Moving towards dynamics

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Moving towards dynamics: Emotional modulation of cognitive and emotional control

Artyom Zinchenko[a,*], Sonja A. Kotz[b,c], Erich Schröger[d], Philipp Kanske[e,f]

[a] Department Psychologie, Ludwig-Maximilians-Universität München, Munich, Germany
[b] Max Planck Institute for Human Cognitive and Brain Sciences, Department of Neuropsychology, Leipzig, Germany
[c] Faculty of Psychology and Neuroscience, Department of Neuropsychology and Psychopharmacology, Maastricht University, the Netherlands
[d] Institute of Psychology, University of Leipzig, Germany
[e] Max Planck Institute for Human Cognitive and Brain Sciences, Research Group Social Stress and Family Health, Leipzig, Germany
[f] Clinical Psychology and Behavioral Neuroscience, Faculty of Psychology, Technische Universität Dresden, Dresden, Germany

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ABSTRACT

Cognitive control is influenced by affective states and the emotional quality of the stimulus it operates on. In the present review, we address how emotional valence influences control processes, distinguish between different types of conflicts (cognitive, emotional), examine physiological correlates of cognition - emotion interactions, and discuss recent work on this interaction in multisensory contexts. We show converging evidence that positive and negative emotions differentially affect cognitive and emotional conflict processing, when the emotional stimulus dimension is or is not task-relevant. These effects are found particularly early in dynamic, multisensory stimuli as the stimulus dimensions can correctly or incorrectly predict one another, and lead to very rapid effects of emotion on cognitive control. We suggest that future research on emotion-cognition interactions should "move towards dynamics" and develop multisensory testing environments that approach real-world complexity.

1. Introduction

Goal-directed behavior requires successful resolution of conflicts by means of cognitive control. When driving, studying for an exam or multitasking, cognitive control enables focusing on task relevant aspects while ignoring task-irrelevant ones. It also supports task-performance and decision-making when there is a discrepancy between some expectations about the world and expectation-incongruent new experiences. In other words, cognitive conflict arises between competing and opposing information sources that result in conflicting response tendencies. In some cases, the source of conflict may be emotional, that is, conflict is created between stimuli of different emotional valence (e.g., the presence of a neutral face and an angry voice). For instance, successful social interaction may require one to identify what emotion an interaction partner is actually experiencing when expressing mixed emotions, such as a positive facial expression, but an anger-trembling voice (Chiew and Braver, 2011). Importantly, both cognitive and emotional control mechanisms are vital components of goal-directed and socially adaptive behavior.

Previous studies have mostly concentrated on cognitive conflict processing, measured with tasks such as the Stroop, Flanker, and Simon tasks (Eriksen and Eriksen, 1974; Simon and Rudell, 1967; Stroop, 1935). For instance, in a classical Stroop task participants are asked to report the font color of a word while ignoring its semantic meaning that represents a color (e.g., GREEN, RED) and can either be congruent (e.g., RED written in red color) or incongruent with the semantic meaning (e.g., RED written in green color). In a modified version of this task, the face-Stroop task, participants are asked to identify the gender of a presented [picture of a] face and ignore a task irrelevant word written on top of the face that can be congruent with the gender of the face (e.g., the word MALE written on a male face) or incongruent with the gender of the face (e.g., the word FEMALE written on a male face). Another popular task is the flanker task. Participants are presented with a central target (e.g., a letter, an arrow) that is flanked by two task-irrelevant distractors (presented either above/below or to the right/left of the target item). The flanking items are congruent or incongruent with the target in some task-relevant feature (e.g., identity of the letter, left-right orientation of an arrow). It has been shown that participants take longer and make more errors when faced with incongruent ([face-] Stroop, flanker) relative to congruent trials, which is indicative of cognitive control. Shortening of reaction times and reduction in errors in incongruent trials would then be indicative of more efficient control.

* Corresponding author at: Max Planck Institute for Human Cognitive and Brain Sciences, Department of Neuropsychology, Leipzig, Germany.
E-mail address: artyom.zinchenko@psy.lmu.de (A. Zinchenko).

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Cognitive control and its underlying neural mechanisms as well as various factors that may affect it, such as affective information, have been studied thoroughly in the past few decades (for an overview, see van Steenbergen, 2015). The goal of the current review is to gather evidence on how emotion affects cognitive conflict processing, and to pinpoint aspects of emotion-cognitive control interactions that are less clear and require further work. At the same time the review aims at providing possible directions for future research. In the following, we first review previous work on how emotion influences cognitive conflict processing. We will examine multiple cognitive and emotional control situations, defined by the task-relevance or -irrelevance of the emotional stimulus dimension, and review the associated physiological correlates. We will also examine whether emotions influence two types of control situations in a valence-specific manner by contrasting studies that used negative and positive emotions. Finally, we will discuss the role of emotions in cognitive and emotional control with a particular focus on how it unfolds in dynamic, multisensory stimulation, and will pinpoint some of the challenges and questions for future research.

2. Emotion and cognitive control

Processing of emotion information plays a vital role in cognitive function, signaling either upcoming danger or potential rewards. Thus, emotions can attract attention (Vuilleumier, 2005) and improve learning and memory processes (Seli et al., 2016; Tyng et al., 2017; Zinchenko et al., 2019b). It has been also proposed that emotion and cognitive control share processing resources and, consequently, can modulate each other (Pessoa, 2009). However, the direction of such modulation is not entirely clear, as it has been shown that task-irrelevant emotional stimulus dimensions can either hinder performance (i.e., increase the RT difference between congruent and incongruent stimuli) or facilitate conflict processing (i.e., reduce this difference). For an overview of different experimental approaches to this question see Table 1. The listed studies and the characteristics that they differ on will be reviewed in dedicated sections below.

Reduced cognitive control performance under negative emotions has been observed in a number of experimental settings (e.g., Hart et al., 2010; Melcher et al., 2011; Padmala et al., 2011; Sommer et al., 2008; Raschle et al., 2017). For instance, Hart et al. (2010) asked participants to indicate the number of items presented in congruent (i.e. the digit 4 in an array of 4) or incongruent (i.e. the digit 4 in an array of 3) arrays in a number Stoop task. Reaction times were even slower in incongruent trials when these were preceded by aversive rather than neutral stimuli. Sommer et al. (2008) presented participants with affective pictures (positive, negative, or neutral) in between blocks of Simon task trials and found that negative, but not positive or neutral pictures led to impaired performance in incongruent trials. Finally, negative emotions presented prior to color-words in a Stroop task both hinder behavioral performance and result in interference-related activation in control-related fronto-parietal brain regions (Melcher et al., 2011). Combined, these results have been mostly interpreted within the biased competition model (Desimone and Duncan, 1995), which argues that task-irrelevant emotional stimuli compete for limited cognitive resources, occupy executive and memory resources, and hinder conflict processing (see also Carretié, 2014).

However, other evidence noted opposite effects. For instance, Kanske and Kotz (2010) showed that task-irrelevant negative emotional words in a color flanker task can reduce the conflict effect. The time required for reporting the color of a centrally presented word flanked by words in different color (i.e., conflicting, incongruent) was reduced when words were negative. It has, thus, been suggested that negative emotional stimuli of high motivational intensity might heighten attentional focusing and facilitate cognitive attentional performance (Gable and Harmon-Jones, 2008, 2010; Kanske and Kotz, 2011b, c; Kanske, 2012). Grützmann et al. (2019) presented participants with a Flanker task on top of task-irrelevant negative and neutral background images. As a result, the authors found that negative relative to neutral pictures resulted in prolonged responses in congruent, but not in incongruent Flanker trials (i.e., the conflict effect was reduced in negative condition). Interestingly, the authors found such a reduction only in blocks where there were 75% of congruent relative to incongruent trials, that is, negative emotions could be specifically effective under the low tonic executive control. Importantly, this seems to occur independent of modality (i.e., whether the source of conflict is visual or auditory; Kanske and Kotz, 2011d; Fenske and Eastwood, 2003) and type of conflict task (for flanker and Simon type of task; Birk et al., 2011; Melcher et al., 2012; Kanske and Kotz, 2010, 2011a; Melcher et al., 2012; but see Fruchtman-Steinbok et al., 2016 for a lack of emotion-cognition interactions in auditory and tactile stimuli[1]). The authors suggested that negative stimuli can, as salient, survival-related signals, facilitate the readiness to act and boost cognitive control (for an overview, see Kanske, 2012).

The discrepancy between the findings may be best explained by the specific role that negative emotion played in the different studies. While emotion itself was not task-relevant and although both groups of studies used comparable conflict processing tasks (i.e., flanker, Stroop etc.), they differed significantly in how they timed the presentation of negative emotion information. The majority of studies that reported emotion-related enhancement of cognitive control presented negative images (or videos and sounds) together with task-relevant information (Grützmann et al., 2019; Kanske and Kotz, 2010, 2011a, b; Zinchenko et al., 2015). Studies that found emotion-related reduction of cognitive control either induced negative emotion or mood prior to the experiment or shortly before the conflict trial (Hart et al., 2010; Sommer et al., 2008). It may therefore be that the emotional quality of task-unrelated stimuli, presented outside the main task may distract information processing and in turn hinder cognitive control. On the other hand, emotion facilitation effects can be observed if the negative emotion and task-relevant information coincide, that is, when behaviorally relevant stimuli that participants react to during a task are emotional (Kanske, 2012). Interestingly, negative stimuli do not necessarily have to be physically present at the time of conflict to coincide with the task and facilitate performance. For instance, it has been shown that sustained fear of bodily harm (fear of possible electrical shocks) could also facilitate cognitive control by reducing the incongruence effect in a color-word Stroop task (Hu et al., 2012). This temporal alignment of information in conflict processing is also in line with data showing that other cognitive processes are influenced by a pre-stimulus interval between the offset of a negative prime and onset of the task (e.g., Bocanegra and Zeelenberg, 2009; Posner et al., 1987).

Another potentially important factor that was suggested to modulate the influence of negative emotions on cognitive control is behavioral relevance. For instance, Cohen et al. (2015a, 2015b) showed that explicit (i.e., behavior-relevant) processing of negative images *prior* to a flanker task could actually facilitate conflict processing. Alternatively, when the negative value of stimuli was behavior-irrelevant, participants showed hindered performance on both congruent and incongruent trials (Cohen et al., 2015a, 2015b, 2016). The authors concluded that negative images presented prior to a cognitive control task might affect performance differently depending on whether they are processed implicitly or explicitly. Therefore, the exact role of the emotion-to-target pre-stimulus time interval as well as behavioral relevance of emotion processing in cognitive control tasks has to date not been entirely clarified.

[1] These authors also argue that it is not emotion that modulates cognitive control, but rather the recruitment of executive resources that modulates the processing of emotion (i.e., negates the distracting effects from negative stimuli), a point of view that we do not explicitly discuss in the current review (for details see Cohen et al., 2012; Cohen, Mor, & Henik, 2015; see also Straub et al., 2019 for more recent evidence).

Table 1
Research articles on emotion-cognitive control interactions. The table contains an overview of studies using different approaches to compare executive control tasks in emotional (negative, positive) and neutral conditions.

Study	Stimuli/Task	Behavioral effects	Neural effects	Behavioral relevance of emotion	Modality	Valence	Control type
Emotion facilitates executive control							
Cohen et al., 2015b	Preceding negative, neutral images/Arrow flanker task	Reduced conflict effect under explicit emotional processing condition.	N/A	Task-*relevant*; presented *before* to the conflict task	Visual	Negative	Cognitive control
Fenske and Eastwood, 2003	Negative, neutral and positive schematic faces/face flanker task	Reduced conflict effect for negative relative to positive emotions	N/A	*Task-relevant;* presented as target in the conflict task	Visual	Negative/ Positive	Emotional control
Grützmann et al., 2019	Arrow-Flanker task and task-irrelevant neutral and negative background images + mostly congruent and mostly incongruent trials conditions	Reduced conflict effect under negative emotion backgrounds/prolonged RTs to negative relative to neutral backgrounds in the mostly (75%) congruent trials condition.	Reduced N200 and correct-related negativity to negative background images.	Task-irrelevant; presented in the background of the conflict task	Visual	Negative	Cognitive control
Hu et al., 2012	Color-Stroop task and threat of electrical shock.	Reduced conflict effect under anticipation of electrical shock.	Threat anticipation resulted in elevated skin conductance responses	Task-*irrelevant*; threat anticipation is within the conflict task	Visual	Negative	Cognitive control
Kanske and Kotz, 2010	Negative and neutral words/Word-flanker task.	Reduced conflict effect in negative stimuli.	Increased N200 conflict effect in negative stimuli.	Task-*irrelevant*; presented as target in the conflict task	Visual	Negative	Cognitive control
Kanske and Kotz, 2011a	Positive and neutral words/Word-flanker task.	Reduced conflict effect in positive stimuli.	Increased N200 conflict effect in positive stimuli.	Task-*irrelevant*; presented as target in the conflict task	Auditory	Positive	Cognitive control
Kanske and Kotz, 2011b	Negative and neutral spoken words/ Auditory Simon task.	Reduced conflict effect in negative stimuli.	Increased N400 conflict effect in negative stimuli/Negative stimuli yielded activation in the right ventral ACC	Task-*irrelevant*; presented as target in the conflict task	Auditory	Negative	Cognitive control
Kanske and Kotz, 2011c	Negative and neutral words/Word-flanker task.	Reduced conflict effect in negative stimuli.	Ventral ACC was activated in conflict trials with negative stimuli. Emotion also increased functional connectivity between the ventral ACC and activation of the dorsal ACC and the amygdala in conflict trials.	Task-*irrelevant*; presented as target in the conflict task	Visual	Negative	Cognitive control
Kanske and Kotz, 2011d	Positive and neutral spoken words/ Auditory Simon task.	Reduced conflict effect in positive stimuli.	Increased N400 conflict effect in positive stimuli	Task-*irrelevant*; presented as target in the conflict task	Auditory	Positive	Cognitive control
Li et al., 2014	Negative, positive and neutral words/ Word-flanker task.	Incongruent stimuli resultsd in slower performance	Negative but not positive emotions resulted in increased N100 to incongruent trials	Task-*irrelevant*; presented as target in the conflict task	Visual	Negative/ Positive	Cognitive control
Zinchenko et al., 2015	Dynamic multisensory videos/Face-Stroop task	Negative emotion resulted in reduced cognitive and emotional conflict effects	Emotion- and control-related modulation of conflict-sensitive N100, P200 and N200	Task-*relevant* and –*irrelevant*; presented as target in the conflict task	Audio-visual	Negative	Cognitive control/ Emotional control
Zinchenko et al., 2017b	Dynamic multisensory videos/Face-Stroop task	Positive emotion resulted in reduced cognitive but not emotional conflict effects	Emotional modulation of the P200 and N200 conflict effects	Task-*relevant* and –*irrelevant*; presented as target in the conflict task	Audio-visual	Positive	Cognitive control/ Emotional control
Zinchenko et al., 2017c	Dynamic multisensory videos/Face-Stroop task	Emotional modulation of cognitive control in younger and older adults.	Emotion- and control-related modulation of conflict-sensitive N100, P200 and N200	Task-*relevant* and –*irrelevant*; presented as target in the conflict task	Audio-visual	Negative	Cognitive control/ Emotional control
Zinchenko et al., 2018.	Dynamic multisensory videos/Face-Stroop task	Emotional modulation of cognitive control in older adults without specific hearing impairments.	Emotion- and control-related modulation of conflict-sensitive N100, P200 and N200	Task-*relevant* and –*irrelevant*; presented as target in the conflict task	Audio-visual	Negative	Cognitive control/ Emotional control
Emotion hinders/has no effect on executive control							

(*continued on next page*)

Table 1 (*continued*)

Study	Stimuli/Task	Behavioral effects	Neural effects	Behavioral relevance of emotion	Modality	Valence	Control type
Cohen et al., 2015b	Preceding negative, neutral images/Arrow flanker task	No emotion- control interaction under implicit emotional processing condition.	N/A	Task-*irrelevant'*; presented *before* the conflict task	Visual	Negative	Cognitive control
Dennis and Chen, 2007	Arrow Flanker task that was preceded by emotional (angry, sad, fearful) or neutral images	No emotion- executive control interaction	Larger N200 conflict effect following fearful images.	Task-*irrelevant*; presented *before* the conflict task	Visual	Negative	Cognitive control
Dennis et al., 2008	Fearful, neutral and control images preceded the Flanker task/Arrow flanker task.	Fearful faces impaired executive Control under low-anxiety state	N/A	Task-*irrelevant*; presented *before* the conflict task	Visual	Negative	Cognitive control
Hart et al., 2010	Numbers, negative emotional images/ number Stoop task	Increased incongruence cost under negative emotion primes.	N/A	Task-*irrelevant*; presented *before* the conflict task	Visual	Negative	Cognitive control
Martin and Kerns, 2011	Comedy videos clips for positive mood induction/Flanker task	No emotional modulation of cognitive control	N/A	Task-*irrelevant*; presented *before* the conflict task	Visual	Positive	Cognitive control
Melcher et al., 2011;	Color-words Stroop task preceded by negative images	Increased incongruence effect when preceded by negative images	Interference-related activation in control-related [fronto-parietal] brain regions	Task-*irrelevant*; presented *before* the conflict task	Visual	Negative	Cognitive control
O'Toole et al., 2011	Arrow Flanker task that was preceded by emotional (angry, sad, fearful) or neutral images	No emotion- executive control interaction	N/A	Task-*irrelevant*; presented *before* the conflict task	Visual	Negative	Cognitive control
Padmala et al., 2011	Negative images/word-face Stoop task	Negative emotion reduced conflict-adaptation effects.	N/A	Task-*irrelevant*; presented *before* the conflict task	Visual	Negative	Cognitive control
Raschle et al., 2017	Numbers, negative images/number Stoop task	No emotion- control interaction	Decreased emotion-related activations within PFC, amygdala, and insular cortex under incongruence	Task-*irrelevant*; presented *before* the conflict task	Visual	Negative	Cognitive control
Sommer et al., 2008	Simon task preceded by negative, positive and neutral images	Impaired performance in incongruent trials of negative condition; no effect of positive condition	Less activation of brain areas associated with task performance in negative, but not in positive condition.	Task-*irrelevant*; presented *before* the conflict task	Visual	Negative, Positive	Cognitive control

3. Conflict-specificity

The majority of studies in the field have concentrated on cognitive control, that is, the source of conflict is between non-emotional stimulus components (e.g., as in the classical Stroop task). However, an increasing number of studies investigate *emotional* conflict processing, that is, when the source of conflict occurs between opposing emotional information sources (e.g., Egner et al., 2008; Soutschek et al., 2013; Torres-Quesada et al., 2014; Zinchenko et al., 2015). For instance, in an emotional conflict face-Stroop task participants were asked to identify the emotion of a presented face and ignored a task irrelevant word written on top of the face that was congruent with the valence of the face (e.g., the word HAPPY written on a happy face) or incongruent with the valence of the face (e.g. the word FEAR written on a happy face). Such incongruencies hinder performance and prolong reaction times, similarly to what is reported in cognitive conflict tasks (Egner et al., 2008; Etkin et al., 2006). Nevertheless, the processing of emotional and cognitive conflicts seems to differ at both the behavioral and neural levels (Egner et al., 2008; Soutschek et al., 2013; Torres-Quesada et al., 2014; but see Chiew and Braver, 2011 for a lack of evidence of control-specific functional dissociation). For instance, Soutschek et al. (2013) examined the effects of additional emotional and neutral cognitive load on an emotional and a cognitive Stroop task. Here, non-emotional working memory load selectively suppressed conflict processing in the cognitive Stroop task, but not in the emotional Stroop task. In contrast, emotional cognitive load hindered performance selectively in the emotional Stroop task. These findings support domain-specific (cognitive, emotional) conflict processing mechanisms. Furthermore, Egner et al. (2008) used functional magnetic resonance imaging (fMRI) to test for domain-specific neural correlates that could be unique for either emotional or cognitive control (Egner et al., 2008). The authors reported activation in lateral prefrontal regions in response to cognitive conflicts and rostral anterior cingulate regions that resolved emotional conflicts. Additionally, the dorsal anterior cingulate (dACC) was active for both conflict types. It has been suggested that the observed dACC activation represents a common conflict-detection mechanism that is observed across emotion and cognitive conflict, but separate neural systems appear to support control processes involved in conflict resolution across emotion and cognitive domains. To reiterate, cognitive and emotional conflict processing recruit partially dissociable and control-specific neuroanatomical networks but they also share a common conflict-detection mechanism.

Similar to the emotional modulation of cognitive control, task relevance of the affective information in emotional control has also been addressed in recent studies (Zinchenko et al., 2017c; Zinchenko et al., 2015, 2018). Here, participants watched short congruent and incongruent audiovisual videos where the emotional valence of the two sensory streams was either congruent or incongruent. Participants identified the valence of the voice and could ignore the face. The voice could be emotional or neutral, with the face being emotional or neutral. Thus, the influence of an emotional or a neutral target on emotional conflict processing was studied. The results indicated that similarly to cognitive conflict tasks, negative targets lead to more efficient conflict processing in the emotional task and to an emotion-specific modulation of event-related potentials (ERPs). Emotional target stimuli are, hence, speeding up both cognitive and emotional control processes.

4. Emotional valence: specifics of positive emotions

Positive and negative emotional stimuli may both be salient and attract attention more readily than neutral stimuli (Pilarczyk and Kuniecki, 2014; Straub et al., 2019). However, valence along the negative-positive dimension may still have complementary, but distinct neuropsychological functions (Fredrickson, 2001). While negative emotions narrow the breadth of attention (Eysenck et al., 2007; Fredrickson, 2001), positive emotions tend to broaden the individual's scope of visual attention (e.g., Johnson et al., 2010). It is therefore an interesting question whether valence modulates cognitive and emotional control in a distinct manner. As most of the studies reviewed up to this point in the manuscript contrasted negative and neutral emotion conditions, we will concentrate on the specifics of positive emotion in the current section and conclude by an overall comparison of positive and negative valence.

Positive emotions may affect conflict processing in different ways. For instance, positive emotions are associated with greater flanker interference (Rowe et al., 2007) and, similarly to negative emotions, may also have detrimental effects on cognitive control when a non-target stimulus (e.g., presented shortly before the target stimulus) is emotional (e.g., Blair et al., 2007; Dreisbach, 2006). On the other hand, positive emotions were also shown to speed up cognitive conflict processing when the behavioral target is emotional, leading to an increased conflict-sensitive N200 response (Kanske and Kotz, 2011a; Kanske and Kotz, 2011c; Zinchenko et al., 2017b). With regard to emotional control, a recent study found that positive emotional targets impede emotional conflict processing (Zinchenko et al., 2017a, 2017b, 2017c). Incongruent positive compared to neutral stimuli yielded increased response times in an emotional conflict task where emotion was behavior-relevant. In line with the behavioral findings, conflict-related P200 and N200 responses were also modulated by emotion. These latter results show that positive emotions may have an opposite effect by either enhancing or hindering performance depending on the type of executive control (i.e., cognitive, emotional).

These results also align well with studies that showed positive emotions to increase distractibility (Dreisbach and Goschke, 2004) and to reduce the use of informative cues in cognitive functions (Fröber and Dreisbach, 2012). For example, positive emotional primes reduced the prediction strength between the cue and a subsequent target (Dreisbach, 2006). When a facial cue is positive in an emotional conflict task, it may form weaker predictions about the upcoming target and reduce the contrast between a positive prime and a target, thus reducing the conflict effect (Zinchenko et al., 2017a, 2017b, 2017c). Finally, a few studies also reported no influence of positive emotion on cognitive control (e.g., Martin and Kerns, 2011).

5. Physiological correlates of cognition - emotion interaction

Previous work has also investigated the physiological correlates of cognitive control and their modulation by negative emotion. Electroencephalography (EEG) studies showed that incongruent stimuli, producing conflict, elicit an early (100 ms) increased negativity in the event-related potential (ERP) in response to dynamic stimuli (e.g., Ho et al., 2015; Kokinous et al., 2014; Pourtois et al., 2000). For instance, Garrido-Vásquez et al. (2018) used dynamic facial expressions as primes presented prior to negatively intoned pseudo-speech sentences. They reported an enhanced N100 response to incongruently primed prosodies (see also Li et al., 2014). Studies using *static* stimuli in classic conflict tasks typically show conflict-related negative increases around 200 ms post-stimulus onset (Bartholow et al., 2005; Kanske and Kotz, 2010; Ladouceur et al., 2007; van Veen and Carter, 2002). For instance, Bartholow and colleagues reported an increased N200 response to incongruent trials in a flanker task. Later negativities have also been observed when conflicting information is more complex, in particular around 400 ms after stimulus onset (N400; Kellenbach et al., 2000; Schirmer and Kotz, 2003; Willems et al., 2008). For instance, Kutas and Hillyard (1980) observed that semantically incongruent sentence endings (e.g., "He planted string beans in his *car*") resulted in an increased N400 response compared to semantically congruent endings (e.g., "He planted string beans in his *garden*"; for a more recent overview see Kutas et al., 2014). These relatively late negative EEG deflections were interpreted as incongruence detection mechanisms when participants are faced with incompatible information (Greenham et al., 2000; Liotti et al., 2000; Rebai et al., 1997). Finally, late positivegoing components of the EEG, in particular the P300 and P600, have been associated with the exertion of inhibitory control to enable execution of the correct response despite conflicting response tendencies (Brouwer et al., 2017; Enriquez-Geppert et al., 2010). To summarize, a number of neurophysiological measures were identified that are sensitive to processing of conflicting or incongruent information.

Investigating the emotional modulation of these EEG markers of conflict processing gives critical insight into how and when emotion can influence cognitive control. Interestingly, when using dynamic, multisensory stimuli, the N100 component is enlarged when the [task-irrelevant] emotional valence of the presented stimuli is negative rather than neutral (Zinchenko et al., 2017a, 2017b, 2017c; Zinchenko et al., 2015; Brouwer et al., 2017). Comparable amplitude increases are also observed in the N200 time-range in static conflict tasks (Kanske and Kotz, 2011a; with the deflections partially being positive, Liu et al., 2012; Pourtois et al., 2000; Spreckelmeyer et al., 2006; Zinchenko et al., 2019a) and in the N400 with more complex stimuli (Kanske and Kotz, 2010; Kanske and Kotz, 2011c). In other words, emotion that coincides with task-relevant targets and speeds up conflict processing goes along with an increase in conflict-related potentials. The modulation of cognitive control by emotion is thus fast and differential.

An explanation for the temporal variation of ERP responses in conflict processing (100–600 ms post stimulus) may be the specific nature of the stimuli. For instance, reading written words in a word flanker task is highly automatized; also, as soon as a stimulus is presented, the conflict arises and conflict related effects occur around 200 ms after stimulus onset (Kanske and Kotz, 2010). In contrast, in an auditory Simon task (see Kanske and Kotz, 2011d), a conflict was only present once participants processed and identified an auditory target, which did not coincide with the stimulus onset and hence only showed relatively late (400 ms). Finally, multisensory, dynamic settings show particularly early modulations of the ERP at around 100 ms post-stimulus. We discuss their particular characteristics in depth in the following section.

6. Dynamic stimuli and cognitive control

Studying cognitive control with multisensory, dynamic stimuli that closely approximate real-life situations is a relatively recent development. Multi- rather than unisensory information leads to very early (~100–200 ms post stimulus) modulations of neural responses (de Gelder and Vroomen, 2000; Klucharev et al., 2003; Knowland et al., 2014; Kokinous et al., 2015; van Wassenhove et al., 2005). Furthermore, in these dynamic settings, visual information typically and naturally precedes auditory information (Chandrasekaran et al., 2009; Garrido-Vásquez et al., 2018; Jessen and Kotz, 2013; Stekelenburg and Vroomen, 2012). Consequently, visual cues can facilitate the processing of the upcoming auditory information (e.g., Besle et al., 2004; Garrido-Vásquez et al., 2018; Klucharev et al., 2003; van Wassenhove et al., 2005; de Gelder and Vroomen, 2000; Ethofer et al., 2006; Gao et al., 2018). Importantly, these early integration effects seem to disappear once auditory and visual information are temporally aligned, that is, when there is no *anticipatory* visual motion (Stekelenburg and Vroomen, 2007). For instance, in a recent study, Föcker and Röder (2019) showed that incongruent pairings of face-voice combinations led to a larger negative response to incongruent than congruent trials in the time range of 400–550 ms (N400). The authors suggested that such relatively late ERP incongruence effects could be caused by the short time period of about 50 ms between the onset of the face and the auditory stimulus used in their study, while some other studies presented preceding videos for a longer time prior to voice onset (e.g., < 500 ms, Zinchenko et al., 2015). These data demonstrate that multisensory modulation of early neural responses at least partially relies on the predictive value of one sensory modality onto another.

The dynamic quality of information may further modulate audio-visual interactions (De Gelder and Bertelson, 2003) as multisensory integration effects are much stronger for dynamic faces than static ones (Campanella and Belin, 2007). The benefit of multisensory [dynamic] information processing has repeatedly been shown in a number of dynamic audiovisual paradigms (Jessen and Kotz, 2011; Jessen and Kotz, 2013; Stekelenburg and Vroomen, 2007; Stekelenburg and Vroomen, 2012). Of note, such early interaction seems not to be affected by an increase in mental and attentional workload (Vroomen et al., 2001) supporting the view of automatic audio-visual binding of cross-modal [emotional] signals (but see Ho et al., 2015 for a different view). Therefore, the use of realistic, dynamic multisensory stimuli may help in the investigation of conflict processing and the impact of emotion on cognitive control.

In several studies, we have used dynamic multisensory audio-visual stimuli to create a version of a face-Stroop conflict task (Zinchenko et al., 2015; see also Zinchenko et al., 2017a, 2017b, 2017c). In this task, participants had to report either the emotional valence or semantic meaning of a non-verbal vocalization and ignore task-irrelevant emotional and neutral face- and lip-movements. Importantly, the face naturally preceded the auditory stream by ~500 ms and could either be congruent (the vocalization “A” paired with lip-movements corresponding to the vocalization “A”) or incongruent (the vocalization “O” paired with lip-movements corresponding to the vocalization “A”), constituting a cognitive conflict. Irrelevant for the task at hand, facial and auditory stimulus segments could either be emotional or neutral. The data clearly show early conflict effects that were observed already ~100 ms after stimulus onset (see also Ho et al., 2015; Kokinous et al., 2014). Moreover, these conflict effects were modulated by task-irrelevant negative emotions, that is, a conflict-specific negative increase was more pronounced for emotional than neutral stimuli. Thus, dynamic, multisensory stimuli may lead to an earlier detection of incongruity and earlier emotion-control interactions.

Importantly, in certain cases the observed findings on emotion-cognition interactions were only possible due to the dynamic, multisensory design. For instance, the valence-specific role of positive emotions in emotional control became apparent when tested specifically in a multisensory context with a strong prediction component and was hidden when tested in unisensory setups (Zinchenko et al., 2017a, 2017b, 2017c; Egner et al., 2008). Additionally, it is dynamic, multisensory stimuli that resulted in the observed early N100 incongruence modulation by negative emotions (Zinchenko et al., 2017a, 2017b, 2017c; Zinchenko et al., 2015), which advanced our understanding of the time-course of emotion-cognition interaction.

Finally, such multisensory designs with high ecological validity are particularly well-suited for research in special populations, such as elderly or older adults with hearing loss, where processing of one or more stimulus modalities (audio, emotions) is degraded due to natural brain changes (Zinchenko et al., 2017c; Zinchenko et al., 2018). For example, it was found that older, but not younger adults show no processing costs in an emotional conflict task where the emotional target word was flanked by congruent or incongruent emotional distractors (i.e., negative, positive), while both age groups showed interference on control trials that required processing of non-emotional targets and distractors (Samanez-Larkin et al., 2009). However, no such effect was observed when stimuli were more realistic (i.e., dynamic and multisensory), where negative emotion facilitated emotional conflict processing in both age groups (Zinchenko et al., 2017a, 2017b, 2017c; Zinchenko et al., 2018).

7. Challenges and questions

Despite immense progress exploring the emotion - cognitive control interaction, there are still many open questions and challenges. Specifically, there is a strong need to move towards more naturalistic stimuli, possibly even testing outside of the lab by measuring situations of self-control (failures) in daily activities (e.g., measured by experience sampling) and testing the influence of emotions on these processes (see

Krönke et al., 2018). This idea may be rather beneficial for studies of emotional conflict processing that are thought to represent processing of such concepts as irony or satire that occur in social interactions and peer-to-peer communication (Pexman, 2008; Watanabe et al., 2014) and can only partially be restaged in lab settings.

Although there is some evidence from EEG and fMRI studies showing that cognitive and emotional conflict processing may be achieved in partially dissociated neural systems (Egner et al., 2008; Torres-Quesada et al., 2014; Zinchenko et al., 2015; but see Chiew and Braver, 2011), we know little about the time-course of the interaction of the various brain regions involved. Therefore, future studies should use combined EEG and fMRI measurements that would enable examining the time-course and localization of cognition-emotion interaction.

A further angle to be explored in cognitive and emotional conflict processing is inter-individual differences. There is evidence that interpersonal characteristics such as effortful control, clinical and subclinical depression and anxiety (Kanske and Kotz, 2012; Zinchenko et al., 2017a, 2017b, 2017c; Zinchenko et al., 2017a), emotional intelligence (Megías et al., 2017), behavioral activation sensitivity (e.g., Dennis and Chen, 2007; but see also O'Toole et al., 2011) as well as trait susceptibility to worry (Owens et al., 2015) modulate participants' emotion and conflict processing, as well as their interaction (for an overview see also Okon-Singer et al., 2013). Exploring whether extreme variants of these individual differences constitute risk factors for mental disorders may support the formulation of etiological models.

8. Conclusion

Emotions are salient stimuli that signal potential threats or opportunities for reward. Therefore, task-relevant and –irrelevant emotions play an important role in modulating executive cognitive control. Such modulation is highly evolutionary adaptive as it can reduce the time that an organism is incapable of acting due to conflicting response tendencies. However, it seems that the role of positive and negative emotions may vary depending on the conflict type (cognitive, emotional) and the time of presentation (prior to the target, as a target). To move towards ecologically valid settings of cognitive control (failures) in everyday life, future studies should push forward experimental approaches with dynamic, multisensory, and realistic stimuli (e.g., testing outside of lab in real-life situations) and combine different neuroimaging methods with experience sampling approaches.

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