). Furthermore, these results were mirrored in the error data (see Supplementary Fig. 1).

2.3.3. Main analysis: Oddball adaptation

Descriptively, participants responded faster in oddball trials following an incongruent trial than in oddball trials after a congruent trial (see Fig. 2A). This pattern of results was qualified by the corresponding 2×2 ANOVA with the factors task and preceding congruency (congruent vs. incongruent). Most importantly, this analysis showed a significant main effect of preceding congruency, $F(1,17) = 35.88$, $p < .001$, $\eta_p^2 = .68$. This effect, however, differed between both tasks, $F(1,17) = 12.96$, $p = .002$, $\eta_p^2 = .43$, whereas the main effect of task did not approach significance ($F < 1$). A robust main effect of previous congruency also emerged when running separate ANOVAs for response repetitions, $F(1,17) = 17.31$,

¹ For interpretation of color in Fig. 1, the reader is referred to the web version of this article.

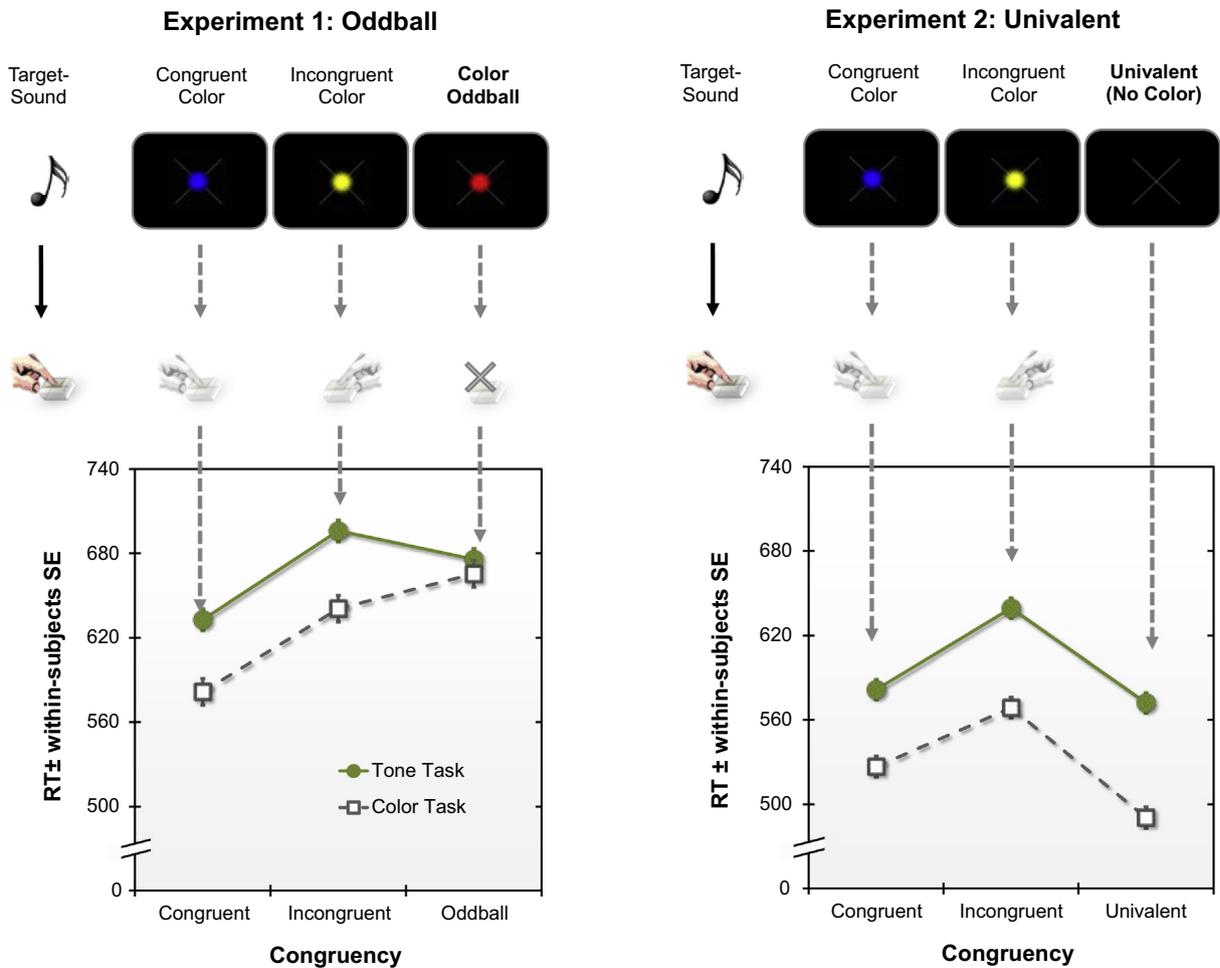


Fig. 1. Basic congruency effects in both experiments, each exemplified for the tone task and the corresponding condition in the color task. In Experiment 1, significant conflict effects were present for both, the incongruent and the oddball condition. Experiment 2 replicated the conflict effect for the incongruent condition but substituted the oddball condition for a univalent condition without additional stimulation, i.e., without conflict. In both experiments, participants were consistently faster in the color task than in the tone task. Error bars represent within-subject standard errors (Loftus & Masson, 1994) computed separately for each task. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

$p < .001$, $\eta_p^2 = .50$, and response switches, $F(1, 17) = 8.37$, $p = .010$, $\eta_p^2 = .33$. To ensure that adaptation effects were present in both tasks, we conducted separate contrast analysis which showed the adaptation effect to be significant for both, the tone task, $t(17) = 2.21$, $p = .041$, $d = 0.74$, and the color task, $t(17) = 5.59$, $p < .001$, $d = 1.86$. Moreover, the analysis of the corresponding error data confirmed that this effect did not result from different speed-accuracy trade-offs (see [Supplementary Fig. 2A](#)). As outlined above, the reported oddball adaptation effects cannot be explained by simple feature integration mechanisms. Still, feature integration is very likely to contribute to typical adaptation effects. To validate whether feature integration might also be at work in the present design, we conducted a follow-up analysis on the oddball effect, i.e., the difference score $RT_{\text{oddball}} - RT_{\text{congruent}}$ (see [Fig. 2B](#)). This measure captures the control mechanisms documented by the preceding analysis but might additionally be influenced by feature integration (see the Introduction/Discussion for the underlying logic). Not surprisingly, the same 2×2 ANOVA as above showed the main effect of preceding congruency, $F(1, 17) = 73.45$, $p < .001$, $\eta_p^2 = .81$, and the interaction of task and preceding congruency to be significant, $F(1, 17) = 22.20$, $p < .001$, $\eta_p^2 = .57$, whereas the main effect of task was not, $F(1, 17) = 1.77$, $p = .674$, $\eta_p^2 = .09$. More importantly, we then compared the effects ($RT_{\text{incongruent_in_N-1}} - RT_{\text{congruent_in_N-1}}$) observed with the pure oddball RT and the RT effect score ($RT_{\text{oddball}} - RT_{\text{congruent}}$) by means of a 2×2 ANOVA with

the factors task (tone vs. color) and measure (oddball RT vs. oddball effect). Crucially, the main effect of measure was significant, $F(1, 17) = 3.96$, $p = .063$, $\eta_p^2 = .19$, indicating stronger conflict adaptation for the oddball effect score than for the pure RT value. Additionally, adaptation was stronger for the color task than for the tone task, $F(1, 17) = 25.49$, $p < .001$, $\eta_p^2 = .60$. Even though the interaction of task and measure approached significance, $F(1, 17) = 3.96$, $p = .063$, $\eta_p^2 = .19$, contrast analyses revealed stronger adaptation effects for the oddball effect than for the oddball RT for both, the tone task, $t(17) = 2.67$, $p = .016$, $d = 0.89$, and the color task, $t(17) = 7.13$, $p < .001$, $d = 2.38$ (see [Supplementary Fig. 2B](#) for corresponding results from the error data).

Taken together, the analysis of the oddball trials showed reliable adaptation effects that can only be explained by cognitive control mechanisms. When also considering the oddball effect score ($RT_{\text{oddball}} - RT_{\text{congruent}}$) – a measure that can also be influenced by feature integration – we found even stronger adaptation effects, suggesting that cognitive control and more basic feature-based mechanisms operate in concert to produce typical conflict adaptation effects.

2.3.4. Control analysis: Congruency adaptation

Replicating previous findings, we found reduced congruency effects following conflict trials (incongruent and oddball trials) as compared with congruent trials without conflict ([Fig. 2C](#)). These

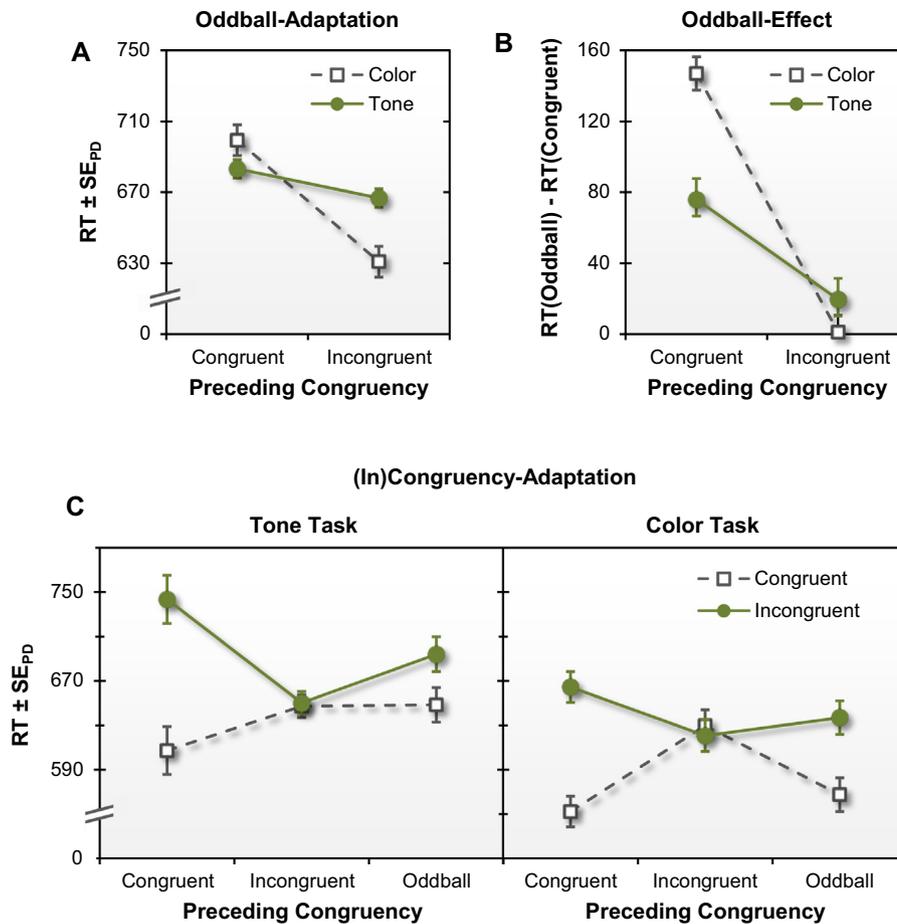


Fig. 2. (A) Adaptation effects in oddball trials, depicted separately for each task. Reactions in oddball trials were faster when they were preceded by a trial with response conflict (incongruent condition) as compared with preceding trials without response conflict (congruent condition). These results can only be explained in terms of higher-level cognitive control mechanisms that were triggered by the experienced response conflict. Error bars represent standard errors of paired differences (SE_{pd} ; Pfister & Janczyk, 2013), calculated separately for each task. (B) The conflict adaptation in oddball trials was more pronounced when considering not the raw RT in oddball trials (see A) but the oddball effect score, i.e., $(RT_{\text{oddball}} - RT_{\text{congruent}})$. This result suggests that more basic feature-based mechanisms might support pure cognitive control. Error bars represent standard errors of paired differences, calculated separately for each task. (C) Control analysis showing typical Gratton-like sequential effects in terms of a reduced congruency effect after incongruent and oddball trials as compared to congruent trials. Error bars represent standard errors of paired differences, calculated separately for each comparison of incongruent and congruent trials.

adaptation effects were confirmed by a $2 \times 3 \times 2$ ANOVA with the factors task, preceding congruency, and current congruency. More precisely, the adaptation effects were mirrored in a significant interaction of preceding congruency and current congruency, $F(2, 16) = 36.54$, $p < .001$, $\eta_p^2 = .82$.

Furthermore, participants were faster in the color task than in the tone task, $F(1, 17) = 18.04$, $p < .001$, $\eta_p^2 = .51$, and generally faster in the congruent condition than in the incongruent condition, $F(1, 17) = 39.25$, $p < .001$, $\eta_p^2 = .70$. Additionally, the interaction of task and preceding congruency was significant, $F(2, 16) = 5.56$, $p = .015$, $\eta_p^2 = .41$, whereas the remaining effects were not ($F(2, 16) = 1.82$, $p = .194$, $\eta_p^2 = .19$, for the three-way interaction, $F < 1$ for the main effect of preceding congruency and the interaction of task and current congruency). These findings were supported by the corresponding error data (see Supplementary Fig. 2C).

2.4. Discussion

Experiment 1 demonstrated trial-to-trial conflict adaptation effects for attention-capturing low-frequency events, “oddballs”, which yielded substantially reduced interference when presented after incongruent trials. This finding has at least two important

theoretical implications. First, conflict adaptation effects (“Gratton-effects”) can be observed even if a contribution of passive priming effects can be definitely excluded. For a concise technical explanation: unlike standard conflict adaptation effects between analogue (in-) congruency conditions, a decrease of oddball interference after incongruent trials cannot be accounted for by bottom-up priming effects like feature integration or repetition priming, because stimulus repetitions – i.e., (partial) repetitions of stimulus features from the previous trial to the current trial – are perfectly counterbalanced across compared sequential conditions. Hence, the present experiment further corroborates the theoretical assumption that the processing of cognitive conflict prompts (pro-)active adjustments in top-down control which allow for rapid and flexible adaptations to changing situational requirements.

It should be noted that conflict adaptation effects in absence of bottom-up priming have been already demonstrated in prior studies. These studies typically used multiple (>2) feature values of the competing stimulus dimensions in order to create congruency transitions which are independent of stimulus repetitions. The studies’ results basically suggest that bottom-up priming and top-down control adaption could contribute independently to conflict adaptation (cf. Notebaert et al., 2006; Ullsperger et al., 2005). However, unlike the present findings, these results do not allow for

further conclusions on the functional characteristics of conflict-triggered control increases. This regards the second implication of Experiment 1: improved performance on oddball trials following conflict stimuli suggests that conflict adaptation (at least in part) relies on a strengthening of sensory selectivity for task-relevant information. This reasoning is based on the fact that incongruent and oddball trials – while yielding conceptually and operationally distinct kinds of interference and being distinguishable in terms of their neural signature (e.g., Melcher & Gruber, 2006) – in the present study used identical kinds (modalities) of task-relevant and task-irrelevant information and, hence, were equivalent with respect to their attentional requirements (i.e. used the same combination of task-relevant and task-irrelevant interfering information). Accordingly, it appears that control adaptation is a rather *general process* which can be principally transferred to any interference condition. At the same time, however, it can be described as *local process*, because it only improves (attentional) processes relevant to the present condition (cf. Funes et al., 2010b; Kiesel, Kunde, & Hoffmann, 2006; Notebaert & Verguts, 2008).

Of note in this context, the present task design does not include a genuine oddball control condition, i.e. baseline neutral trials which occur equally often as the (in-)congruency conditions (cf. Melcher & Gruber, 2006). Therefore, strictly spoken, the present experiment alone cannot definitely rule out that the adaptation effect defined for oddball stimuli can be likewise observed for prevalent neutral trials, and thus in absence of sensory competition. However, a substantial number of previous studies already investigated post-conflict sequential effects in prevalent neutral trials in various experimental settings, and apparently none of them yielded a Gratton-like speedup in this trial type (e.g. Bugg, 2008; Davelaar & Stevens, 2009; Lamers & Roelofs, 2011; Wendt, Luna-Rodriguez, & Jacobson, 2014)), for which, moreover, there would be no straightforward theoretical explanation in terms of either control adaptation or sensory priming: first, prevalent neutral trials represent a “low-level” baseline condition which should be relatively robust against fluctuations in control strength, and, second, compared sequential conditions (CONG-NEUTR vs. INCONG-NEUTR) are perfectly counterbalanced for stimulus and response repetitions. Taken together, there is strong evidence that the adaptation effect defined for oddball stimuli is ultimately bound to the rareness of occurrence of the neutral stimulus feature and, thus, is based on strengthened attentional selectivity.

Generally, in conflict processing two basic control mechanisms of top-down selection can be distinguished: (a) an attentional or stimulus-based mechanism of sensory selection and (b) a motor-related mechanism of response selection (cf. Egner et al., 2007). The attentional mechanism can be described as adaptive weighting of cortical representations in sensory pathways with an amplification of relevant stimuli or stimulus features relative to task-irrelevant ones. Motor-related mechanism in conflict processing, on the other hand, weight or select between competing motor tendencies (cf. Nieuwenhuis & Yeung, 2005). A third mechanism that might explain the observed results is a strengthening of the relevant S–R mapping rules. Stimulus processing according to abstract S–R rules, however, is more likely to be observed in settings with numerous potential target stimuli than in settings with only a limited range of potentially relevant targets (Kiesel, Kunde, Pohl, & Hoffmann, 2006; Pohl, Kiesel, Kunde, & Hoffmann, 2010). With the present small target set, we therefore assume influences of S–R rules to play only a minor role, even though this mechanism might still contribute to the present effects.

The facilitation of performance during oddballs following stimulus-incongruent trials in the present paradigm thus emphasizes a central role of attentional control (i.e. locally increased sensory selection) in conflict adaptation, while motor-related control may

play only a minor role. This conclusion is based on the fact that oddball stimuli of the present paradigm are response-ineligible and therefore presumably involve pure attentional competition without imposing increased demands on motor selection (cf. Melcher & Gruber, 2006). The notion that control adaptation mainly concerns attentional (rather than motor) selection is additionally supported by an investigation of Egner et al. (2007), in which they adopted a modified Stroop paradigm which included two independent sources of conflict: (a) stimulus-based (or Stroop) conflict stemming from incongruent irrelevant stimulus features and (b) response-based (or Simon) conflict stemming from incompatible response tendencies related to stimulus location. Results showed that trials including response-based conflict were not improved after the processing of stimulus-based conflict, which suggests that conflict-triggered control increases after stimulus-based conflict mainly relies on increased sensory attentional (rather than motor) selection. In Experiment 2, we sought to further elucidate the functional characteristics of the assumed increased attentional selectivity in conflict adaptation.

3. Experiment 2: Univalent

3.1. Introduction

In Experiment 2, we addressed the basic question as to whether strengthened selection following conflict processing in the current multimodal setup primarily involves amplification of relevant stimuli or inhibition of irrelevant distracting stimuli (or both to a similar degree). To this end, we adopted a modified version of the audio-visual interference task of Experiment 1. The experimental design was created to define sequential effects of stimulus-incongruent stimuli on trials of a univalent condition (which, in this sense, replaced the former oddball condition). Trials of the univalent condition consisted either of an auditory stimulus in absence of visual distractors or, inversely, of a visual stimulus in absence of auditory distractors.

In contrast to the oddball trials of Experiment 1, the univalent trials could occur in both, task switch and task repetition trials which allowed us to define behavioral measures of amplification and of inhibition, each separately for the two stimulation modalities. Importantly, the complementary processes of inhibition and amplification of visual and auditory information are arguably confounded in the processing of bivalent (congruent or incongruent) stimuli of the same task. More specifically, conflict trials in the visual task (including distracting incongruent auditory information) may be resolved either by the amplification of visual processing and/or by the inhibition of auditory processing. Accordingly, conflict adaptation to incongruent trials of the visual task should either facilitate the processing of subsequent univalent trials of the color task and/or impair the processing of subsequent univalent trials of the auditory task, providing behavioral measures of visual amplification and auditory inhibition, respectively. The inverse logic can be applied to conflict trials of the auditory task, which should either facilitate performance of subsequent univalent auditory trials and/or impair performance on subsequent univalent visual trials, providing behavioral measures of auditory amplification and visual inhibition, respectively.

Hence, in a nutshell, the outlined study design allowed directly contrasting the roles of amplificatory selection (amplification of relevant information) and inhibitory selection (inhibition of irrelevant information) in conflict processing against each other, separately for visual and auditory stimuli. Thereby, we expected to find evidence for an important contribution of inhibition of irrelevant information to conflict resolution (i.e., conflict-triggered control increases) which is similar to or even greater than the

contribution of target amplification, irrespective of the sensory modality.

3.2. Method

3.2.1. Participants and apparatus

Eighteen new right-handed participants (mean age: 25.18 years (SD = 3.76), 5 males, 1 left-handed) were recruited and fulfilled the same criteria as in Experiment 1. The general method was similar to Experiment 1 with the following modifications.

3.2.2. Procedure

Most importantly, we substituted the oddball condition by a univalent condition, i.e., a condition where only the relevant target dimension (tone or color) was presented together with the task cue. Univalent trials were equally frequent as congruent and incongruent trials (one third each) and appeared in both, task switch and task repetition trials. As in Experiment 1, a pre-defined sequence ensured that univalent trials never occurred directly after each other. Following a training block of 84 trials, participants completed three experimental blocks of 200, 194, and 200 trials, respectively (594 trials in total).

3.3. Results

3.3.1. Data treatment and analyses

Trials with wrong responses (4.61%) or response omissions (1.56%), and trials following such errors were excluded from RT analyses. After testing for basic univalent and congruency effects for both tasks, we focused the analyses on univalent trials. These trials were analyzed as a function of task sequence (task repetition vs. task switch), task (tone vs. color), and preceding congruency (congruent vs. incongruent). As in Experiment 1, we also analyzed congruent and incongruent trials as a function of task (tone vs. color) and preceding trial type (incongruent vs. congruent vs. univalent). To avoid violations of sphericity, we again used multivariate repeated-measures ANOVAs for all reported tests.

3.3.2. Basic univalent and congruency effects

As expected, RTs were higher in the incongruent condition than in the congruent and the univalent condition (Fig. 1). A 2×3 ANOVA with the factors task and congruency showed both, the main effect of task, $F(1, 17) = 34.68$, $p < .001$, $\eta_p^2 = .67$, and the main effect of congruency to be significant, $F(2, 16) = 26.20$, $p < .001$, $\eta_p^2 = .77$. A significant interaction of task and congruency, $F(2, 16) = 6.43$, $p = .009$, $\eta_p^2 = .45$, was driven by a stronger congruency effect in the tone task than in the color task. Crucially, contrast analyses revealed that the congruency effect was reliable in both tasks (both $ps < .001$). Interestingly, univalent trials were even faster than congruent trials for the color task, $t(17) = 3.53$, $p = .003$, $d = 1.18$, but not for the tone task, $t(17) = 1.17$, $p = .256$, $d = 0.39$. These results suggest that, in contrast to the oddball condition of Experiment 1, the univalent condition did not involve any conflict (see Supplementary Fig. 1 for converging evidence from the error data).

3.3.3. Main analysis: Univalent switch and repeat trials

Fig. 3A shows the results for univalent switch trials. As hypothesized, reactions were faster in univalent trials following a congruent trial of the previous task as compared with an incongruent trial in the previous task. Descriptively, these results suggest a persisting inhibition of the conflicting stimulus features. In contrast, adaptation effects in univalent task repetition trials did not show pronounced adaptation effects (Fig. 3B). A $2 \times 2 \times 2$ ANOVA with the factors of task sequence, task, and preceding congruency confirmed this interpretation and showed the crucial interaction of

task sequence and preceding congruency to be significant, $F(1, 17) = 7.85$, $p = .012$, $\eta_p^2 = .32$. Contrast analyses confirmed that adaptation effects in task switch trials were significant for the tone task, $t(17) = 2.40$, $p = .028$, $d = 0.80$, and marginally significant for the color task, $t(17) = 1.94$, $p = .069$, $d = 0.65$. In task repetition trials, adaptation effects were non-significantly reversed in both, the tone task, $t(17) = -0.21$, $p = .837$, $d = -0.07$, and the color task, $t(17) = -1.45$, $p = .163$, $d = -0.49$.

Furthermore, reactions were faster in task repetition trials than in task switch trials, $F(1, 17) = 63.14$, $p < .001$, $\eta_p^2 = .79$, and reactions in the color task were faster than in the tone task, $F(1, 17) = 20.30$, $p < .001$, $\eta_p^2 = .54$. No other effect was significant; $F(1, 17) = 2.44$, $p = .137$, $\eta_p^2 = .13$, for the main effect of preceding congruency, $F < 1$ for all remaining interactions. This pattern of results was also present in the error data (see Supplementary Fig. 3A and B).

To ensure that the critical interaction of task sequence and preceding congruency was not driven by item-specific priming processes, we re-ran the analysis of univalent switch and repeat trials while removing any color or tone repetitions from the data. The interaction of task sequence and preceding congruency remained significant in this analysis, $F(1, 17) = 8.56$, $p = .009$, $\eta_p^2 = .34$, suggesting that the observed effects are not due to item-specific priming. We thank an anonymous reviewer for suggesting this analysis.

3.3.4. Control analysis: Congruency adaptation

As in Experiment 1, we found reduced congruency effects following incongruent trials as compared with trials without conflict (congruent and univalent; Fig. 2C). These adaptation effects were confirmed by a $2 \times 3 \times 2$ ANOVA with the factors task, preceding congruency, and current congruency. More precisely, the descriptive adaptation effects were mirrored in a significant interaction of preceding congruency and current congruency, $F(2, 16) = 12.71$, $p < .001$, $\eta_p^2 = .61$. Furthermore, all three main effects were significant (all $ps < .001$) whereas the interaction of task and preceding congruency, $F(2, 16) = 1.45$, $p = .263$, $\eta_p^2 = .15$, and the interaction of task and congruency were not, $F(1, 17) = 3.12$, $p = .091$, $\eta_p^2 = .16$.

A significant three-way interaction, $F(2, 16) = 5.79$, $p = .013$, $\eta_p^2 = .42$, was driven by smaller congruency effects ($RT_{\text{incongruent}} - RT_{\text{congruent}}$) after congruent trials in the color task than in the tone task, $t(17) = 3.49$, $p = .003$, $d = 1.16$. To the contrary, equal congruency effects resulted in both tasks after incongruent, $t(17) = -0.99$, $p = .335$, $d = -0.33$, and univalent trials, $t(17) = 0.27$, $p = .792$, $d = 0.09$. Furthermore, error data support the crucial interaction of preceding congruency and current congruency, whereas the three-way interaction was not significant in this analysis (see Supplementary Fig. 3C).

3.4. Discussion

In Experiment 2, we sought to discern the contributions of distractor inhibition and target amplification to conflict resolution, or more exactly to conflict-triggered increases in attentional control. Basically, the data analyses revealed a clear indication of distractor inhibition to be an important part of attentional conflict adaptation. More specifically, the modality in which the irrelevant distractor was presented in a previous conflict trial yielded substantial costs when it served as modality of the relevant information in the present trial (even when the specific feature value of the modality changed). We explain this finding in terms of persisting inhibition, i.e., to reflect the maintenance of inhibitory neural modulations of sensory processing. An alternative explanation that does not imply active inhibition of task-relevant information, however, might be derived from experiments that showed evidence for post-conflict slowing (Verguts, Notebaert, Wühr, & Kunde, 2011).

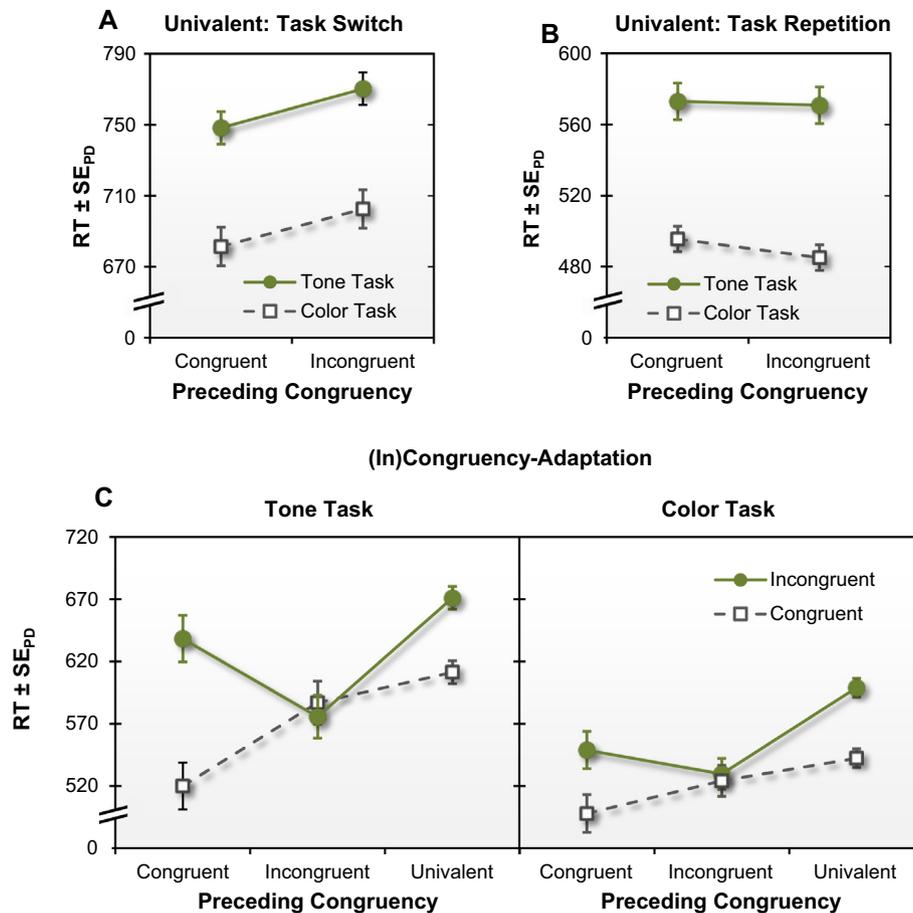


Fig. 3. (A) Adaptation effects in univalent switch trials, depicted separately for each task. Reactions were faster when a univalent trial was preceded by a congruent trial of the previous task as compared with an incongruent trial. This pattern of results suggests that the conflicting stimulus features were actively inhibited. Error bars represent standard errors of paired differences (SE_{PD} ; Pfister and Janczyk, 2013), calculated separately for each task. (B) In contrast, adaptation effects were non-significantly reversed in univalent task repetition trials. Error bars represent standard errors of paired differences, calculated separately for each task. (C) Control analysis showing typical Gratton-like sequential effects in terms of a reduced congruency effect after incongruent trials. Error bars represent standard errors of paired differences, calculated separately for each comparison of incongruent and congruent trials.

Performance costs in univalent switch trials following incongruent rather than congruent trials might therefore merely reflect post-conflict slowing rather than sustained inhibition of the incongruent information of the preceding trial. Even though such effects cannot be ruled out entirely on the basis of the current design, post-conflict slowing typically only becomes evident in tasks that do not share any relevant or irrelevant information with the conflict-inducing event and are otherwise overshadowed by conflict-adaptation processes (for a discussion, see Verguts et al., 2011). Converging evidence for a central role of active inhibition of conflicting information for following performance further comes from findings on aftereffects of conflict trials on an intermittent visual search task (Wendt, Luna-Rodriguez, & Jacobsen, 2012). Search times in this study were analysed as a function of whether the search target was associated with relevant features or irrelevant features of a preceding flanker task. The resulting benefit for search targets that were associated with relevant features as compared to irrelevant features likewise can be explained by persisting distractor inhibition as we observed for univalent switch trials in the present design.

As a second result, Experiment 2 did not reveal any indication of target amplification as part of attentional conflict adaptation. Taken together, the outlined pattern of findings suggest that the reduced distraction by oddball stimuli after incongruent trials in Experiment 1 is mainly or even entirely based on inhibition of

the sensory modality of the oddball stimulus during conflict processing. Several previous studies likewise emphasize a major role of distractor inhibition in information selection which – at least under certain conditions – may have stronger consequences for subsequent information processing than the amplificatory selection of relevant information (cf. Fanini et al., 2006; Nobre et al., 2006). Nobre et al. (2006), for instance, investigated behavioral and electrophysiological correlates of feature-based information selection within the visual domain. To this end, they adopted a task-switching priming paradigm in which subjects responded either to the color or the internal motion direction of presented objects (grid patterns) in a block-wise manner. Similar to the present experiment's rational, inhibitive processing of irrelevant information was indexed by performance decrements related to the detection of stimulus features which had been ignored in the previous (conflict) trial. Moreover, the electrophysiological signature of this sequential effect additionally substantiated that the observed performance impairments are related to modulations of early stages of sensory processing (rather than response selection stages). Fanini et al. (2006) adopted a feature discrimination task including three-dimensional visual stimuli which varied in color, spatial orientation and motion direction. Similar to the present work, the authors could demonstrate effects of active stimulus inhibition following conflict trials. Importantly, the corresponding negative priming effects occurred both for specific feature values

and whole feature dimensions, suggesting that conflict triggered inhibition may work at different levels of sensory processing, simultaneously.

4. General discussion

The aim of the present study was to elucidate the functional characteristics of attentional control adaptation in interference processing. For this purpose, we investigated sequential effects in an audio-visual interference task that was explicitly designed to exclude explanations in terms of sensory priming. The observed sequential effects thus most probably reflect proper increases in cognitive control. Thereby, the present experiments feature prominent differences to previous studies investigating control adaptation in interference processing. First, prior studies mostly used a purely visual stimulation. By contrast, the present experiments adopted an inter-/multimodal interference paradigm with an audio-visual stimulation which arguably has a high external validity, because attentional competition outside the laboratory mostly concerns different sensory modalities simultaneously. Moreover, the use of a multimodal stimulation bears the important advantage that competing stimuli can be more effectively separated with respect to their neural representation (i.e. activations in sensory cortices), so that in functional neuroimaging studies attentional modulations of single stimuli can be related to brain activations in a straightforward manner (cf. Egner & Hirsch, 2005). Important to emphasize in this context, the traditional notion of a strictly modular organization of the human neocortex can be no longer sustained, and in the last years many studies demonstrated cross-modal influences on sensory-specific brain regions, including primary sensory cortices (see Driver & Noesselt, 2008; Ghazanfar & Schroeder, 2006; Hirst, Javadi Khomami, Gharat, & Zangenehpour, 2012). Therefore, to substantiate the ascription of brain activations to single stimuli (i.e. stimulus modalities), independent “localizer scans” should be included in order to determine brain responses when subjects passively perceive the stimuli in the context of the respective experiment (cf. Berger & Ehrsson, 2014). Second, prior studies investigating control adaptation in interference paradigms mostly (or even exclusively) defined sequential effects between identical or equivalent (in-)congruency conditions. These paradigms require to include an increased stimulus set (with multiple stimulus-response mappings) in order to rule out sensory priming as an explanation for resulting sequential effects (e.g., Egner & Hirsch, 2005; Kim & Cho, 2014; Nieuwenhuis & Yeung, 2005; Schmidt & Weissman, 2014; Weissman et al., 2014). Moreover, the investigation of sequential effects between identical task conditions constricts the interpretability of observed control adaptation effects because it remains unclear as to how generally the alleged underlying control mechanisms operate, i.e., whether they are restricted to the processing of incongruency conditions. Basically, if control adaptation indeed consists in a general increase of attentional selectivity, control adaptation following a specific interference condition should improve performance in other conditions of attentional competition, too. Based on the latter rationale, in the present work we investigated the influence of preceding incongruency interference (i.e., “response conflict”) on the capability to overcome attentional distraction by oddball stimuli, which indeed appeared to be improved. Other studies observed a complete elimination of conflict adaptation effects when investigated sequences included different kinds of conflict, which basically contradicts the notion of transferable control increases (cf. Egner et al., 2007; Freitas & Clark, 2014; Funes et al., 2010a, 2010b; Wendt et al., 2006). However, other than in the present work, different kinds of interference in these studies referred to different task paradigms including differential task rules and

stimuli. Therefore, from the perspective of the present study, the absence of conflict adaptation effects in these studies is not surprising, because investigated conflict sequences required different attentional foci (i.e. sensory orientations) as defined by the kinds or modalities of the relevant to-be-selected information and the irrelevant to-be-ignored information, so that increasing attentional selectivity in the first instance (i.e., trial) could not improve performance in the second. And even though this reasoning is likely to apply to all types of cognitive conflict, recent evidence suggests that adaptations to affective task disturbances might involve more general mechanisms (Wirth et al., 2015).

Taken together, the present findings suggest that control adaptation occurs between different kinds of cognitive conflict if, and only if, they require the same attentional focus, or at least overlapping attentional foci (cf. Freitas & Clark, 2014). This conclusion raises the important question about the specific attentional mechanisms on which conflict adaptation in such a multimodal setting operates. Does it operate on amplification of task-relevant information or inhibition of task-irrelevant information, or on both simultaneously? Our findings suggest that conflict adaptation mainly works on inhibition of task-irrelevant information and yielded no indication for an important contribution of amplificatory processes. This conclusion is seemingly opposed to the findings of Egner and Hirsch (2005) who investigated sequential effects in the fMRI data of a Stroop-like paradigm. In this task, subjects were presented with name labels superimposed on face pictures of prominent persons, while they had to identify either the name or the face picture as either an actor or political figure. The authors found conflict adaptation in the visual cortex in terms of increased (i.e. “amplified”) activation in the fusiform face area (FFA) after conflict trials in which faces served as targets. Inversely, however, there was no decreased (i.e. “inhibited”) FFA activation after conflict trials in which faces served as distractors. The authors concluded that target-feature amplification is the primary mechanism for conflict resolution (for a similar conclusion, see Notebaert & Verguts, 2008). However, from a neuroscientific point of view, it appears unlikely that inhibitive processes do not contribute to interference resolution at all. Attentional functioning in general is considered to operate in a push-pull fashion comprising both suppressing “irrelevant” brain response in sensory cortices and enhancing the “relevant” ones (cf. Mangun & Hillyard, 1991; Smith, Singh, & Greenlee, 2000; Treue, 2001). Thereby the relative proportion of amplificatory and inhibitive processing arguably varies between different situations. The latter assertion can reconcile the putative discrepancy between our findings and the findings of Egner and Hirsch which were found under quite different experimental conditions. Most importantly, whereas we used a multimodal (audio-visual) interference task, Egner and Hirsch adopted a unimodal (purely visual) paradigm. Accordingly, one may speculate that sensory selection within one modality favors target amplification whereas sensory selection between different modalities favors distractor inhibition. This speculation can be substantiated by a recent study of Porcu and colleagues (Porcu, Keitel, & Müller, 2014) who have investigated passive sensory processing of stimuli from different modalities and found reduced early sensory competition (in terms of reciprocal inhibition) when concurring stimuli came from different modalities compared to concurring stimuli presented in the same modality. Reduced or absent reciprocal suppression when passively perceiving competing stimuli presumably allows for a stronger active suppressive regulation during goal-directed modulations of sensation, and, inversely, a strong reciprocal suppression when passively perceiving stimuli can be plausibly assumed to facilitate amplificatory processes during active attentional selection. Taken together, the outlined findings suggest that the prominent question about which attentional sub-processes underlie conflict resolution or conflict

adaptation cannot be generally answered. Rather the quantitative contributions of amplificatory and inhibitory selection appear to crucially depend on the kind and sensory properties of the competing stimuli and particularly on how they compete during passive, unbiased perception. In this context, it is an important issue for future studies to investigate the neural implementation (i.e. brain activations and connectivities) of inhibitory and amplificatory processes in control adaptation. Generally, brain imaging studies investigating selective attentional processing traditionally focused on the demonstration of activation increases in sensory regions specialized for the selected (i.e. relevant) stimulus. Thereby, studies could demonstrate increased activation in sensory regions specialized for selected spatial locations (Luck, Chelazzi, Hillyard, & Desimone, 1997), object features (Corbetta, Miezin, Shulman, & Petersen, 1991) and also whole sensory modalities (e.g. Langner et al., 2011), which partly even occurred when subjects only anticipated stimuli in absence of a proper stimulation (Chawla, Rees, & Friston, 1999). However, the mentioned literature is mostly neutral with respect to the fate of the ignored (irrelevant) stimuli, i.e. it remains unclear whether neural activation in regions processing the irrelevant stimulus was reduced (inhibited) or unaffected during selection. Moreover, activation variations in sensory regions under identical or equivalent sensory conditions may be considered only the expression of attentional selection and does not inform on the underlying neural control mechanisms. Basically, task-related modulations in sensory regions may be considered the result of top-down influences emanating from prefronto-parietal regions. It is an important issue for future neuroimaging studies to further elucidate this network function by identifying and quantifying the inter-regional relationships of the specific brain areas involved, i.e. the functional connectivity between sensory regions on the one hand and executive control regions on the other. For this purpose, the present task paradigm may represent a well-suited and useful tool.

5. Conclusions

With the present behavioral study, we present an intermodal selective attention task in which subjects alternately focus on visual or auditory stimuli. Thereby, the currently irrelevant (i.e., unattended) modality may interfere with the relevant one leading to increased attentional competition. The specific task design allowed us to investigate trial-to-trial sequential effects of competition which, crucially, cannot be explained by sensory priming and therefore most probably reflect proper control adaptation. In two experiments we further elucidated the underlying neurocognitive mechanism. First, we could substantiate the notion that control adaptation is based – at least in part – on local adjustments in attentional selection, i.e., increased selective weighting of the sensory input. Accordingly, adaptation to conflict trials could improve performance in different conditions of competition which shared the same attentional requirements. Second, our findings indicated a strong contribution of distractor inhibition but not of target amplification to attentional control adaptation. Yet, it is important to note that all relevant findings occurred analogously in the visual task (when competition emanated from irrelevant auditory stimuli) and in the auditory task (when competition emanated from irrelevant visual stimuli). This indicates that the derived functional characteristics of control adaptation, despite exhibiting some discrepancy with prior plausible findings, arguably cover a broad scope. The study provides a promising operational basis for subsequent neuroimaging investigations to define brain activations and connectivities underlying the adaptive control of attentional selection.

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Appendix A. Supplementary materials

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.bandc.2015.03.003>.

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