Behavioral and neural mechanisms underlying selective attention in anxiety and value-driven selection modulated by associative learning

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Those who dare, can, those who know no fear, go forward.
Field Marshal Živojin Mišić

Ask, and it shall be given to you; seek, and you shall find; knock, and it shall be opened to you. For everyone who asks, receives; and the one who seeks, finds; and to the one who knocks, it shall be opened. Matthew, 7, 7-8.

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1 General introduction

In everyday life people’s attention is challenged by numerous relevant and irrelevant stimuli. The survival and well-being of people depend on prioritizing relevant and ignoring irrelevant environmental distractors. People must reorient attention rather quickly and change the current pattern of behavior when facing novel, potentially rewarding or threatening stimuli (Corbetta et al., 2008). This suggests that attention as a central, organized function in perception, cognition and action, filters dynamic sensory information and mediates responses to achieve behavioral goals. Attention selects stimuli for further cognitive processing and the mechanism underlying this process is either voluntary, driven by top-down goals, or involuntary, driven by physical attractiveness of stimuli (Anderson 2013; Wolfe 1994; Müller et al. 2009; Zehetleitner et al. 2012). There is an ongoing debate regarding how people employ their attention within visual modality. Current theories of attention take into consideration a possibility of top-down control over the allocation of attention (Folk et al. 1992; Bacon and Egeth 1994; Müller and Krummenacher 2006; Zehetleitner et al. 2011). These theoretical accounts suggest that the implementation of top-down control can modulate bottom-up salience signals in regard to behavioral goals of the observer. Visual search studies showed that the observer's attention can be captured by a physically salient object (e.g., a red item) (Connor et al. 2004; Wolfe et al. 1989; Desimone and Duncan 1995; Awh et al. 2012), however, this is a matter of debate since numerous studies have shown that interference by irrelevant singletons can be reduced or even prevented (Müller et al. 2009; Leber and Egeth 2006; Leber and Egeth 2006). The advocates of stimulus-driven attention debated to provide evidence that an abrupt physically salient stimuli captures attention if it falls within the ‘zoom lens’ of attention regardless of the observer’s current goals, or even contrary to top-down control setting (Theeuwes 1991; 2010; Van der Stigchel et al. 2009; Theeuwes and Failing 2020), whereas the advocates of goal-driven attention argued that purely bottom-up attention does not exist since attentional selection is always an outcome of top-down intentions (Folk et al. 1992). Voluntary or involuntary way of attentional processing operating with strategies using prior experience is affected by selection history (Theeuwes, 2019; Awh et al. 2012) driven attentional selection, and beyond that the role of emotional associative learning; however, recent studies provide a novel perspective on attentional selection demonstrating a crucial role of a reward (Anderson 2013; Chelazzi et al. 2013).

Over the past 15 years there has been a vivid debate about the extent to which a stimulus, previously associated (conditioned) with reward, still captures attention. This is not surprising since the importance of bliss and the absence of pain in leading a life were discussed even in Ancient Greece (e.g., Epicurus, Ancient Greek: Ἐπίκουρος). The appearance of a reward-related stimulus still continues this function afterward even when no longer signaling a reward. A pioneering study related to the influence of reward-learning associations on selective visual attention was Libera's work (Libera et al., 2006). Applying a prime-probe task, Libera et al. have shown that a monetary reward used as feedback modulates efficiency in a visual selective attention task, thus demonstrating that rewarding may be used as a reward regime in operant-type of learning in shaping a behavior (Skinner, 1954), but also for more sophisticated forms of learning in visual attentional selection. Recently, the paradigm most widely used to examine the phenomenon of attentional selection is the value-driven attentional capture paradigm (e.g., Anderson et al. 2011).

In order to behave adaptively, human attention is directed voluntarily (goal-driven) or involuntarily (stimulus-driven), using the the strategies of past experiences (history-driven) (Awh et al. 2012); however, prior research emphasizes that attention may be driven by motivational and emotional value of stimuli (Bourgeois et al., 2016), whereas the influence of reward-learning on attentional processes has rapidly become an area of intensive research (Anderson, 2016b). In a search task attention is oriented more toward emotional than to neutral faces (Frischen et al., 2008), whereas ERP studies (Zinchenko et al., 2015, 2017) demonstrate a strong influence of emotion on cognitive and emotional conflict processing, emphasizing the importance of emotion in decision making. A fundamental question arises whether there is a difference between the influence of motivational and emotional values of stimuli on attentional selection and capture. Prior research has mainly used a monetary reward as a motivational stimulus in the value-driven attentional capture paradigm (Anderson et al., 2011; Le Pelley et al., 2015; Nissens et al., 2017; Watson et al., 2019). In addition to positive reinforcement, punishment may also be employed to similarly capture attention, thus indicating that the motivational significance of the outcome (a large magnitude of reward/punishment naturally results in greater arousal than a small magnitude of reward/punishment), rather than outcome valence, exerts a crucial influence on attentional capture (Le Pelley et al., 2016). An fMRI study (Kahnt et al., 2014) has demonstrated, in task outcome prediction, that neural coding patterns in the prediction of outcome values are similar concerning rewarding and aversive stimuli, suggesting a unique valence-related network.

A recent study by Kim and Anderson (2020) used emotional faces as an emotional (social) reward to examine the attentional capture effect through reward-learning associations. Rather than using standard monetary feedback for correct responses in a visual search task in the association phase, a positive or neutral valence photograph (i.e., happy face *vs.* neutral face) was associated with a color-defined target (red vs. green). In the non-reward phase, participants searched for a shape singleton target (i.e., a circle among diamonds or a diamond among circles) ignoring the color of presented items. Typically, results demonstrated that in the non-reward phase of the experiment, attention can be captured by previously rewarded items; thus, participants responded more slowly or less accurately in the distractor-present compared to the distractor-absent trials. Numerous studies (Anderson et al., 2011; Le Pelley et al., 2015; Nissens et al., 2017; Watson et al., 2019) suggest that an irrelevant distractor previously associated with motivational and emotional stimuli, captures attention equally. However, is that really the case? Kim and Anderson (2020) showed no significant effect between high- and low-emotional reward in the association phase, whereas, in the non-reward phase a difference was found between an absent-distractor and a low-, and high-value distractor, but not between a low-distractor and high-distractor. This challenges attentional capture based on emotional values.

Strong evidence demonstrates that selective attention is determined by top-down attentional control, bottom-up attentional capture and history-driven selection (Awh et al. 2012). Recently, a growing number of studies (Anderson et al., 2011; Le Pelley et al., 2015; Nissens et al., 2017; Watson et al., 2019) have shown that reward-oriented stimuli may involuntarily capture attention in an automatic manner, even when those stimuli are task-irrelevant. However, it remains unclear to what extent attentional capture occurs if an irrelevant distractor is previously associated with motivational (e.g., monetary compensation) compared to emotional (e.g., happy faces) rewards. Solid evidence (Le Pelley et al. 2011; Beesley et al. 2015; Chao et al. 2021) has been provided that, in addition to existing forms of attentional selection, learned predictiveness (expectation) may fundamentally modulate visual attention and shape perception.

Many open questions remained. In this work we addressed several fundamental issues: to what extent an irrelevant distractor stimulus previously associated with reward, may still capture attention. Does attentional capture by an irrelevant distractor stimulus, previously associated with reward, depend on whether the reward value is motivational or emotional. Does attentional capture by a distractor stimulus, previously associated with reward, depend on the applied associative learning (i.e., Pavlovian conditioning, instrumental learning). Does attentional capture depend on individual differences (e.g., psychological traits) among people.

The introduction (1.2.) outlines phenomena of attentional selection in general, in particular top-down, bottom-up and history-driven selection. The following subsection (1.3.) describes in more detail goal-directed attentional selection as a critical component of attention since in our everyday life we are constantly updated through visual input using it as a source of attentional navigation to guide our attention. Paying attention to a particular object is considered to be guided by volitional control since it represents the current selection goals of the observer. Following subsection (1.4.) describes stimulus-driven attentional selection and pointing out theoretical accounts that demonstrate the automated and pure bottom-up mechanisms. Moreover, the subsection (1.5.) provides description in regard to attentional capture which is a common phenomena registered in studies exploring bottom-up attentional selection. Exposure to physically salient (e.g., red item) attracts the observer's attention in an automatic manner, which often is not possible to avoid, especially with novel salient stimuli (e.g., abrupt onsets). In addition, the next subsection (1.6.) explains history selection as the interaction between top-down and bottom-up attentional selection mechanisms, since many decisions of the observer are driven by previous experience. Previous experience determines further attentional behavior in such a way that implicit or explicit experience shapes the current action of attentional selection. Since history selection may occur in such a way that neutral stimuli, previously associated with reward (e.g., monetary or emotional), can capture attention, chapter (2) explains the role of reward in attentional selection. Reward-based learning history and selection-history in a value-driven attentional capture paradigm was described in the subsections (2.1 and 2.2). In addition to that, the next chapter explains in detail the value driven attentional capture paradigm. Subsection 2.3. provides some theoretical accounts that hold Pavlovian conditioning and instrumental learning as main types of the associative learning of significance in value-driven attention selection, which is considered an important component of history selection. Moreover, Chapter 3 introduces goal-driven, stimulus-driven and history-driven selection through the neurological mechanisms, in particular summarizing recent EEG attention studies. Main aims of the doctoral thesis are presented in Chapter 4. The crucial Chapter 5 includes three individual studies as the main part of the cumulative doctoral dissertation. Finally, Chapter 6 highlights General Discussion on three studies including a crucial experiment (four behavioral and one EEG). Suggestions for the further studies are provided at the end of the Discussion section. Summary of findings are provided in Chapter 7.

1.2. Attentional selection

In everyday life, our selective attention, as a perceptual gatekeeper, is directed to relevant stimuli that enable survival and well-being, and ignoring irrelevant distractor-stimuli. Attentional selection occurs as an interaction between the observer’s goals (current selection goals) and physical features of stimuli (salience of the objects) (Liesefeld and Müller 2020; Töllner et al. 2012; Krummenacher et al. 2002). Over the past four decades researchers have debated to what extent is attentional selection determined by voluntary control, in a top-down manner (Töllner et al. 2012; Zehetleitner et al. 2012; Müller et al. 2007), whereas to what extent it is driven by physical stimulus features in an involuntary, automatic and bottom-up manner (Burnham 2007; Corbetta and Shulman 2002). In previous decades, these two forms of attentional selection were conceptually defined by psychologists as voluntary, goal-driven (e.g., searching for a key in a bag with plenty of other items) and involuntary, captured by a physically salient stimulus in a stimulus-driven manner (a doorbell sound) (Connor et al. 2004; Wolfe et al. 1989; Desimone and Duncan 1995; Awh et al. 2012). Voluntary attentional control is goal-specific, hence, whereas involuntary attentional control is automatic due to being stimulus-driven. In the literature, the terms “goal-driven” and “stimulus-driven” are often referred to as “top-down” and “bottom-up attention" (Wolfe 2021; Wolfe 1994), and less frequently as "exogenous attention" and "endogenous (central) attention" (Posner 1980). Both models of attentional selection are complementary and serve a function of behavioral adaptation. In addition to goal-driven and stimulus-driven, studies suggest attentional selection based on a past selection episode, referred to as "selection history" in the literature (Awh et al. 2012; Chun 2000; Jiang 2018; Geng and Behrmann 2002; Shaw and Shaw 1977). Awh et al., (2012) proposed that the attentional priority map should be extended beyond the existing framework of top-down and bottom-up processing to selection-history.

According to the 'pure-capture' view of Folk et al. (2006), preattentive processing drives the allocation of the spatial attention in a bottom-up fashion; however, this capture is contingent on the eliciting stimulus carrying a feature property consistent with the current attentional set. Preattentive processing is an initial phase of analysis providing a fast representation of the visual field in terms of 'basic' or 'simple' visual features such as shape, color, orientation, or brightness (Treisman and Souther 1985; Wolfe 1994). Thus, preattentive representations are assumed to insure a bottom-up component that, via interaction with top-down and goal-driven attention, guides the serial association of attentional resources (Folk and Remington 2006). Furthermore, a recent study by Bertleff et al. (2016) using neuroimaging examined the behavioral and neural effects of top-down spatial focused attention on coding of highly salient distractors and their tendencies to capture attention. In this study, an irrelevant distractor was combined with a spatial cueing paradigm revealing bottom-up attentional capture only when attention was dispersed across the whole search display, including the distractor location as well. Results showed that top-down focused spatial attention presents automatic attentional capture via supporting attentional control processes by opposing spatial bias towards a prominent distractor.

Also, bottom-up and top-down attention are questions which are still controversial. The N2pc component of EEG usually reflects early selective attention by a top-down driven process (Töllner et al. 2012). For example, visual search of feature singletons is slowed in case a task-irrelevant, but salient psychical distractor singleton is displayed; however, it is unclear at what stage of processing the selection of the task-relevant target occurs. Findings by Töllner et al. (2012), in whose study the likelihood of a distractor was systematically varied, showed there was no distractor-elicited N2pc, which demonstrated that participants did not shift attention to the distractor before selecting the target. Thus, preattentive vision is a top-down driven process.

1.3. Goal-driven attentional selection

In everyday life, people guide their behavior according to their own goals. It is a commonly accepted view that attentional selection represents interplay between two attentional control mechanisms such as goal-driven (top-down) control and stimulus-driven (bottom-up) control (Müller et al. 2009; Zehetleitner et al. 2012). People aim to guide their own behavior in accordance with current goals in such a way as to use 'volition' or 'act of will' (Rosenholtz et al. 2012; Wolfe 2021), thus they can use either its salience or its relevance for behavioral goals in selecting relevant information from a visual scene (Schubö and Müller 2009). In the literature, goal-driven attention is sometimes also referred to as the top-down process (Corbetta & Shulman, 2002; Stigchel et al., 2009). Thus, it is a voluntary process in which a particular feature, object, or location relevant for the present behavioral goals, is selected internally and focused upon (Katsuki & Constantinidis, 2014, for a review). In addition, two modes of attention are referred to as endogenous versus exogenous attention (Carrasco, 2011; Posner, 1980), causing a slight confusion regarding scientific terminology. Goal-driven selection may also be performed automatically if the search stimulus is known in advance. This phenomenon is referred to as contingent attentional capture (Folk et al., 1992).

However, there is debate whether and how goal-directed and stimulus-driven attention interact. Some researchers have pointed out that stimulus-driven control of attention is cognitively impenetrable, and works in a 'preattentive' and automatic manner (Theeuwes et al. 2006; Cohen and Magen 1999), while others argued that stimulus-driven attention can be influenced by the top-down attentional set (Found and Müller 1996; Müller et al. 1995; Müller and Krummenacher 2006). Müller at al. (2003) proposed a dimension-weighting account (DWA), that fundamentally extends the guided search model presented by Wolfe et al. (1994). The DWA model proposed that attentional weight may be allocated to different visual dimensions such as motion, orientation or color, but with total weight being limited. For example, preferential weighting of one dimension drives expedited detection of singleton feature targets defined in this dimension, relative to targets defined in other dimensions (Müller et al. 2003). However, if the target dimension would be changed across trials, the target detection would be delayed. Thus, response facilitation comes from the transmission of dimension-specific feature contrast signals (see Müller and Krummenacher 2006 , for a discussion).

1.4. Stimulus-driven attentional selection

Theoretically considered, purely stimulus-driven control refers to an occurrence of attentional capture by psychically salient stimuli in an automatic manner. New physically salient stimuli, so-called abrupt onsets, may capture attention in a purely stimulus-driven manner (Eriksen and Hoffman 1972; Theeuwes and Failing 2020), thus demonstrating their particular capacity for attentional capture in an automatic and reflexive way. Early studies (Belopolsky and Theeuwes 2010; Yantis and Jonides 1990; Müller et al. 2009) have suggested an interaction between stimulus-driven and goal-driven selection. By focusing attention in a goal-driven manner on a particular point in space, stimuli that commonly capture attention (abrupt visual onsets) may be completely ignored (Theeuwes, 2019). In addition, a prior study argued that distractor inhibition is a local phenomenon which may influence all presented distractors in the task (Müller et al. 2007). This demonstrates that involuntary attentional capture may also be partly controlled by attention. Goal-driven attention is under the observer's complete voluntary control; a person performs a selection of objects at any given moment (Theeuwes, 2010).

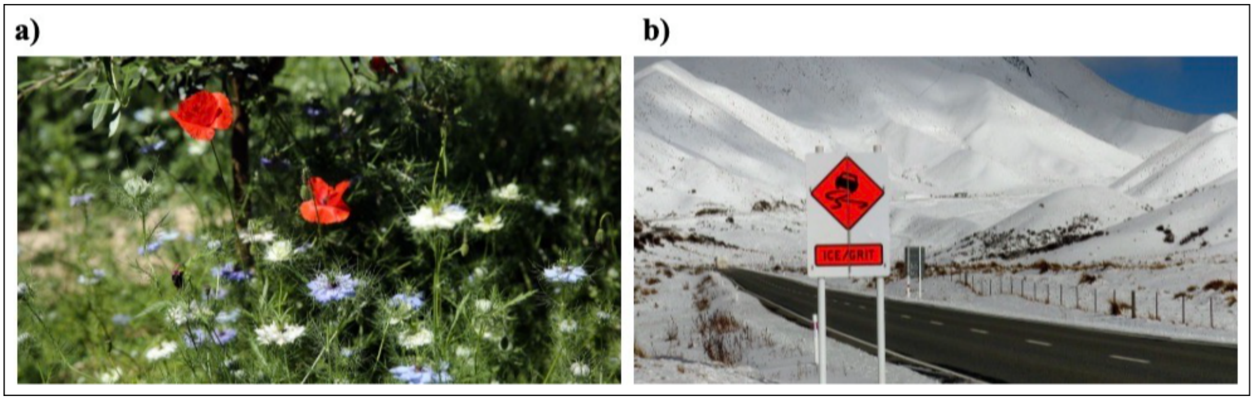
1.5. Attentional capture

Searching for a target can disrupt top-down attention by task-irrelevant physically salient distractors and capture attention (see Figure 1). This phenomenon of engaging attention beyond the observer’s voluntary control is referred to as attentional capture, or ability of humans' perceptual system to find an object next to the others distracting objects (Wolfe 1994). Moreover, it is coordinated with oculomotor capture (Le Pelley et al. 2015). Attentional capture during visual search is a phenomenon of fundamental importance since the core function of attention in everyday life is related to visual search behavior (Geyer et al., 2019). Attentional selection is a dynamic process highly related to experience (learning). Attentional capture is involuntary, automatic and performed in a stimulus-driven fashion.

An early view by Wolfe (1994) proposed a model colloquially named ‘Guided search 2.0’, initially based on work by Treisman et al. (1984) and Julesz (1984) work which distinguished between a preattentive processing of basic visual features such as color or motion, and subsequently a limited-capacity stage that processes more complex operations such as face recognition, object-identification or reading. Guided search 2.0 model proposed that the spatial deployment of the limited-capacity process is under attentional control, and that attentional deployment of limited resources is guided by the output of the process that occurs earlier as a parallel process (Wolfe 1994). Thus, a preattentive processing of attention plays an important role in the visual search. The guided search model proposes a single processing route involving a two-stage architecture: first, a preattentive, parallel stage, local salience-based feature contrast was taken into account, that can be also top-down modulated or ‘weighted’ before the integration into a priority map (Müller et al. 1995), and second, a limited-capacity stage operates at higher level of complexity such as face or object identification (Zehetleitner et al. 2012; Zehetleitner et al. 2009; Zehetleitner et al. 2009; Müller and Krummenacher 2006). In that regard, top-down weight setting on a given trial can modulate potential interference by a salient distractor (Zehetleitner et al. 2012).

The guided search model has been updated to version 4.0 (Wolfe and Gray 2007), and recently to version 6.0 (Wolfe 2021), extending that attention is ‘guided’ in such a way that scenes or object can be processed in an intelligent order, whereas this particular guidance comes from (1) top-down and (2) bottom-up feature guidance, (3) prior history (e.g., priming), (4) reward, and (5) scene syntax and semantics. These sources are mixed into a spatial ‘priority map’ which is a landscape playing a fundamental role in the visual search and attentional processes; for discussion see (Zhang et al. 2019; Fecteau and Munoz 2006; Liesefeld and Müller 2020).

Figure 1. Attentional capture by salient stimuli. Salient stimuli automatically attract an observer's attention, such as beautiful red flowers (a), hence salient stimuli are often used as warning signals of impending danger (b).



Note. Pictures adopted from https://www.flickr.com/.

In addition, human perception is also driven by statistical properties of the search for target objects. For example, we expect to find a pen on a desk and not on the floor since a pen and work are mutually related through a common action context and semantics, and we learn that a pen is usually found on a desk (Sauter et al. 2021). Observers in a visual search task may use these statistical regularities in such a way as to become faster in target search when the target appears at particular locations more frequently. In addition, this visual search pattern related to statistical regularities influences distractor suppression. Previous studies (Sauter et al. 2018; Sauter et al. 2019) have demonstrated that ignoring salient distractors occurring at particular frequent versus non-frequent locations results in less distractor interference. However, it seems that the implementation of this idea differs for different dimensions such as orientation versus color (Sauter et al. 2021).

In regard to DWA (Found and Müller 1996; Müller et al. 2009), for recent discussions, see (Liesefeld et al. 2018; Liesefeld and Müller 2019; Liesefeld and Müller 2020), the dimensional association is fundamental for the level of learnt distractor inhibition, for example the priority map with the same-dimension distractors versus a saliency map specific to the distractor dimension with different-dimension distractors (Sauter et al. 2021). Vecera et al. (2014) argue that early processing in attentional capture tasks is dominated by the stimulus-driven modality; however, the accumulation of experience leads to a shift toward goal-driven modality. In the beginning, attention is captured in an involuntary, automatic manner—biased by physical salience or reward-based selection history—whereas processing is afterward directed to task-relevant locations in a more voluntary manner (Failing & Theeuwes, 2018; Vecera et al., 2014). This demonstrates that attentional selection is characterized by quite vigorous dynamics. Involuntarily attentional capture is rapidly reoriented toward a relevant target. Prior literature suggests a process of active suppression as a possible explanation of a mechanism underlying this attentional reorientation (Sawaki & Luck, 2013). The findings of ERP studies confirmed that attention actively suppresses task-irrelevant distractors (Sawaki and Luck 2013; Neumann and DeSchepper 1991). Moreover, previous studies (Zhang et al. 2021; Sauter et al. 2018; Allenmark et al. 2019; Liesefeld and Müller 2020) have shown that the way the suppression of a likely distractor location is represented may be modulated by how distractors are defined relative to the target. For example, if a distractor and a target are in the same dimension (e.g., orientation or color) suppression appears to be implemented at a supra-dimensional level of 'attentional priority' computation, influencing both the distractor and the target in comparison with a level od dimension-specific 'feature-contrast' computation when the distractor and the target are defined through a different dimension such as the distractor-color and target-orientation. In that case, suppression influences only distractor signals (Zhang et al. 2021). Interestingly, early studies (Pollmann et al. 2000; Found and Müller 1996; Müller et al. 2003) observed 'feature-specific' intertrial effects for the color but not for the orientation, indicating the intertrials should be taken into account considering attentional selection.

The role of individual differences is underestimated. Increasing evidence demonstrates the association of selective attention with individual differences among people (e.g., personality traits, age). Compared to adults, adolescents show a prominent tendency toward attentional capture by a distractor associated with reward (Roper et al., 2014), thus suggesting that the value-driven attentional capture effect persists longer in adults. In addition, some studies (Roper et al., 2014) found that younger persons compared to older ones tend to capture attention more easily—the attentional capture effect present in both groups was nevertheless more stable over time in younger—emphasizing the importance of individual differences. Roper et al. have shown this difference cannot be attributed to age-related visual working memory capacity; hence, the assumption is this may involve some yet unknown age-related mechanisms. Luminance sensitivity varies among individuals (Gunther & Dobkins, 2002).

1.6. History-driven attentional selection

Selection history is a mechanism of attention taking place through implicit or explicit learning, a process based on previous experience according to which certain stimuli acquire a "value" causing future selection episodes to be driven by a historical component, whereas above and beyond top-down and bottom-up factors. History-driven attentional selection is not driven by the observer's goals, nor by physically salient stimuli features. A previous study (Sha and Jiang 2016) demonstrated a solid effect of history selection in the value-driven attentional capture task in such a way that participants who performed some training search for a color target (red, green) would be affected in the subsequent task when the shape-search was task relevant as we have mentioned earlier. In addition, objects may be prioritized based exclusively on previous selection history, even in case of less salient stimuli (Awh et al., 2012; Failing & Theeuwes, 2018; Theeuwes, 2018). For example, a previous study by Souter et al. (2021) demonstrated that the task-relevant target was easier to find if it appeared at a more frequent versus less frequent location, with implications in regard to distractor suppression. Thus, previous learning of the observer affects their current attentional selection. A recent neuroimaging study by Zhang et al., (2021) using the distractor-location learning paradigm by Sauter (2018) involving two-dimension distractors (orientation, color) has demonstrated that a signal in the early visual cortex is significantly reduced for the distractors and also the target that occurred in the frequent distractor locations in comparison with rare locations. In a similar behavioral study (Zhang et al. 2019) exploring the target location effect, it has been shown that learned distractor location inhibition is not based on the priority map per se, but may be implemented at a lower, dimension-based level.

In addition, an intense debate regarding attentional control has been hampered by insufficiently precise terminology; more exactly, the terms top-down and bottom-up and history differ in meaning. Namely, according to Theeuwes and Failing (2018; 2018) top-down attentional selection is defined as slow, effortful, and controlled rather than automatic and is often equated with “voluntary” or “intentional” processes, whereas selection history is fast, automatic and does not require much effort. Hence, selection history is the main characteristic of visual selective attention. Gaspelin and Luck (2018) argued that the use of the term “top-down” as equivalent to “voluntary” is not conceptually appropriate since although selection history shares common features with bottom-up selection, selection history is nevertheless a form of top-down control of selection. The mechanisms underlying history-driven selection are stimulus signaling reward, “priming” and “learning of statistical regularities” (Theeuwes 2018).

Moreover, in everyday life, some people are highly focused while performing cognitive and/or motor tasks (e.g., playing chess, driving a car), whereas others are less focused and demonstrate a tendency toward easy attentional capture by internal (e.g., anxiety thoughts) or external distractors (attractive food). What do achievement in task prioritization in more successful people and attention fluctuation in less successful ones depend on? Apart from pronounced individual differences among people, the fundamental question is whether high prioritization of a relevant task and ignoring irrelevant but salient stimuli are trained. If this is the case, the question is to what extent the ability to learn underlies the process of attention and how this reflects the attentional capture effect. A component concerning individual differences among people has been somewhat excluded from the debate on attentional selection in a top-down or bottom-up manner, including history-driven selection (Burnham 2007; Corbetta and Shulman 2002; Anderson et al. 2011). To what extent individual differences may determine attentional selection (e.g., capture) remains unclear.

2. The role of reward in attentional selection

Adaptation to external conditions is directly linked to reward-seeking behavior and avoiding punishment-based stimuli. Historically, in 1911, Thorndike revealed the ‘law of effect’ in a series of experiments using animals (Thorndike 1911), indicating that among several behavioral responses made to the same situations, those responses followed by satisfaction (i.e., reward) would be more likely to recur. Although Thorndike was interested in exploring the frequency of overt behavior using animal models, the effect of reward has been demonstrated as remarkable in humans by prioritizing selective attention toward reward (Awh et al. 2012). Stimuli associated with motivational and emotional value may influence attention, visual perception, and eye movement (Bucker et al., 2015; Mulckhuyse, 2018; Vuilleumier, 2015). In line with the principles of self-preservation, human attention is prioritized in such a way that attentional selection is driven by salient reward-based stimuli. Increasing evidence demonstrated that reward-based stimuli capture attention frequently opposed to relevant task requirements (Anderson et al., 2011; Kim & Anderson, 2020). Irrelevant distractors often capture attention when presented simultaneously with a relevant task even to the extent of possibly improving attentional performance (Sussman et al., 2013). Recently, evidence demonstrating that attentional selection may be modulated by stimuli - previously associated with motivational and emotional value - has been provided in the value-driven attention selection design (Anderson et al., 2011; Anderson & Halpern, 2017; Bourgeois et al., 2016; Goschy et al., 2014; Kim & Anderson, 2020; Vuilleumier, 2015). Attentional capture by a reward-based distractor has been shown to be rapid and involuntary (Bucker et al., 2015; Hinojosa et al., 2015; Le Pelley et al., 2015; Nissens et al., 2017; Watson et al., 2019). Le Pelley (2016) discussed whether this learned-value effect is under voluntary control (top-down) or automatic (bottom-up). This is still somewhat unclear. Anderson and Halpern (Anderson & Halpern, 2017) suggest both history-driven attentional selection and reward-learning association in the value-driven attentional capture paradigm.

However, in line with the principles of associative learning, a reward-based stimulus may belong to a wide range of positive or negative rewards (reinforcement). A growing number of psychology and neuroscience studies demonstrate a reciprocal interplay between cognition and emotion, whereas emotional information (e.g., emotional faces, words or sounds) may capture attention most directly in visual search, spatial cueing, or attentional blink tasks (Vuilleumier & Huang, 2009). Some studies have used social photographs such as facial expression of happiness in attentional blink (Miyazawa & Iwasaki, 2010) or facial expression of anger to examine attentional capture through the face in the crowd effect (Pinkham et al., 2010). Other studies (Sussman et al., 2013) have used social photographs with pleasant and unpleasant valence and low and high arousal as distractors in a dot-probe task—requiring participants to identify the color of a dot presented simultaneously with these social photographs—to examine attentional capture by emotionally salient distractors. Interestingly, attentional (i.e., behavioral) performance may even be enhanced in the presence of a low-arousal negative photograph compared to positive and neutral photographs. Positive and negative reinforcement such as shock (an aversive stimulus) have also been used to examine attentional capture by signals of threat (Mulckhuyse, 2018; Nissens et al., 2017; Schmidt et al., 2015). In general, their findings demonstrated that the display of an irrelevant distractor previously associated with fear slowed a visual search more than a distractor with no fear association. Thus, learned fear-associations have the ability to capture our attention by irrelevant distractors even when we ignore them and focus on relevant targets in the visual search task. Recent studies with the value-driven attentional capture paradigm have mainly used positive reinforcement such as monetary compensation in the association phase (Anderson et al., 2011; Le Pelley et al., 2015; Nissens et al., 2017; Watson et al., 2019). Recently, Kim and Anderson (2020) have examined a happy (positive-valence) and neutral (neutral-valence) face as a social reward in the association phase. The idea behind this approach is that faces are also a form of social reward similar to monetary compensation due to sharing the same neuronal population (Izuma et al., 2008).

2.1. Reward-based learning and selection-history in the value-driven attentional capture paradigm

There is an ongoing debate whether the attentional capture in the cue-reward association paradigms is biased toward the influence of reward or selection-history. Anderson and Halpern (2017) suggest the influence of both reward-learning association and selection-history in the value-driven attentional capture paradigm. Despite strong evidence that an irrelevant distractor, previously associated with reward, still captures attention—through prolonged reaction time in the presence of a high-value distractor compared with a low-value distractor in the non-reward phase (Anderson et al., 2011, 2013; Kim & Anderson, 2020)—this effect has not been confirmed in a prior study (Sha & Jiang, 2016). To what extent attentional capture by irrelevant distractors, previously associated with reward, reflects the actual effect of reward and to what extent this effect arises from stimuli search history remains unclear. La Pelley (2016) highlights this issue arguing that attentional capture may result from selection history. Due to intensive repetition of a stimulus feature serving as a target (e.g., a red or a green circle) in the association phase, attentional capture in the non-reward phase may only be the participant's inability to inhibit the past stimulus-set and adapt to the new stimulus set. According to this interpretation, selection-history causes attentional capture regardless of the reward magnitude or even the presence of the reward. A similar argument has been pointed out by Sha and Jiang (2016), suggesting that attentional capture by a task-irrelevant distractor may result from search history, and not from stimulus-rewards associations. In a replication study Anderson and Halpern (2017) responded to the aforementioned criticism by conducting a study without reward, suggesting afterward that attentional capture in the value-driven attention capture paradigm cannot be reduced to selection-history. Most studies (Anderson, 2015a, 2015b; Anderson, Faulkner, et al., 2013; Anderson, Laurent, et al., 2013, 2014; Anderson, Leal, et al., 2014; Anderson & Yantis, 2012; Laurent et al., 2015; Roper et al., 2014) did not include testing with no reward (control condition) in the association phase; hence, data comparing the effect with and without the use of reward-based stimuli are missing. Le Pelley (2016) proposes a simple solution for the aforementioned issue suggesting that researchers should consider only a statistically significant difference between high-value color and low-value color in trials—due to their equal appearance in the association phase—hence, this may be a valid indicator of attentional capture by a distractor previously associated with reward.

Selection history can modulate attentional capture. Some studies using a monetary reward as feedback found only differences between high-value distractor and absent-distractor, whereas not between low and high-value distractors (Roper et al., 2014). In numerous prior studies by Anderson et al. using social feedback as a reward showed no significant differences between low-value and high-value in the association phase (Anderson, 2016a, 2017; Anderson & Kim, 2018; Kim & Anderson, 2020), explaining that participants may have easily searched for two color-defined targets. In addition to the absence of an effect in the association phase, these studies frequently found no effect for accuracy in the non-reward phase, whereas significant difference regarding RTs was reported only between an absent-distractor and value-distractor (low-, and high-distractor), however, with no significant effect of difference between low and high value distractors (Anderson, 2017; Kim & Anderson, 2020). This suggests the obtained attentional capture effect may nevertheless arise from history-driven selection and not due to a distractor previously associated with a social reward. These data challenge the validity of a task for testing attentional capture that has recently been frequently used in visual attention research. An interesting visual search study by Le Pelley et al. (2015) addressed these issues using a variant of the additional singleton paradigm and eye-tracking procedure. Participants were rewarded for a correct response regarding a line orientation (vertical or horizontal) in a rhombus target; however, reward magnitude depended on the color of a singleton distractor (i.e., high-value distractor and low-value distractor), whereas distractor-absent trials were equally rewarded.

2.2. Value-driven attentional capture paradigm

In recent decades, research on reward-driven attentional selection, or reward-based learning history, has often been conducted using the value-driven attentional capture paradigm (Anderson et al. 2011). Typically, the value-driven attentional capture paradigm consists of two primary phases: the initial phase of establishing an association between the features of a neutral, however, task-relevant target stimulus (e.g., a color singleton) and a monetary (e.g., low vs. high amount of money) or social (e.g., a happy vs. neutral face) reward; and a subsequent test phase (e.g., a shape singleton) in which a previously associated stimulus is presented in the onset as a task-irrelevant distractor. In the initial phase, participants are trained to localize a color singleton (e.g., a set of 4, 6 or 8 circles) during shape-visual search and then report the orientation of a line within the circle (horizontal vs. vertical) as fast and as accurately as possible being either rewarded with a monetary (low vs. high magnitude monetary reward) or social reward (neutral vs. pleasant affective social reward) for correct responses, or omitting a reward for incorrect responses. The value-driven attentional capture paradigm integrates the principle of Pavlovian conditioning (Watson et al. 2019) or instrumental learning (Anderson and Yantis 2013;

Anderson et al. 2011) with a positive reward (a participant is rewarded for a correct but omits the reward for an incorrect response) and the principle of attentional selection in visual perception search tasks (a participant is focused on task relevant stimuli while irrelevant stimuli are ignored) in a manner of top-down search.

The value-driven attentional capture paradigm relies on the design characteristics of the additional-singleton search paradigm. The additional-singleton search paradigm, according to Theeuwes and Failing (2020), points out at least four crucial functional principles. First, the color of the distractor singleton is never the target, thus reducing the possibility for observers in the task to direct attention to the distractor, confusing it with the target. Of note, Allenmark et al., (2019) found that color swapping was a key factor for additional capture, which was in line with an early study by Müller et al. (2010) showing, for example, that the frequency of the distractor presence influences attentional capture, thus the competition between the target and the distractor in the visual task can be top-down modulated in favor of the target. Second, the observers search for a color-singleton or shape-singleton and report the orientation of a line (vertical vs. horizontal) within a circle or a diamond afterward. This is referred to as a compound search task. This procedure completely equalizes response performance in search for a target color-singleton and shape-singleton, thus resulting in conclusions concerning color and shape interference rather than response interference. Third, the target and a distractor are equally likely to appear in all parts of the visual field to prevent observers' bias toward a certain location. Fourth, the target and a distractor are displayed simultaneously to achieve the effect of a competition to capture the observer's attention. Furthermore, a typical value-driven attentional capture paradigm may have several methodological issues. In the association phase, participants initially search for a color singleton, whereas in the test phase, search for a shape-singleton, in order to report the orientation of a bar inside the target item. However, the bars in other non-target items are tilted, which deviates from the classical additional singleton search paradigm (Theeuwes, 1992): in that case participants might completely ignore the color or the shape of a singleton and complete the task relying upon the orientation. Attentional capture through an indirect path (conditioning) is possibly more difficult to establish compared to direct exposure of attractive ecological stimuli that guide our attention directly. The principles of conditioning (a neutral stimulus such as color, unconditioned emotional reaction such as exposure of a pleasant picture) are thus minimized since the key feature of the paradigm (i.e., color) has only a secondary priority in maximizing visual search performance in the tasks. The aforementioned principles of the additional-singleton are applied in the typical value-driven attentional capture paradigm.

2.3. Pavlovian conditioning versus instrumental learning in attentional capture paradigms

Since the value-driven attentional capture paradigm is crucially based on associative learning, a fundamental question is to what extent the association process and the strength of the achieved association may influence the capture effects. The issue of Pavlovian-instrumental conditioning in the value-driven attentional capture paradigm has been similarly pointed out by Le Pelley et al. (2015; 2016). Most research on the influence of rewards on the attentional capture effect has mainly used the visual search paradigm divided into the cue-reward association phase (e.g., color) / the phase of associating reward with a cue (e.g., color) and the non-reward phase (Anderson et al., 2011; Le Pelley et al., 2016). Mechanisms underlying this paradigm arise from the basic principles of associative learning and visual perception. Associative learning indicates establishing an association either between two stimuli (i.e., classical conditioning) or between behavior and stimulus/reward (i.e., instrumental learning) (Hall, 1991). In a typical instrumental (operant) learning paradigm the subject's response/ behavior becomes an instrument for obtaining a reward of different magnitude or avoiding punishment. Namely, in the value driven attentional capture paradigm in the association phase a stimulus feature (cue) is constantly paired with a reward (e.g., money) if the participant's response/behavior fulfilled a criterion set in advance in the task (e.g., identification of a horizontal or vertical line). The participant's response thus becomes an instrument for obtaining or missing a reward.

Typically, two stimuli associated with different reward magnitude are presented successively in this process; hence, the stimulus X is constantly paired with a reward of relatively large magnitude, whereas the stimulus Y is constantly paired with a reward of smaller magnitude, indicating that in this stimulus versus outcome attention is later/afterward captured more strongly by the stimulus X than the stimulus Y (Le Pelley et al., 2016). Thus, the association phase in the value-driven attentional capture paradigm uses the principles of instrumental learning more than those of Pavlovian conditioning since the participant’s response is an instrument for obtaining the reward. In a typical paradigm of Pavlovian classical conditioning, matching of two stimuli is performed: a neutral stimulus (the future “conditioned” stimulus that does not commonly elicit a response) and the unconditioned stimulus (this stimulus inherently elicits a response). In the non-reward phase, participants’ behavioral response is not related to obtaining the reward, however, a signal (high-value distractor) leads to automatic and involuntary reaction of attentional capture that is consistent with the principles of Pavlovian conditioning.

Recent studies (Bucker & Theeuwes, 2017; Le Pelley et al., 2015, 2016; Mine & Saiki, 2018; Watson et al., 2019) have confirmed that Pavlovian conditioning is sufficient for the accomplished value-driven attentional capture effect. Reward magnitude plays a key role since a high-value stimulus captures attention, whereas a low-value stimulus captures attention less strongly or there is even no such effect. It would be expected that low-value and high-value distractors capture attention equally due to equal predictiveness of positive reinforcement (Le Pelley et al., 2016); however, empirical evidence shows that reward magnitude makes a crucial difference. Is there a possibility to represent attentional capture on a discrete scale, ranging from no effect to full attentional capture effect? Perhaps, a low-magnitude reward cannot evoke even the slightest natural unconditioned response after reinforcement, hence, the process of cue-reward association cannot even occur. It has been shown no attentional capture effect in some replication studies using this paradigm (e.g., Sha and Jiang 2016). Thus, in the non-reward phase, an irrelevant distractor may not have a maximum capacity for attentional capture due to at least two significant methodological flaws related to target stimulus features in the association phase.

First, a line inside a task-irrelevant distractor in the non-reward phase is tilted, whereas horizontal or vertical in the association phase; hence, target-stimulus and distractor-stimulus features are different, whereas these features should be identical according to the principles of associative learning. Anderson et al. (2012) claim that the stimulus-reward association in the value-driven attentional capture paradigm may be generalized even to the extent of a possible generalization in the second task. A stimulus feature (e.g., color) associated with a reward in the training phase, may capture attention through generalization in a novel non-reward task only because the distractor used shares that feature, although the stimulus is not the same. Researchers have often presented a variety of the number of items in this paradigm (e.g., 6 or 8). This may be problematic given that a large set of homogeneous stimuli may modulate perception efficiency in a visual search task (Schubö et al., 2007). This may influence attentional capture to some extent.

Second, a target-stimulus feature (color) in the association phase is only a secondary aid in directing toward a primary target-stimulus, that is, the orientation of a line (horizontal or vertical). Hence, modifying the behavior of attentional selection in a visual task is essentially associated with the orientation of a line inside the target and not with the target color. Stimulus color is not primary due to serving only a discriminative function, whereas successful performance in the perception of orientation is a crucial instrument for obtaining a reward. Thus, the value-driven attentional capture paradigm is more in line with Pavlovian type of learning by classical conditioning.

3. Attentional control and anxiety

In everyday life, human perception is limited to cognitive processing of fragments from external (e.g., the physical world) and/or internal (e.g., psychophysiology) stimulation since the environment provides much more information than could be processed. Hence, goal-driven perception and action depend on attention directing limited resources of human cognition towards a selected set of relevant items (Awh et al. 2012). The literature on attention defines attentional control in terms of the dichotomy between top-down and bottom-up control (Posner 1980; Posner and Petersen 1990; Folk et al. 1992; Wolfe et al. 1989; Desimone and Duncan 1995), also referred to as 'endogenous' and 'exogenous' control (Awh et al. 2012).

Although the observer's attention is guided by current goals based on volition processes and in accordance with 'free will' (Theeuwes and Failing 2020), previous literature has provided strong evidence that internal emotional states such as fear or anxiety may influence attentional control at some point. In particular, the Attentional Control Theory (ACT) proposed that attentional control is strongly affected by anxiety. Since the emotion of fear causes immediate response to conditioned or unconditioned stimuli (Ghassemzadeh et al., 2019) by focusing the observer's attention toward a threat (Öhman et al., 2001; Vuilleumier, 2005), the emotion of anxiety results in response to distant and uncertain harm (Joseph E. LeDoux & Pine, 2016). The ACT proposes three sub-components of attentional control: inhibition, switching, and updating (Eysenck et al. 2007). The inhibition function prevents attentional resources from being distributed to task-irrelevant stimuli, i.e., inhibition is the ability to ignore distractions and focus attention on the task-relevant stimuli (Wong et al. 2013). Previous studies have demonstrated that high levels of anxiety reduce the response efficiency in the Emotional Stroop task (Reinholdt-Dunne et al. 2009), or the Go/ No-Go task (Gomez et al. 2007). Of note, recent studies (Kim et al., 2021) have demonstrated inconsistent results by finding higher efficiency of goal-directed attention under threat of electric shock, thus indicating that a threat resulting in increased anxiety may be beneficial for attention in such a way as to optimize visual search.

3.1. Neural mechanisms under attentional control: EEG approach

An abundant body of literature provides strong evidence that event-related potentials (ERPs) may reflect attentional selection such as *posterior-contralateral negativity* (N2pc). According to Luck (2014) a method to avoid overall differences between the left visual field (LVF) and the right visual field (RVF) targets and overall differences between the left and right cerebral hemispheres is creating a collapsed *contralateral waveform* (the average RVF for the left hemisphere and LVF for the right hemisphere), and a collapsed *ipsilateral waveform* (the average of LVF for the left hemisphere and RVF for the right hemisphere). Since, traditionally, electrodes such as PO7 and PO8 were considered critical for the N2pc the following formula can be used: [(PO8 – PO7 [left target]) + (PO7 – PO8 [right target])/2]).

3.2. Neural mechanisms under attentional control and effects of state anxiety

The temporospatial deployment of visual attention is behaviorally guided by top-down and bottom-up mechanisms of attention in such a way that the observer's attention may be navigated by current goals relevant for survival and well-being, whereas ignoring psychically salient stimuli that interfere with attentional selection (Dodwell et al. 2021). Selective attention as a gatekeeper of human perception is volitionally directed to relevant goals that provide survival and well-being, whereas ignoring irrelevant distractors. The priority map of attentional selection is associated with distributed neural networks including frontal, partial, and temporal lobes (Theeuwes and Failing 2020). There is assumption that top-down attention is linked with the frontal brain regions and anterior cingulate, whereas bottom-up attention linked with the early visual areas such as superior colliculus (Itti and Koch 2001). Selection history and visual statistical learning are linked with the medial temporal lobe, including the hippocampus. Interaction between these three attentional modes are defined in the priority map (Thompson and Bichot 2005).

Fundamental understanding of the association between the emotion of anxiety and attentional control would be fragmented without a critical understanding of stress since quite often anxiety is the emotional and behavioral part of stress reaction toward a stressor and the prefrontal cortex (PFC) reaction to stress. The research on the role of the prefrontal cortex and subcortical structures began during World War II. It has been shown that even the pilots who were well-trained during peacetime make serious errors in wartime in situations requiring flexibility in thinking and decision making due to the effect of stress that weakens the prefrontal cortex function (Arnsten, 2009). The PFC is the most important structure of cognitive abilities and psychic functions which is strongly influenced by emotions and emotional processes and plays the role of thought, action, and emotion regulation through a broad connection with other brain regions (Cardinal et al. 2002). The PFC is also responsible for managing new information and working memory, that is, for retaining the current event for a certain time, connecting it to long-term memory, and planning further actions by regulating behavior, thoughts, and emotions. In addition, the PCF plays a key role in the inhibition of inadequate actions, i.e., it tests the reality and monitors errors allowing adequate decision-making in accordance with the information received from the environment. The ultimate goal is the inhibition of inadequate actions and flexible regulation of behavior directed at adequate adaptation. Higher-order mental abilities controlled by the prefrontal cortex depend on the proper functioning of neural networks that are highly sensitive to the influence of stress. Even a mild effect of acute stress adversely affects the prefrontal cortex functions, whereas the chronic influence of stress may lead to structural alterations (Arnsten 2009). In the absence of stress, the prefrontal cortex functions by controlling higher-order cognitive processes and inhibiting inadequate reactions of the subcortical structures, the hypothalamus, and the amygdala. Due to the effect of stress, the subcortical circuits surrounding the amygdala take over these functions, whereas the prefrontal cortex function weakens. The biological response is directed toward rapid reaction, that is, from slow thought regulation by the prefrontal cortex and reality testing to reflexive and emotional responses of the amygdala through hypothalamic and brainstem pathways leading to the release of high levels of noradrenaline (NA) and dopamine (DA).

Chronic stress may have significant consequences on people's health both neurophysiologically and psychologically (Arnsten 2009; Hammen 2006). For example, emotionally significant experiences tend to be well remembered. The amygdala plays the most prominent role in this process. In case of a catastrophic event, the activation of the amygdala leads to coding and emotional response to the situation. A problem arises in case of a prolonged influence of stress when emotionally coded memories interpreted by the amygdala become a source of chronic anxiety (Vuilleumier 2005).

Along these lines, it seems that high-anxious individuals preferentially allocate their attentional resources to stimuli that are threat-related (Eysenck et al. 2007). Thus, the threat-related stimuli may be internal (e.g., anxious thoughts) or external (e.g., electric shock). Since neurological mechanisms underlying attentional selection involve numerous brain regions, effects of extreme stress or anxiety may affect these systems in such a way as to reduce attentional effectiveness.

3.3. Functional brain asymmetry, emotional face perception, and anxiety

Empirical evidence demonstrated that functional brain asymmetry (FBA) is related to emotional face perception. According to Ekman and Friesen's (Ekman and Friesen 1971) widely accepted observations, basic emotions include facial expressions representing emotions of happiness, surprise (positive emotions), fear, sadness, anger, and disgust (negative emotions). Facial expressions play an important role in social communication (Stanković et al. 2019). Early studies reported that processing of basic emotions is right biased in such a way that the right hemisphere (RH) would prevail the left hemisphere (LH) in emotional processing, particularly in the perception of basic facial expressions (Gainotti 2019; Gainotti 2019). This mainstream research view is known as the Right Hemisphere Hypothesis (RHH) highlighting RH structures in emotional processing. Moreover, the Valence-Specific Hypothesis (VSH) proposed that the perception of facial expressions of negative emotions such as sadness, fear, anger, and disgust are processed in the RT, whereas positive emotions such as happiness and surprise are processed in the LH (Prete et al. 2014; Canli 1999). Finally, a research view of Motivational (approach - withdrawal) Hypothesis (MH) proposes that hemispheric specialization for face perception is based on approach or withdrawal motivation. In particular, the LH is specialized for emotional face perception (happiness, surprise, anger) related to approach motivation, whereas the RH is specialized for emotional face perception (sadness, fear, disgust) (Harmon-Jones et al. 2010;

Harmon-Jones 2004). However, numerous recent studies have shown inconsistent results (Stanković and Nešić 2019; Stanković et al. 2019; Stanković et al. 2015; Prete et al. 2022). Along these lines, recent work (Stanković 2020; Stanković and Nešić 2020) proposed a hemispheric functional-equivalence model (HFE), in particular the dominance of the RH by default but with a wide range of neuropsychological networks to the LH that allows a high level of interhemispheric cooperation.

Interestingly, recent studies (Stanković and Nešić 2020) have shown that stress (e.g., state anxiety) may have an impact on hemispheric specialization for facial expression of emotions in such a way as to facilitate functional hemispheric equivalence. Since recent studies (Stojiljković and Stanković 2018; Stanković et al. 2021) have demonstrated high prevalence of stress and anxiety in healthy individuals, research questions regarding hemispheric specialization in face perception under stress condition should be examined in more detail.

4. Thesis main aims

There are three main aims in this doctoral dissertation. The first aim is to consider behavioral mechanisms, particularly the response speed and accuracy, underlying emotion-driven attentional selection modulated via reward manipulated by emotional associative learning, using a modified value-driven attentional capture paradigm. The second aim is to underscore underlying neural mechanisms of attentional capture using EEG, such as ERPs, approach with experimentally induced state anxiety. And, the third aim is to underscore underlying behavioral mechanisms related to hemispheric specialization, emotional face perception and anxiety.

The present dissertation aimed to investigate cognitive and behavioral mechanisms underlying attentional capture (e.g., distractor interference) linked with emotional associative learning, in particular: whether a task-irrelevant target color (red versus green) previously associated with either a happy or, respectively, neutral feedback face, would interfere with a visual search for a response-singleton shape target, and whether a neutral stimuli distractor (e.g., a red and a green circle), previously serving as a target and consequently conditioned with this social reward feedback, would interfere differently in visual search for a diamond amongst circle shapes on the 'distractor-present' trials. A modified value-driven attentional capture paradigm (Anderson et al. 2011) using happy and neutral facial expressions (Kim and Anderson 2020) was applied, and in addition, pleasant and neutral pictures as social feedback reward served to examine the association between emotional learning (e.g., reward) and attentional selection.

Furthermore, the present dissertation aimed to examine behavioral and neural mechanisms (ERPs) underlying attentional control under the emotion of anxiety, in particular: whether a goal-directed visual search for two targets would be influenced by experimentally induced state anxiety due to impairment/facilitation of top-down attention. In parallel, we examined whether psychological anxiety would modulate neural (e.g., mean N2pc) goal-driven attention in the dual-target visual search task due to facilitation or impairment of top-down attentional control. Moreover, we examined whether goal-directed visual search would be affected by the presence of a physically salient distractor such as a red item due to enhancement/ reduction of bottom-up attentional capture. In addition, we examined how anxiety modulates neural mechanisms (e.g., PD) in stimulus-driven attention under a physically salient distractor (i.e., a red item) due to the facilitation of bottom-up attention.

5. Cumulative thesis

Cumulative thesis includes four independent manuscripts (5.1-4).

5.1. Color-valence-driven facilitation, but no emotion-driven interference, in the "valence-driven attentional-capture paradigm"

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Color-valence-driven facilitation, but no emotion-driven interference, in the "valence-driven attentional-capture paradigm"

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Abstract

While some studies suggest that attentional capture could be driven by *emotion*-associated features, valence-dependent distractor-interference effects have proved hard to demonstrate. In three experiments, we examined the role of color and valence preference in variants of the 'valence-driven attentional-capture paradigm': an association phase, in which two alternative *target* colors, red vs. green, were paired with emotionally neutral vs. pleasant feedback photographs, was followed by a test phase requiring search for a singleton-shape target in the presence vs. absence of a task-irrelevant emotion-associated color. In the test phase, the valence-associated color was either a distractor color (Experiments 1 and 2), or a target color (Experiment 3). We failed to find any significant valence association and valence-based attentional capture with the traditional average reaction-time measures. However, we found a consistent positive correlation between individual participants' color-valence preference in the association phase and their valence-based effect in the test phase, across all three experiments. While this relationship held for all participants, the majority actually exhibited a valence preference for red over green (and vice versa for the minority), which gave rise to marked color-related asymmetries in the average measures. The valence-preferred color appeared to facilitate test performance in a spatially non-specific manner when the color appeared in a *distractor*, but (additionally or instead) positionally specifically when it appeared in the target. This suggests that, while *distractor* color signals are registered and facilitate responding, they are effectively kept out of attentional-priority computation to prevent attentional capture.

Key words: attentional capture, distractor interference, facilitation, emotional associative learning

Introduction

Human behavior – and attention – are strongly driven by reward to ensure survival and well-being. People usually direct their attention to salient and behaviorally relevant stimuli, while ignoring non-salient and irrelevant distractors. Attention plays a central role in perception, cognition, and action, by prioritizing task-relevant over irrelevant sensory information to achieve behavioral goals. However, a non-salient object may be task-relevant, placing salience and relevance into conflict. Classical theories of attention assume two basic modes of attentional selection: stimulus- and goal-driven attention (e.g., Desimone & Duncan, 1995; Müller & Rabbitt, 1989; Theeuwes, 2019; Wolfe, 2021). Goal-driven attention is considered voluntary, involving a top-down set for task-relevant information; by contrast, stimulus-driven attention is considered involuntary, such as when attention is captured (bottom-up) by physically salient stimuli that may be irrelevant to the task (i.e., that are outside the task set). Both modes of attention play an important role in individuals' adaptation to the environment, by allocating attention based on behavioral goals (the task at hand) while remaining open to new stimuli (outside the task set) which may be survival-relevant. Thus, for example, the attentional set for task-relevant stimulus features may be breached by irrelevant but salient distractors that signal a potential reward.

Value-driven attentional capture

Of note, the goal-directed attentional set may also be breached by emotional stimuli (Arnell et al., 2007), that is: emotionally salient signals may influence behavioral performance in a similar way to physically salient stimuli. Accordingly, given the interplay between cognition and emotion (Vuilleumier & Huang, 2009), emotionally important stimuli, compared to neutral stimuli, attract more attentional resources. Recently, 'selection history' itself has been suggested as a third mode of attentional selection (for reviews see Anderson et al., 2021; Awh et al., 2012; Bucker & Theeuwes, 2017; but see, Liesefeld & Müller, 2021). One particularly influential factor in history-based attentional control involves the association of target features with reward value or emotion (Anderson et al., 2011; Anderson & Halpern, 2017; Bourgeois et al., 2016; Vuilleumier, 2015). The most investigated such association concerns the pairing of monetary reward with arbitrary stimulus features, such as color (Anderson et al., 2011) or stimulus location (Schlagbauer et al., 2014), in the so-called ‘value-driven attentional-capture paradigm’ – in which a task-irrelevant but (previously) reward-associated *distractor* stimulus is shown to interfere with search for the relevant but emotionally neutral target. The typical value-driven attentional-capture paradigm (e.g. Anderson et al., 2011) is a modified version of Theeuwes’ (1992) additional-singleton search paradigm. It consists of two phases: an initial association phase and a subsequent test phase (i.e., shape-search). In the association phase, participants learn to associate certain stimulus features (e.g., red vs. green color) with monetary (e.g., a high vs. low amount of money) or social (e.g., a happy vs. neutral face) reward. Importantly, in the association phase, the rewarded feature is task-relevant: for instance, participants have to find either the single red or the single green circle in an array of heterogeneously colored non-target circles (i.e., the target is not a pop-out item; instead, search is top-down ‘template’-guided by knowledge of the potential target colors, red or green) and respond to the orientation of the bar in the red- or green-colored target, upon which they receive high or low monetary-reward feedback. In the subsequent test phase, participants search for an odd-one-out (or ‘singleton’) shape target (e.g., a diamond among circles or vice versa) and discriminate the orientation of the bar inside that shape. Critically, the reward-associated feature (e.g., color) is introduced as a task-irrelevant distractor in the test phase (e.g., a red circle). Typically, reaction time (RT) is prolonged and/or response accuracy decreased in the presence of a high-reward- relative to a low-reward-associated distractor even though both types of distractors are of similar physical salience (Anderson, 2013; Anderson et al., 2011; but see Sha & Jiang, 2016).[1] This pattern has been taken to be indicative of ‘attentional capture’ (or theoretically more neutral: ‘interference’[2]) by value-associated distractors even in the absence of reward feedback.

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[1] To what extent the physical saliency was actually equated in the relevant studies is unclear, as they did not provide the luminance of the differently colored (i.e., the target/distractor as well as the non-target) items. Uncontrolled luminance variations could have given rise to differences in physical item saliency, potentially influencing the result pattern.

[2] That is, the high-reward-associated distractor interferes more with performance than the low-reward-associated distractor, whether the differential interference occurs as a result of more frequent ‘capture of attention’ by the former distractor or some other effect, such as an increased ‘non-spatial filtering cost’ (e.g., Ferrante et al., 2018).

Emotion-driven attentional capture

Furthermore, social emotional stimuli, too, have intrinsic or learnt reward value, and the neural encoding patterns in reward-based and social learning are fundamentally similar (Behrens et al., 2008). This supports the notion of a common mechanism underlying modulations of selective attention through reward-based and social-emotional learning (Compton, 2003; Izuma et al., 2008). Stimuli previously associated with unpleasant (e.g., an angry face) or pleasant (e.g., a happy face) social feedback have been shown to modulate search performance (Anderson, 2016, 2017; Anderson & Kim, 2018; Kim & Anderson, 2020). For example, Anderson (2017) used angry and neutral faces, and Kim and Anderson (2020) happy and neutral faces in the training phase of an attentional-capture paradigm, predicting that high-valence (80% of angry/happy faces, 20% neutral faces), relative to the low-valence (20% of angry/happy faces, 80% neutral faces), feedback associations would also give rise to (greater) attentional capture (interference) in the subsequent test phase. However, both studies failed to find a significant valence-dependent modulation of distractor interference in the test phase; instead, the presence of any distractor color, whether associated with high or low-valence feedback, induced a general (rather than a differential) performance cost relative to the distractor-absent baseline condition. Presenting exclusively neutral faces as feedback in a control experiment (Experiment 2), Anderson (2017) found no attentional capture/interference of the neutral-face associated distractor (relative to the distractor-absent baseline), which they took as evidence to rule out a pure search-history or pure emotion-history effect. It should be noted, though, that the two alternative target-defining colors (red, green) in the association phase of their Experiment 2 were both followed by neutral-face feedback – so, in contrast to the typical value-driven attentional-capture paradigm, the colors did not provide predictive information about differential (e.g., high vs. low) reward outcomes. Sali et al. (2014) found no evidence of a capture effect (in the test phase) even when the two colors had been followed by the same, high reward (in the association phase) – suggesting that unique predictiveness of reward outcomes is critical for observing distractor interference. Accordingly, rather than providing grounds to reject a pure emotion-history account of the general (i.e., valence-independent) interference effect observed in his

Experiment 1, the null-result in Anderson's (2017) Experiment 2 might simply be attributable to the lack of unique reward predictiveness in what was intended as a critical control condition. Thus, it remains unclear what mechanisms underlie emotion-associated distractor interference.

Color preferences and color-emotion associations

Of note, numerous studies of value-driven attentional capture, whether they employed monetary reward (Anderson et al., 2011; Anderson & Halpern, 2017; Cho & Cho, 2021; Qi et al., 2013; Sha & Jiang, 2016) or social reward such as emotional faces (Anderson, 2016, 2017; Anderson & Kim, 2018; Kim & Anderson, 2020), exclusively used red or green as target colors in the association phase and as distractor colors in the test phase – though without presenting the associative-learning (association phase) and attentional-capture (test-phase) effects separately for the two colors paired with reward. Critically, however, recent studies (Jonauskaite, Althaus, et al., 2019; Jonauskaite et al., 2020) of color-emotion associations found, for instance, that the color red was often linked with emotions of anger or love, whereas green or purple were not systematically related with specific emotions. In general, red is preferred over green in the spontaneous selection paradigm, though this preference also appears modulable by emotional context: red is preferred over green if it is followed by a happy face but not when followed by an angry face (Maier et al., 2009). Despite the evidence for short-term modulatory influences, given such pre-established, stable color preferences and color-emotion associations, it remains unclear whether the reward-based manipulations administered in value-driven attentional-capture paradigms (which are short-term interventions by nature) work for both colors equally. For instance, for observers who have a general preference for red over green, would the association of high versus low reward with red have the same effects as the association of differential rewards with green? It might be that, for those observers, 'red' is less, or not at all, modulable by reward-based manipulations (especially manipulations involving emotional rewards) than 'green', and the opposite may be true for observers who prefer 'green' over 'red'. For this reason, associative-learning and attentional-interference effects averaged across the two colors may not turn out significant. Given this, we argue that it is important to examine the associative-learning (association phase) and attentional-capture (test-phase) effects separately for the alternative colors paired with high and, respectively, low reward.

Individual differences in emotion-driven attentional capture

Moreover, it is as yet not known to what extent the magnitude of emotion-associated distractor interference (in the test phase) depends on the *individual* strength of the previously (i.e., in the association phase) established association between a neutral stimulus (i.e., an arbitrary target color) and emotional (social) reward (e.g., a happy face). By examining only mean differences (across participants) between the reward-related (e.g., high- vs. low-valence-associated) distractor conditions in the test phase, the extant literature has tended to ignore the learning vector underlying emotion-driven attentional capture. However, one would expect the attentional-capture (interference) effect exhibited by a given observer to correlate positively with the strength of the reward association she/he acquired in the association phase, that is: participants who develop a more distinctive association of a given target color to the non-neutral (e.g., happy-face) versus the neutral (neutral-face) reward stimulus in the learning phase should show a greater difference in interference between the two types of emotion-associated distractor in the test phase. In fact, such a correlative relationship may be observable despite the absence of a mean difference: if different observers exhibit different preferences (e.g., some preferring and so acquiring stronger associations with happy relative to neutral faces, others preferring neutral over happy faces), systematic but preference-dependent associative-learning effects may be canceled out in the averaging across the individual observers. In other words, one cannot infer the absence of such a relationship from an absent mean-RT-difference effect. To test this, in the present study, we not only examined for mean, ‘group’ differences in interference between the two distractor types in the test phase, but we also conducted a correlation analysis using the individual learnt reward association in the association phase as a predictor of the differential valence-dependent capture/interference effect in the test phase.

To this end, we adopted and modified a value-driven attentional-capture paradigm (modeled after Kim & Anderson, 2020) in three experiments. Critically, in the association phase, participants were presented with facial-emotional expressions (as social feedback; Experiments 1 and 3) or, respectively, emotional scenes (Experiment 2) for them to come to associate an (originally) neutral, green versus red color stimulus with (emotionally) pleasant versus neutral feedback. In the test phases of Experiments 1 and 2, the reward-associated color was entirely task-irrelevant, as in the standard paradigm adopted from Kim and Anderson (2020). In contrast, in Experiment 3, the reward-associated color was rendered potentially task-relevant in the test phase. The happy and neutral faces were selected from the Karolinska Directed Emotional Faces inventory (Lundqvist et al., 1998), and the affective scenes from the International Affective Picture System (IAPS, Lang et al., 1997) and the Emotional picture Set (EmoPics, Wessa et al., 2010). We investigated the effects of these two types of stimuli based on a previous suggestion that facial-emotional expressions may predominantly elicit emotion perception (i.e., recognition), whereas emotional scenes, with different (low, high) arousal potential, may predominantly elicit emotional experience (Britton et al., 2006). In addition, we manipulated the arousal level of the emotional-feedback stimuli in the association phase (Experiment 2) and the exposure time of the search display in the test phase (all experiments) to foster color to emotional-reward association (with higher arousal expected to lead to better learning) and, respectively, differential attentional capture by the reward-associated color distractors (with shorter exposure times expected to lead to more pronounced interference).

Experiment 1

Experiment 1 was designed to re-examine whether a task-irrelevant color (red, green) – previously associated with a either an emotionally happy or, respectively, neutral (pleasant- vs. neutral-valence) feedback face – would interfere, and interfere differentially, with visual search for a response-critical singleton-shape target (a diamond amongst circle shapes). In Kim and Anderson’s (2020) study, the high- and low-valence emotional-face feedback did not make a difference in either search accuracy or RT in the training phase. However, in the subsequent test phase, they found evidence of distractor interference (i.e., reduced RTs performance on distractor-absent vs. -present trials), but no valence-dependent difference between the two (pleasant- and neutral-emotion-associated) distractor conditions. Of note, though, they used a relatively long (1800 ms) search-display duration in the test phase of their paradigm. Here, we tested both short- (300 ms) and long-duration (1500 ms) search displays in separate sessions. The reason for introducing short-duration displays was that valence-dependent modulations of attentional capture (interference) may be better demonstrable if task-control mechanisms are placed under stress, such as by the need to process (and respond to) the search displays rapidly. Under such conditions, when perceptual and response decision processes have to operate at speed, distractors may summon attention relatively automatically because any (reactive) control processes (Geng, 2014) to mitigate distractor interference may come into play too late to influence stimulus-driven attention allocations (see also Sauter et al., 2021). Also, saliency-based effects may be short-lived, because "salience is represented in the visual system only briefly after a visual image enters the brain" (Donk & van Zoest, 2008, p. 733). Accordingly, one would expect capture effects to be enhanced when display duration is brief (introducing speed stress), rather than long.

Potentially critically, as reviewed above, the specific colors associated with differential rewards have tended to be ignored in previous studies employing the value-driven attentional-capture paradigm (Anderson et al., 2011; 2016; 2017; Anderson & Halpern, 2017; Anderson & Kim, 2018; Kim & Anderson, 2020; Cho & Cho, 2021; Qi et al., 2013; Sha & Jiang, 2016)[3]. However, given the possibility of color-emotion interactions (e.g., Jonauskaite, Althaus, et al., 2019; Jonauskaite et al., 2020), we expressly included 'color' as a factor in our statistical analyses (even though we counterbalanced the specific color-to-valence associations across participants). As argued in the Introduction, this might reveal color-valence association effects that might remain hidden in analyses averaged across the alternative colors.

Method

Participants

A total of 36 (16 males) healthy university students (*Mean* age = 29.03, *SD* = 4.19 years) participated in Experiment 1. The number of participants was based on sample sizes employed in previous studies (Anderson, 2017; Kim & Anderson, 2020), ranging from 24 to 28 participants.

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[3] Also, the luminance of the color stimuli has typically not been reported, so that color-luminance confounds cannot be ruled out.

We increased the sample size to 36 for the online experiment. Participants were recruited through a public announcement. Exclusion criteria for participation were (self-reported) diagnosis of a neurological or psychiatric disorder, or, respectively, color blindness. Upon recruitment, detailed experimental instructions were sent to each participant via email, and then participants accessed an online (experimental) platform Pavlovia to perform the experiment. Participants signed informed consent prior to the experiment and were compensated for their service at a rate of 9 Euro per hour. The study was approved by the Ethics Board of the LMU Faculty of Psychology and Educational Sciences.

Apparatus and stimuli

We used the free open-source cross-platform PsychoPy3 (Peirce et al., 2019) for stimulus presentation and data collection, while the experiment was run via the online platform Pavlovia (https://pavlovia.org). Participants were instructed to be alone in a quiet room, adopting a viewing distance of 60 cm from the monitor. The screen size was 13.3 inches, as confirmed by all participants.

In the *training phase*, the search display consisted of a ring (radius of 5.4° at the viewing distance) of eight circles spaced equidistantly from the central fixation cross (circle: 2° in diameter), each with an oriented white bar (subtending 1.6° × 0.3°) inside. The response-relevant 'target' item was either a single green or red circle, whereas the remaining seven non-target circles were of different non-repeating (i.e., heterogeneous) colors, randomly selected from blue, yellow, cyan, magenta, silver, gray, olive, purple, teal, navy[4]. None of the non-target colors appeared twice within a given trial display. The target was equally likely to appear at any of the eight ring positions (i.e., target location was randomized across trials). The bar inside the (red or green) target circle was either vertical or horizontal, whereas the bars in the non-target circles were randomly tilted 45° to the left or the right. The feedback pictures were 58 photographs of happy faces and 58 of neutral faces (50% female and 50% male faces), selected from the

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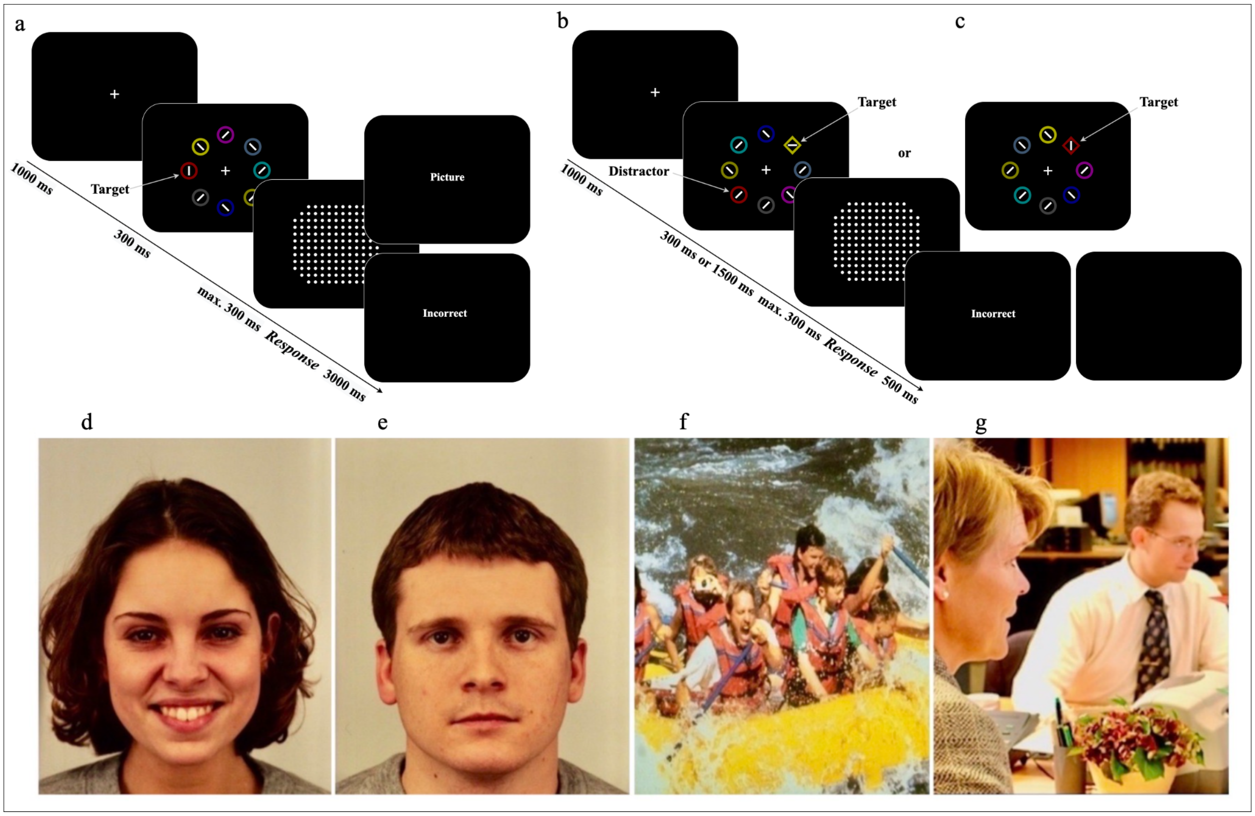
[4] The colors were adjusted to be of near-equal luminance on the local laptop used to program the experimental code. Nevertheless, given that Experiment 1 was run online, equi-luminant stimulus presentation could not be ensured on the participants' individual computers. However, in the lab-based Experiments 2 and 3, we took care to minimize any confounding luminance differences potentially contributing to physical item saleincy (see Method of Experiment 2).

Karolinska Directed Emotional Faces picture set (Lundqvist et al., 1998). Following Kim and Anderson (2020), happy (pleasant-valence) and neutral (neutral-valence) faces were used as social reward feedback for correct responses in the association phase. Happy faces are considered to be of high social-reward magnitude, as compared to (low-magnitude) neutral faces.

In the *test phase*, the search display consisted of a ring composed of seven non-target circles plus a singleton-shape diamond, the response-relevant target, in heterogeneous colors; the circle and diamond stimuli subtended 2° of visual angle, and the set of possible colors was the same as in the association phase. The bars in the non-targets were again either left- or right-tilted, and that in the target either vertical or horizontal. Importantly, while the non-target circles were of different colors, one circle could be red or green (i.e., possess the color of one of the targets in the association phase). The target was never red or green.

Procedure

Fig. 1. *The emotion-driven attentional-capture paradigm used in Experiments 1, 2 and 3.*



Note. (a) In the association phase, participants were instructed to find a (single) red or green ‘target’ circle (amongst heterogeneously colored non-target circles) and report whether the bar *inside the target circle was oriented vertically or horizontally. Upon a correct response, participants were 'rewarded' by the presentation of a pleasant (d and, respectively, f) or neutral (e and, respectively, g) photograph; an incorrect response was followed by the text message "Incorrect" and the absence of a photograph. (b) In the test phase (Experiments 1 and 2), participants were instructed to report the orientation of the bar inside the singleton diamond (i.e., shape) 'target' amongst homogeneous non-target circles, disregarding the colors of the stimuli. c) In the test phase of Experiment 3, instead of the reward-associated colors (red or green) appearing in a non-target circle (acting as 'distractors') as in Experiments 1 and 2, the singleton-diamond 'target' was red or green in two thirds of the trials; in the remaining third, none of the (target or non-target) stimuli was ever red or green. The instruction was again to ignore the item colors, as the target could be reliably detected (on all trials) only by its odd-one-out shape. Examples of (d) a pleasant-valence face (AF20HAS - happy face); (e) a neutral-valence face (AM31NES - neutral face); (f) a pleasant-valence and high-arousal scene (IAPS_8370 - Rafting); and (g) a neutral-valence and low-arousal scene (EmoPics_124 - Office), from the Karolinska Directed Emotional Faces, International Affective Picture System, and EmoPics sets.*

In the association phase (Fig. 1a), a trial started with a fixation cross (subtending 1° × 1° of visual angle) in the center of the monitor for 1000 ms. Next, a search display appeared for a duration of 300 ms, and was immediately masked by a dot mask (subtending 6.4° × 6.4°) presented for 300 ms. Participants were instructed to fixate the central cross, and, upon the onset of the search display, report the orientation of the bar inside the target circle by pressing the "J" key with their right-hand index finger for vertical or the "F" key with their left-hand index finger for horizontal, as fast and accurately as possible. Displays were presented for the full exposure duration, unless a participant issued a response prior to the full 300 ms, in which case the display was immediately terminated by the mask. A correct response was followed by the presentation of a pleasant-valence or, alternatively, a neutral-valence photograph for 3 seconds – see Fig.s 1d and 1e for examples (an incorrect response was followed by a frame displaying the message "Incorrect", also for 3 seconds). Participants were instructed to view and take-in the content of the feedback photographs. The association of the target color (either red or green) with the valence of the feedback photograph (either pleasant or neutral) was fixed for each participant, but counterbalanced across participants. The next trial began after an inter-trial interval (ITI) of 500 ms. A total of 348 trials, subdivided into four blocks of 87 trials each, were presented in the association phase. Each (neutral and happy) feedback face was displayed three times in the association phase. Trial blocks were separated by short breaks (of a length determined by the participants themselves).

After the association phase (Fig. 1b), participants took a short break before continuing with the test phase. A trial started with a fixation cross for 1000 ms in the center of the monitor, followed by a search display. In separate trial blocks, this search display was presented for either 300 ms (short-exposure block) or 1500 ms (long-exposure block) and then superseded by a 300-ms dot-mask. Both short- and long-exposure displays were presented for the full duration or until a response was made. Participants were instructed to maintain fixation on the central cross during presentation of the search display and, ignoring the color of the display items[5], to find the target diamond and report the orientation of the bar inside it by pressing the “J” key for the vertical and the “F” key for the horizontal as fast and accurately as possible. Incorrect responses were followed by the warning message “Incorrect”, presented in the screen center for 500 ms (no feedback was provided upon correct responses). The next trial began after an ITI of 500 ms.

Importantly, in half of the test trials, one of the non-target circles – referred to as ‘distractor’ – appeared in a color, either red or green, that had been associated with happy or, respectively, neutral faces in the association phase (distractor-present trials); the other half were distractor-absent trials, in which none of the non-target circles was red or green. On distractor-present trials, the emotion-associated distractor circle was equally likely red or green (i.e., the distractor color was equally likely associated with the pleasant or neutral facial emotion). The test phase consisted of four trial blocks: two blocks with short and two with long display exposure (i.e., 2 × 280 = 560 trials in total). Both the association and test phases were preceded

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[5] The ‘ignore-the-color’ instruction is typical in this type of study. So, we modeled our instruction after Anderson et al. (2011), who told their participants that “color was irrelevant to the test phase and should be ignored” (p. 10368).

by 10 practice trials, permitting participants to become familiarized with the task. Practice trials were excluded from further statistical analysis.

Data processing and statistical analysis

Practice trials, trials with response errors, and trials with RTs shorter than 150 ms or longer than 3000 ms (on average, 2% and, respectively, 2% of the total trials) were excluded from further analysis. To correct for speed-accuracy trade-offs (SATOs), we applied a 'kill-the-twin' procedure (Eriksen, 1988) for each condition (in all experiments). This procedure assumes that each incorrect response reflects a guess, where the occurrence of a correct guess is equally likely. Accordingly, for each incorrect-response trial, a correct-response trial with an RT equal, or approximately equal, to the incorrect RT (a 'twin') is removed from an individual's RT distribution (for a given condition) – effectively eliminating any SATO effect. This way, (fast) correct guesses were excluded to obtain an unconfounded picture of the non-guess RT distribution. In the analysis, we primarily focused on the SATO-corrected RT results.

Moreover, because the color-to-valence association was fixed for a given participant and counterbalanced across participants, individual differences in the general response-speed level may have had a large impact on the measurement of valence-based reward and color effects. To illustrate, suppose group A has the red (target) color associated with a happy face and the green color with a neutral face, and vice versa for group B. In addition, suppose both groups have the same target-color and valence-association effects, but differ in their individual response times (typical large variations across participants). If we plan to assess the valence-association effect for, say, the red target (which is associated with a positive emotion in one group and a neutral emotion in the other group), directly comparing the response times between two groups might be rather noisy, due to inter-individual differences in general response speed between the two groups. However, the difference can be removed by using a relative measure, i.e., relative response speed to the individual mean RT. Accordingly, in the training session, we first calculated the mean RTs for each observer and then estimated the relative response speed (relative RT) on each trial by subtracting the individual mean RT to average out the inter-individual differences ($rRT_i^{(k)} = RT_i^{(k)} - mRT_i^{(k)}$, for a given observer *k* on trial *i*). In the test session, the block(ed) factor Exposure Duration (short vs. long) of the search displays only influenced the general RT level (with short durations leading to overall faster responses than long durations, 642 ms vs. 675 ms), but did not interact with the color-valence association (see Results section below). Accordingly, we also removed this factor by subtracting the condition-block mean of the individual observer ($rRT_{b,i}^{(k)} = RT_{b,i}^{(k)} - mRT_{b,i}^{(k)}$, for a given observer *k* on trial *i* in block *b*). In addition, we calculated the relative response-speed ratio based on the relative RT and the mean RT ($ratioRT_{i}^{(k)} = rRT_{i}^{(k)}/RT_{i}^{(k)}$) as a second indicator. The analyses revealed the relative RTs and ratio RTs to yield largely comparable results. Thus, in the results section, we only report the statistics of the relative RTs, which are a time measure and so easier to understand intuitively than the ratio measure.

Data were analyzed employing analyses of variance (ANOVAs), followed up, if necessary, by paired t-tests (with Bonferroni correction for multiple comparison) or Dunnett *t*-tests to a given baseline condition. In addition, we provide Bayesian ANOVAs with default settings (i.e., r-scale fixed effects = 0.5, r-scale random effects = 1, r-scale covariates = 0.354) if it is applicable. All Bayes factors reported for main effects and interactions are “inclusion” Bayes factors calculated across matched models. Bayes factors compare models with a particular predictor to models excluding that predictor, providing a measure of the extent to which the data support inclusion of a factor in the model. Bayes factors quantify the evidence for the alternative hypothesis relative to the null hypothesis. Values below 0.33 can be taken to support the null hypothesis, whereas values greater than 3 are taken to provide strong support for the alternative hypothesis (Kass & Raftery, 1995). All statistical analyses were performed using *R* (RStudio Team, 2020).

Results

Association phase

Performance accuracy was high overall (91.2%), and highest and lowest for the red target associated with a happy and, respectively, neutral face (94.6% vs. 86.0%; green target associated with a neutral vs. a happy face: 93.1% vs. 90.5%).[6] The relatively high accuracy allowed us to apply the kill-the-twin SATO correction.

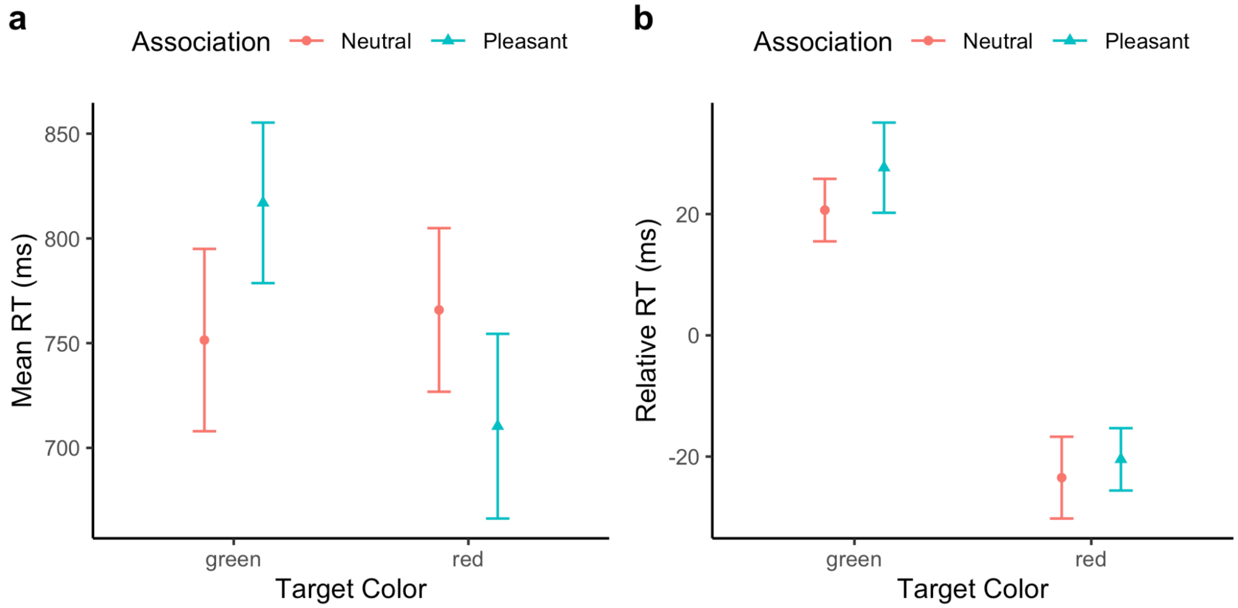

Fig. 2. *(**a**) Mean SATO-corrected RTs, and associated standard errors (SEs), for the facial-emotion feedback (happy vs. neutral face) associated with a red and, respectively, green target color. (**b**) Relative RTs, and associated SEs, for the facial-emotion feedback (happy vs. neutral face) associated with a red and, respectively, green target color. The error bars represent one SE.*

The mean SATO-corrected RT was 759 ms overall. The mean RTs for targets of the color associated with the high- and, respectively, low-valence face feedback are illustrated in Fig. 2a. Recall that the valence-color association was fixed for a given participant (i.e., participants with a red target associated with a happy face would receive a green target associated with a neutral face, and vice versa). Accordingly, the adjacent target-color bars (to the left and, respectively, right) in Fig. 2a depict RTs from different sets of participants. Accordingly, the comparison might be confounded by general differences in response speed between the two groups. Thus, to better dissociate the influences of the target color and valence associated with a given color, we first

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[6] Recall that the 'red-happy' and 'green-neutral' accuracy scores came from one group, which performed overall more accurately than the 'red-neutral' and 'green-happy' group. Given that we were not interested in absolute group differences, we did not statistically analyze these data further. As for RT performance, the kill-the-twin procedure was meant to take care of any such differences.

calculated the relative response speed for each participant for each condition. The mean relative RTs are depicted in Fig. 2b. By visual inspection, the red target was responded to generally faster (evidenced by the negative relative RT) than the green target; and for both target colors, association with a pleasant (vs. a neutral) face led to a slight slowing of response speed. A two-way ANOVA (Altman & Krzywinski, 2015) of the relative RTs with the factors Target Color (red vs. green) and Valence association (neutral vs. pleasant) confirmed a significant main effect of Target Color, $F(1, 33) = 56.47$, $p < .001$, $\eta^2_p = 0.456$, $BF_{incl} > 100$. However, neither the main effect of Valence, $F(1, 33) = 0.67$, $p = .42$, $\eta^2_p = 0.010$, $BF_{incl} = 0.314$, nor the Valence × Target-Color interaction was significant, $F(1, 33) = 0.106$, $p = .75$, $\eta^2_p = 0.002$, $BF_{incl} = 0.324$.

Thus, in the association session, red targets were generally responded to more rapidly (by 46 ms, on average) than green targets, and RTs were little influenced by whether a given target color was associated with positive or neutral emotional feedback (if anything, association with positive feedback slowed responding, though by only 2.4 ms on average).

Test phase

Response accuracy in the test phase was 90.5% overall, and comparable across all conditions (range: from 89.9% to 90.9%). A repeated-measures ANOVA of the mean RTs with the factors Distractor Valence (neutral, pleasant, absent) and Exposure Duration (short vs. long) revealed a significant main effect of Exposure Duration, $F(1, 35) = 7.03$, $p = .01$, $\eta^2_p = 0.167$, $BF_{incl} > 100$, but neither the main effect of Valence, $F(2, 70) = 1.37$, $p = .26$, $\eta^2_p = 0.038$, $BF_{incl} = 0.050$, nor the Valence × Exposure-Duration interaction, $F(2, 70) = .423$, $p = .65$, $\eta^2_p = 0.012$, $BF_{incl} = 0.025$, was significant. Given the valence effects were not modulated by Exposure Duration, we collapsed the data across this factor in the mean SATO-corrected RTs (depicted in Fig. 3a, separately for distractor-absent trials and trials with the two valence-associated color distractors) before proceeding with the analysis of the relative RTs (Fig. 3b).

Recall that the color-valence association was fixed for a given participant. Accordingly (for the reasons outlined above), analysis of the relative RTs allowed us to more appropriately separate the color- and valence-based effects in the independent-group data. As can be seen from Fig. 3b, the relative RTs were faster (by 12 ms) in the presence of a red versus a green distractor, and numerically they were slower (by 4 ms) in the presence of a positive versus a neutral emotion-associated distractor. We first compared the two distractor-present condition (green and red) against the distractor-absent baseline using a Dunnett's test, which revealed significantly slower responses in the presence of a green distractor (distractor-interference effect: 12.8 ms, p = .011), but not in the presence of a red distractor (interference effect: 1.3 ms, p = .94). Excluding the distractor-absent condition, we further conducted a two-way factorial ANOVA of the relative RTs with the factors Distractor Color (red vs. green) and Distractor Valence association (neutral vs. pleasant). This ANOVA revealed only the main effect of Distractor Color to be significant, $F(1, 33) = 4.8$, $p = .036$, $\eta^2_p = 0.069$, $BF_{incl} = 1.38$; neither the main effect of Valence, $F(1, 33) = 0.923$, $p = .34$, $\eta^2_p = 0.013$, $BF_{incl} = 0.270$, nor the Valence × Distractor-Color interaction reached significance, $F(1, 33) = 0.003$, $p = .96$, $\eta^2_p < .001$, $BF_{incl} = 0.218$. Thus, in the test session, the only statistically robust effect was that of distractor color – with green, but not red, distractors impeding search (relative to the baseline), mirroring the color effect in the association phase. While RTs were 4.4 ms slower with a pleasant- versus neutral-emotion-associated color distractor (a tendency seen for both colors), this valence-dependent modulation was not reliable.

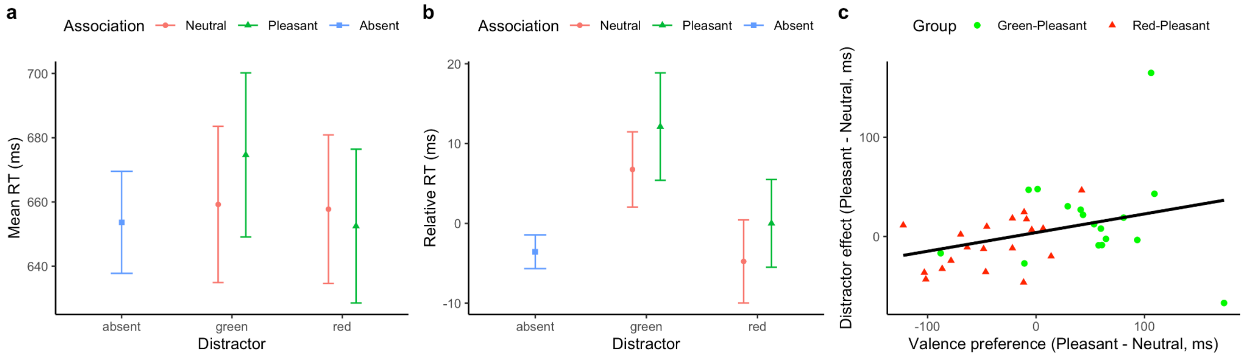

Fig. 3. *(**a**) Mean SATO-corrected RTs, and associated standard errors (SEs), for the distractor-absent baseline and the two distractor colors (green vs. red) dependent on their valence association (pleasant vs. neutral). (**b**) Relative RTs, and associated SEs, for the distractor-absent baseline and and the two distractor colors (green vs. red) dependent on their valence association (pleasant vs. neutral). (**c**) Correlation between the color-valence preference in the association phase and the distractor (interference) effect in the test phase, with the color of the individual participants' data points corresponding to two groups.*

Association/Test-phase correlation

To further examine for a correlation between color-to-emotional-reward learning in the association phase and distractor interference in the test phase, we first calculated individual observers' *color-valence preference*, defined (and measured) as the difference in relative RTs between target colors associated with pleasant minus neutral face feedback in the association phase. A positive valence-preference value indicates that the pleasant-emotion-associated color slowed responses relative to the neutral color, while a negative value indicates that the pleasant-emotion-associated color facilitated responding. Then, we correlated the individual valence-preference scores with the distractor-effect scores (i.e., the relative RT difference of the pleasant minus the neutral distractor conditions) in the test phase. Fig. 3c depicts the correlation between the valence-based reward effect in the association phase and the distractor effect in the test phase. The correlation turned out significant, $r = .33$, $p = .049$, and it was positive even when calculated separately for the two groups (pleasant-emotion associated with red vs. green). That is, participants who exhibited *slower* responses to the pleasant- versus neutral-emotion-associated target color in the association phase (53% of the participants, showing a positive 'pleasant' minus 'neutral' difference) tended to show greater *interference* by the pleasant- versus neutral-emotion-associated distractor color in the test phase; conversely, participants who responded *faster* to the pleasant- versus neutral-emotion-associated target color in the association phase (47%, showing a negative 'pleasant' minus 'neutral' difference) tended to show greater *facilitation* by the pleasant- versus neutral-emotion-associated distractor color in the test phase.

Discussion

The results of Experiment 1 showed that, in the initial association phase, the relative response speed was modulated primarily by the target color as such, with little effect of the (pleasant vs. neutral) emotional-face feedback associated with a particular target color. If anything, pleasant feedback tended to slow responses to the target (in particular for green targets), which is the opposite of what one would have expected from monetary-reward manipulations (e.g., Anderson et al., 2011). The finding of no, or at best very weak, effects of the emotional feedback manipulation on RTs to the color targets in the association phase is consistent with Kim and Anderson (2020), who also obtained no evidence of a color-to-social-reward association (though they did not examine for association effects separately for the two colors). Note, however, that the absence of a reliable effect in the association phase is not unusual in studies using social (instead of monetary) reward feedback (Anderson, 2016; Anderson & Kim, 2018; Kim & Anderson, 2020)

Furthermore, Experiment 1 failed to establish a valence-dependent modulation of attentional capture/interference (see Fig. 3b) on the level of the mean relative RTs in the test phase (numerically, pleasant-emotion associated distractors slowed responses by only 4.4 ms compared to neutral distractors, which was not significantly different). The lack of reliable differential capture/interference between high- and low-valence-associated distractors would appear to be in accord with Kim and Anderson (2017; 2020). Note though that, in contrast to the present result pattern, Kim and Anderson (2020) did find a general emotion- or search-history-related attentional-capture/interference effect: significantly prolonged RTs in the presence, versus the absence, of any (previously) reward-associated distractor. In the present experiment, no such general interference effect was observed; rather, only green, but not red, distractors gave rise to interference relative to the distractor-absent baseline (Fig. 3b).[7]

Interestingly, though, we found a positive correlation between the initial valence preference and the distractor interference effect: the longer observers ‘dwelled’ on the pleasant-emotion-associated target color in the training phase (recall, that the relative RTs tended to be longer, rather than shorter, for pleasant color), the more this color, now presented in a distractor, interfered in the test phase. This is different to the typical reward-based attentional-capture/ interference effect, where the high- reward-associated target color is detected faster in the training phase and then interferes more when introduced as a distractor color in the test phase, compared to the low-reward-associated color. Here, observers who responded faster to the pleasant- relative to the neutral-emotion-associated color in the association phase also responded faster in the test session, whereas those who responded slower to the pleasant- relative to the

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[7] The overall effect reported by Kim and Anderson (2020) may actually also have been driven by the green distractors. This could potentially be assessed in a distractor-color-dependent re-analysis of their data.

neutral-emotion-associated color in the training phase also responded slower in the test phase. That is, observers exhibited a general underlying effect that was expressed in either facilitation or interference. This general effect likely reflects the congruency between the color-valence pair assigned to a given observer in the training phase and her/his own color-valence preference. For some observers, such as people from Asian cultures, red may tend to be connoted as pleasant, whereas for others it is connoted as negative. Given that colors are evaluated based on acquired, and relatively stable, color-emotion mental representations (e.g., Jonauskaite, 2019)[8], our correlation findings can be taken to indicate that, when the color-valence pairing assigned in the training phase was congruent with participants' color-valence preference, performance was facilitated, and vice versa with incongruent pairings. The individual color-valence preferences are probably little, if at all, altered in the association phase; they are certainly not reversed by incongruent pairings. Thus, this phase can serve to identify the congruency of the color-valence pairing and with individuals' preference, rather than to establish the preference in the first instance. This preference did then carry through to the test phase, being the main factor driving the positive correlation (Fig. 3c). It should be noted that the positive correlation was not inflated by color preference per se. Both groups exhibited the same positive trend. Thus, the fact that the congruency of the color-valence pairing and participants' own preference influenced RTs in the same direction, regardless of whether the critical color item was a target or a distractor, suggests that the presence of color that fits a participant's color-valence preference may generally *facilitate* task performance.

In summary, Experiment 1 failed to find evidence of an emotional-reward-feedback-dependent modulation of attentional capture/interference by task-irrelevant distractor colors. However, rather than ruling out the existence of such a modulation, this failure may be owing to the use of facial-emotional feedback stimuli in Experiment 1. Given that emotional scenes are neuro-cognitively processed differently to facial expressions (Britton et al., 2006) and can be better manipulated on the valence and arousal dimensions, we introduced emotional scenes as

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[8] Jonauskaite (2019), in a study of 'yellow–joy' associations covering 55 countries, found that participants who live further away from the equator and also in countries with more rain are more likely to associate yellow color with the emotion of joy.

reward feedback in Experiment 2 to (re-)examine for an emotional-reward effect on attentional interference/capture.

Experiment 2

Experiment 2 was designed to examine whether socially evocative photographs would modulate attentional interference/capture through valence-associative learning. Given that arousal is the second key dimension of the emotional stimuli, we tested for valence-dependent attentional-capture/interference effects following an association phase in which the alternative colors (red and green) were paired with either high- or low-arousal scenes, in separate experimental sessions. Given that memory consolidation of perceptually encoded, task-relevant visual items is enhanced by arousal (Lee et al., 2015; Mather & Nesmith, 2008; Sutherland & Mather, 2012), we considered it important to systematically vary the arousal (high vs. low), as well as the valence (pleasant vs. neutral), values of our emotional reward-feedback stimuli. And as evoked arousal may last longer than the duration of a single trials, we manipulated the arousal level in separate sessions, thus avoiding potential contamination of the arousal state evoked by a low-arousal feedback scene on a given trial by the presentation of a high-arousal feedback scene in the preceding trial. We expected the association of a given target color to the emotional feedback scene to be enhanced in the association phase, leading to increased attentional-capture/ interference by the corresponding distractor color in the test phase, in the high-arousal, as compared to the low-arousal, session. Apart from the added arousal manipulation of the emotional-scene feedback in the association phase (a within-subject manipulation), the design of Experiment 2 was in all other respects (including the factor Exposure Time in the test phase) the same as in Experiment 1, allowing for a direct comparison.

Given that in online Experiment 1, it was not possible to ensure equal display settings across participants, in particular, as regards the color luminance, we ran Experiment 2 in the laboratory to ensure a better control of the experimental settings.

Method

Participants

A new group of 38 (15 males) healthy university students was recruited (*Mean* age = 24.71, *SD* = 2.49). Sample size was determined in the same way as in Experiment 1. Participants provided informed written consent prior to starting the experiment and were compensated for their participation at a rate of 9 Euro per hour. The experiment was approved by the Ethics Board of the LMU Faculty of Psychology and Educational Sciences.

Apparatus and stimuli

Experiment 2 was generally similar to Experiment 1, except that it was conducted in a sound-attenuated and dimly lit laboratory cabin. Participants were seated in front of the monitor, positioned at eye level, with a viewing distance at 60 cm. Stimuli were presented on a color-calibrated (120 cd/m² D65 whitepoint) 24" TFT-LCD monitor (ASUS VG248QE, screen resolution 1920 x 1080 pixels, frame rate 120 Hz). Stimulus presentation and response collection were controlled using PsychoPy3 (Peirce, 2008; Peirce et al., 2019; Peirce & MacAskill, 2018). The search displays were the same as those used in Experiment 1 – though, given that Experiment 1 was performed on-line, we had limited control over participants' monitor settings. In Experiment 2, all (differently-colored) display items appeared subjectively equally bright (as judged by the experimenters), and luminance measurements by the Chroma Meter (Konica Minolta CS-100A) revealed the item luminances to be highly similar: 15.9 cd/m² and 16.7 cd/m² for the red and, respectively, green target/distractor items, and an average of 18.7 (range: 15.2 – 22.4) cd/m² for the other, heterogeneously-colored non-target/distractor items (the black screen-background luminance was 0.14 cd/m²). Thus, the critical colors (red and green) did not stand out from the stimulus array by virtue of their luminance.

A total of 344 photographs depicting a social context (with one or more persons, selected from the IAPS (Lang et al., 1997) and EmoPics (Wessa et al., 2010), were presented as social-reward stimuli. Selection of the IAPS photo-stimuli was based on the pictures' valence (neutral, pleasant) and arousal (low, high) values, yielding four sets, each of 86 pictures: neutral / low-arousal (mean valence: 5.16, arousal: 2.87), neutral / high-arousal (mean valence: 5.62, arousal:

3.56), pleasant / low-arousal (mean valence: 6.84, arousal: 4.41), and pleasant / high-arousal (mean valence: 7.11, arousal: 5.57).

Procedure

The procedure was the same as in Experiment 1, apart from the following differences. Instead of happy and neutral emotional faces, we presented emotional scenes (pleasant- and neutral-valence social-context photos) as reward feedback in the association phase (see examples in Fig.s 1f and 1g). Furthermore, the experiment was subdivided into two separate sessions: one with low-arousal and the other with high-arousal scenes (both sessions presenting 50% pleasant and 50% neutral photos) as reward feedback in the association phase. The two sessions were separated by seven to ten days to avoid potential transfer effects, with the (low- vs. high-arousal) session order counterbalanced across participants. In particular, in the high arousal session, red color was followed by a neutral and green color by a pleasant feedback scene for 20 participants, and vice versa for the other, 17 participants; in the low arousal session, this mapping was reversed across the same participants. Thus, the association of a target color with neutral versus pleasant feedback was swapped across the high- and low-arousal sessions. None of the pleasant and neutral photographs appeared twice. Exposure time was manipulated as in Experiment 1: the search displays in the test phase were presented in short-exposure (300 ms) or long-exposure blocks (1500 ms), with search-display presentation terminated by dot-masks (presented for 300 ms).

The association phases consisted of a total of 174 trials per session (i.e., 2 x 174 = 348 trials in total), preceded by 10 practice trials. The test phases consisted of 280 short-exposure and 280 long-exposure trials (i.e., 2 × 560 = 1120 trials in total), also preceded by 10 practice trials. Given the two sessions, Experiment 2 consisted of twice as many trials as Experiment 1.

After completing the test phase of the experiment, participants rated the valence and arousal of all previously displayed photographs. The photographs were presented in random order, for an unlimited exposure duration; participants rated each photograph first on pleasure and then on arousal on a Likert-type 9-point scale: valence: 1 for very unpleasant, 9 for very pleasant; arousal: 1 for not aroused and 9 for very aroused. An ANOVA of the ratings confirmed that, by and large, our participants perceived the pictures as intended by our selection: rated valence was higher for pleasant versus neutral pictures: 7.03 vs. 5.61, $F(1, 36) = 53.65$, $p < .001$, $\eta_g^2 = 0.602$; and rated arousal was higher for high- vs. low-arousal pictures 3.67 vs. 3.12, $F(1, 36) = 5.45$, $p = .036$, $\eta_g^2 = 0.033$.[9]

Results

Association phase

The overall accuracy was 93.0%, with accuracy appearing comparable across all conditions. The mean SATO-corrected RTs are shown in Fig. 4a. Given the fact that the valence-color association was balanced across participants, relative RTs (subtracting mean RTs of individuals) would better dissociate the target-color and reward-valence effects. Fig. 4b shows the relative RTs as a function of target color and color-to-valence association. As in Experiment 1, red targets were responded to (on average, 32 ms) faster than green targets, and targets associated with the pleasant feedback were responded to numerically (by 15 ms) slower than targets associated with the neutral feedback. A two-way ANOVA revealed the main effect of Target Color to be significant, $F(1, 36) = 4.99$, $p = .032$, $\eta^2_p = 0.122$, $BF_{incl} = 62.23$, but neither the main effect of Valence, $F(1, 36) = 2.32$, $p = .136$, $\eta^2_p = 0.061$, $BF_{incl} = 0.480$, nor the Valence × Target-Color interaction, $F(1, 36) = 2.25$, $p = .142$, $\eta^2_p = 0.059$, $BF_{incl} = 0.363$, were significant. Thus, pleasant versus neutral emotional-scene feedback did not significantly modulate the RTs to the associated color-defined targets in Experiment 2; if anything, pleasant-emotion-associated colors were responded to slower (rather than faster) than neutral colors, which is similar to Experiment 1.

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[9] Their interaction was also significant, $F(1, 36) = 21.03$, $p < .001$, $\eta^2_G = 0.148$, owing to a lack of an effect of low vs. high arousal for neutral pictures (1.94 vs. 2.49, $t(1, 36) = -1.94$, $p = .382$).

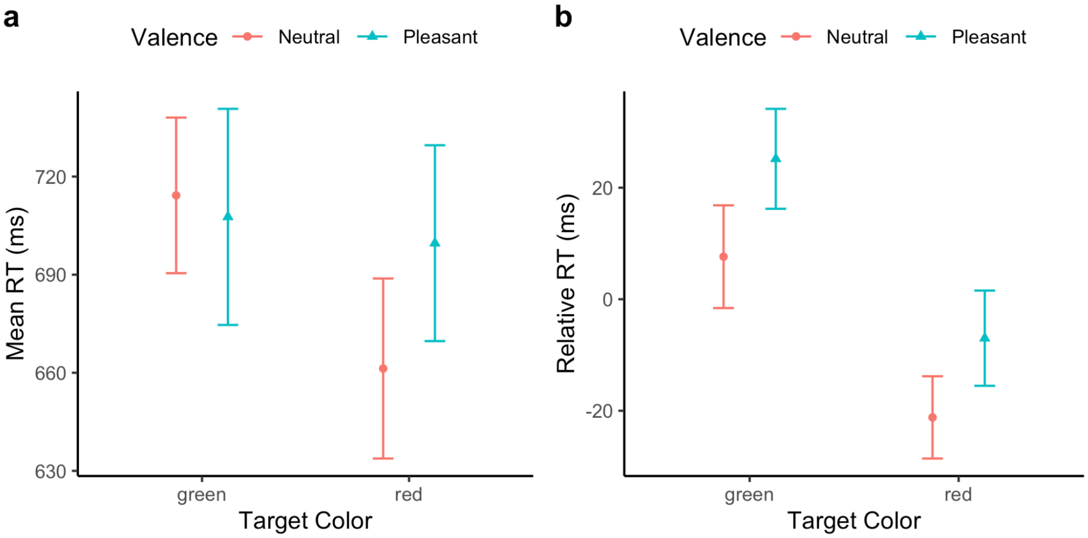

Fig. 4. *(**a**) Mean SATO-corrected RTs, and associated standard errors (SEs), for the emotional-scene feedback (pleasant vs. neutral scene) associated with a red and, respectively, green target color. (**b**) Relative RTs, and associated SEs, for the emotional-scene feedback (pleasant vs. neutral scene) associated with a red and, respectively, green target color. The error bars represent one SE.*

Test phase

With 93.3%, the overall response accuracy was relatively high in the test phase. A within-subject repeated-measures of the mean SATO-corrected RTs with the factors Arousal (High vs. Low), Distractor Valence association (pleasant, neutral, absent), and Exposure Duration (short vs. long) revealed only a significant main effect of Exposure Duration, $F(1, 36) = 6.56$, $p = .015$, $\eta^2_p = 0.01$, $BF_{incl} = 87.2$, with faster RTs to short-duration displays (mirroring the findings of Experiment 1). But there were no main effects of Arousal, $F(1,36) = 3.62$, $p = .065$ or Valence, $F(2, 72) = 1.32$, $p = .27$, and no interactions, *F*s < 1.1, *p*s > .29. Thus, to further assess the effects of color and color-valence association, we averaged the data across the Exposure-Time and Arousal factors in the mean SATA-corrected RTs (see Fig. 5a) and removed both factors from the relative RTs (see Methods section) in the following analyses (Fig. 5b).

Fig. 5a depicts the corresponding mean SATO-corrected RTs. The grand mean RT was 584 ms, and mean RTs were comparable across the distractor color and valence-association conditions (ranging from 566 ms in the neutral-red distractor condition to 602 ms in the neutral-green distractor condition). As can be seen from the mean relative RTs depicted in Fig. 5b, the results mirrored the pattern obtained in Experiment 1. Again, the presence of a green, but not a red, distractor led to a slowing of RTs relative to the distractor-absent baseline (green distractor: distractor-interference effect of 10.8 ms, [Dunnett test] p = .004; red distractor: distractor-facilitation effect of -0.3 ms, p = .99). Excluding the distractor-absent condition, a two-way repeated-measures ANOVA with the factors Distractor Color and Color-Valence association revealed only a significant main effect of Distractor Color, $F(1, 36) = 6.17$, $p = .018$, $\eta^2_p = 0.146$, $BF_{incl} = 3.92$, with RTs being overall faster (by 11 ms) with a red versus a green distractor in the test display. But there was no effect involving Valence (main effect: $F(1, 36) = 0.477$, $p = .494$, $\eta^2_p = 0.013$, $BF_{incl} = 0.189$; Valence × Distractor-Color interaction, $F(1, 36) = 0.01$, $p = .92$, $\eta^2_p < .001$, $BF_{incl} = 0.153$); that is, while RTs were some 3 ms slower with a pleasant- versus a neutral-emotion-associated color distractor (a tendency seen for both colors), this valence-dependent modulation was not reliable.

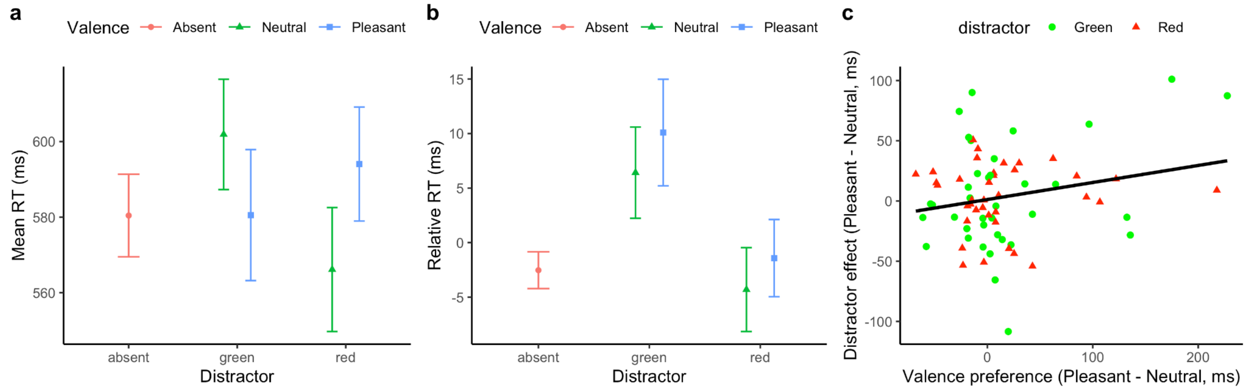

Fig. 5. *(**a**) Mean SATO-corrected RTs, and associated standard errors (SEs), for the distractor-absent baseline and the two distractor colors (green vs. red), dependent on their valence association (pleasant vs. neutral). (**b**) Relative RTs, and associated SEs, for the distractor-absent baseline and and the two distractor colors (green vs. red), dependent on their valence association (pleasant vs. neutral). (**c**) Correlation between the valence preference in the association phase and the distractor (interference) effect in the test phase, separated for the green and red distractors.*

Association/Test-phase correlation

Fig. 5c depicts the correlation between the color-valence preference in the association phase and distractor interference in the test phase. As can be seen, the pattern is similar to that observed in Experiment 1: the valence preference correlated positively (and marginally significantly) with distractor interference: r = .28, p = .09. Thus, again, participants who responded *slower* to the pleasant- versus neutral-emotion-associated target color in the association phase tended to show greater *interference* by the pleasant- versus neutral-emotion-associated distractor color in the test phase; participants who responded *faster* to the pleasant- versus neutral-emotion-associated target color in the association phase tended to show the converse effect, that is, greater *facilitation* by the pleasant- versus neutral-emotion-associated distractor color in the test phase.

Given that Experiments 1 and 2 shared essentially the same experimental paradigm, except for the type of emotional pictures presented as reward feedback in the association phase, we further combined both experiments to conduct the correlation analysis. This combined analysis yielded a statistically robust positive correlation: r = .31, p = .008.

Discussion

Similar to Experiment 1 (with used emotional-face feedback), Experiment 2 (which used emotional-scene feedback) failed to establish reliable effects of the emotional-reward valence associated with a particular target color in the association phase and the respective distractor color in the test phase. Instead, the distractor-interference/capture pattern appeared dominated by the congruency between the color-valence pairing and the individual preference participants brought along to the experiment: the presence of the valence-associated color, in a task-irrelevant distractor item, that fits to an individual participant's color-valence preference tended to facilitate performance, regardless of response speed to the red or the green color. This dissociation can be seen from Fig. 5c: the red and green distractor exhibited a similar positive correlation.

Although neither experiment yielded a significant difference in terms of mean relative response speed (i.e., RTs averaged across participants) in value-based associative learning and interference, both experiments revealed a similar, positive correlation between the color-valence preference measured in the association phase and distractor interference exhibited in the test phase: the longer participants dwelled on the pleasant- (as compared to the neutral-) emotion-associated color in the training phase, the greater its interference in the test phase. Our findings point to the in-/congruency of the color-valence pairing introduced in the association phase with individuals' color-valence preferences being the major factor in emotion-based distractor-induced interference/facilitation. These pre-established preferences dominated any short-term valence-associated learning and interference effects in the average statistics, with the underlying (preference) effects being revealed only by the correlation analysis.

Experiment 3

In the typical value-driven *attentional-capture* paradigm, the different value-associated color stimuli are presented exclusively as distractors in the test phase – that is, the colors associated with the various value levels never appear at the location of the shape-defined target (but only at non-target locations) in the test display, so as to measure their interference with target search. However, in variants of this paradigm designed specifically to examine for *emotion*-associated distractor interference, differential effects of distractor colors associated with pleasant versus neutral emotions have been hard to demonstrate (our Experiments 1 and 2 add to the failures to show such effects). In principle, though, an enhanced 'priority' signal of a value- or emotion-associated color should also be demonstrable on trials in which the color occurs at the target location. In this case, however, the enhanced color signal should combine with the signal singling out the target in the shape dimension, that is: the value-/emotion-associated color signal should combine with the shape signal, thus boosting the attentional priority of the target signal (by generating a redundancy gain driven by coactivation at the priority-map level; e.g., Krummenacher et al., 2001, 2002; 2014) and so facilitating the allocation of attention to the target location. This may be so especially when 'color' is potentially helpful in detecting and localizing the target – as opposed to when it is only distractive, as in the standard *involuntary*-attentional-capture paradigm, in which case 'color' may actually be quite effectively ignored as 'irrelevant' by top-down dimensional set (e.g., Müller et al., 2009) – also referred to as 'second-order feature suppression' by Gaspelin and Luck (2018) and Won et al. (2019). And, color might be construed as helpful, or 'relevant', if the value-/emotion-associated color is more likely to occur at the location of the (shape-defined) target, rather than that of a non-target location. On this background, we hypothesized that a valence-associated color effect may be better demonstrable under test-phase conditions in which the pleasant- versus neutral-emotion-associated colors are statistically biased to occur at the target location (as compared to when they never occur at the target location, as in Experiments 1 and 2). As social reward stimuli in the association phase, we used the same neutral- and pleasant-face photographs as in Experiment 1. For the reasons outlined above, we nevertheless expected a valence-dependent facilitation of the RTs to the target – in particular because participants have less incentive to down-modulate color processing when an emotion-associated color appears in the target, compared to when it appears in a distractor. In the latter case, even singleton signals from the (irrelevant and potentially interfering) color dimension can be relatively efficiently kept out of priority computations, especially when they occur frequently (e.g., Geyer et al., 2008; Liesefeld et al., 2019; Müller et al., 2009; Won et al., 2020).

On the other hand: if, as hypothesized (in the Discussion of Experiments 1 and 2), observers' pre-established color-valence preferences impede the formation of experimentally manipulated color-valence associations, we should not see any valence-modulated effects of the critical colors even if these occur in the target (as in Experiment 3) rather than a distractor (Experiments 1 and 2).

Method

Participants

A new group of 25 LMU-Munich students participated in Experiment 3 for monetary compensation (12 males; *mean age* = 25.46, SD = 2.79, years). Given that the large sample size in Experiments 1 and 2 yielded similar effect sizes as previous studies (significant differences between the distractor absent condition and distractor present conditions, but not between high- and low-valence conditions), we used a similar sample size of 25 as employed in the previous study (Kim & Anderson, 2020). Protocols were the same as for Experiments 1 and 2.

Apparatus and stimuli

Like Experiment 2, Experiment 3 was conducted in a sound-attenuated and dimly lit laboratory cabin, using the same monitor. The stimulus details were the same as in Experiment 1, with one critical difference in the test phase: the color of the singleton diamond (i.e., the shape) was red (33%), green (33%), or one of the other colors (i.e., equally likely blue, yellow, cyan, magenta, silver, gray, olive, purple, teal, navy; 33% in total). None of the colors appeared twice in a given trial display. Importantly, a non-target circle appeared never in the (red or green) color that had been paired with the emotional-face feedback in the association phase. The luminances of the search items were the same as in Experiment 2 (see above), with the red and green items.

Procedure

The procedure was the same as in Experiment 1, except that, in the test-phase display, the (task-relevant) target colors from the association phase (red, green) would appear, in two thirds of the trials, in the now relevant target (diamond) shape. The target was uniquely (i.e., on all trials) defined by being the only diamond shape (amongst homogeneous circle non-target shapes); that is, the color of the diamond item was as such irrelevant for performing the task (and would not possibly aid performance in one third of the trials in which it was blue, yellow, cyan, magenta, silver, gray, olive, purple, teal, or navy). Accordingly, participants were told to search for and respond to the diamond-shaped target, ignoring the colors.

Results

Association phase

Overall response accuracy was 90.4%, ranging from 86.2% for the green-neutral target to 93.4% for the red-neutral target. The mean SATO-corrected RTs are shown in Fig. 6a, and the relative mean RTs (subtracting individuals' mean RTs from their scores; see above) are depicted in Fig. 6b. As in Experiments 1 and 2, responding to the red target was (by 52 ms, on average) faster than responding to the green target, and RTs were comparable between color targets associated with pleasant and, respectively, neutral feedback (numerically, RTs were slightly, by 3 ms, shorter for pleasant- vs. neutral-emotion-associated color targets). A two-way ANOVA revealed Target-Color main effect to be significant, *F*(1, 23) = 22.13, *p* < .001, $\eta^2_p = 0.324$, $BF_{incl} > 100$, while there was no effect involving the Valence association (main effect, *F*(1, 23) = 0.25, *p* = .62, $\eta^2_p = 0.004$, $BF_{incl} = 0.291$; Valence × Target-Color interaction, *F*(1, 23) = .16, *p* = .69, $\eta^2_p = 0.002$, $BF_{incl} = 0.368$). This pattern corroborates the findings of Experiments 1 and 2.

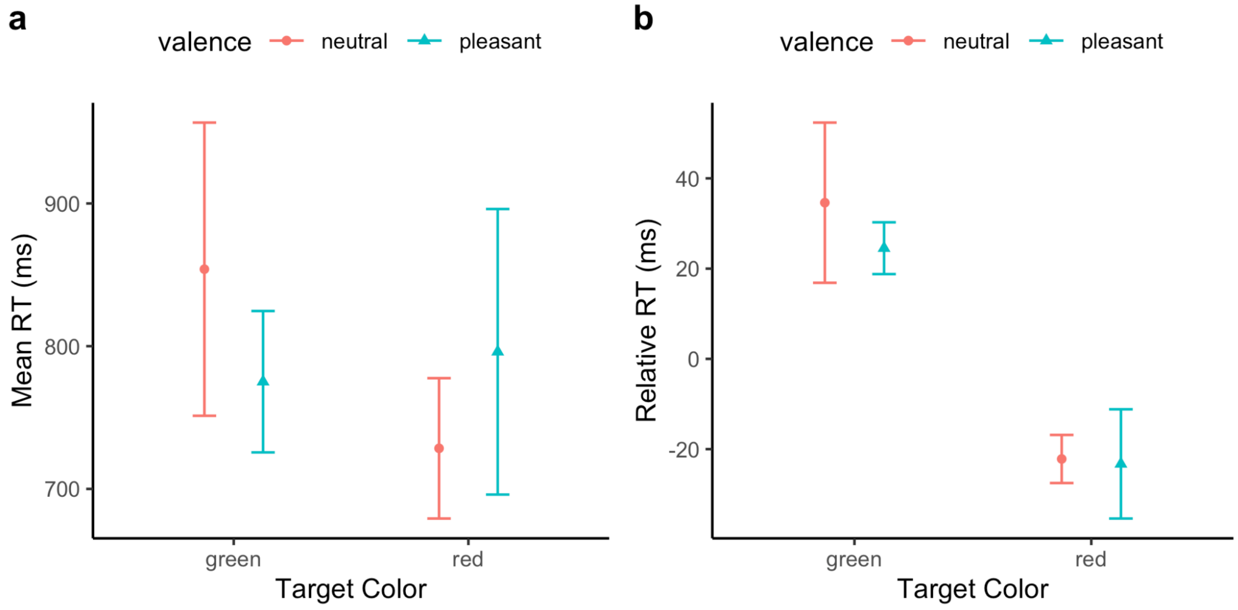

Fig. 6. ***(a)*** *Mean SATO-corrected RTs, and associated standard errors (SEs), for the facial-emotion feedback (happy vs. neutral face) associated with a red and, respectively, green target color.* (**b**) *Relative RTs, and associated SEs, for the facial-emotion feedback (happy vs. neutral face) associated with a red and, respectively, green target color. The error bars represent one SE.*

Test phase

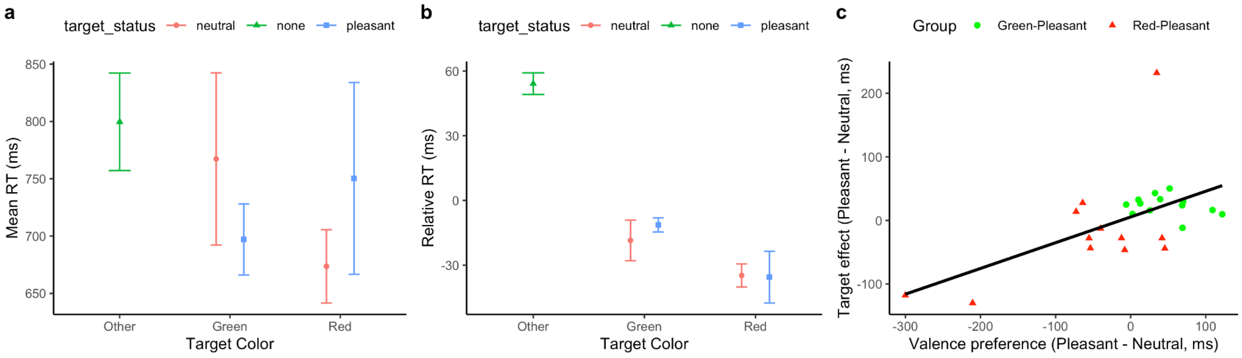

*Fig. 7 (**a**) Mean SATO-corrected RTs, and associated standard errors (SEs), for the 'other' (i.e., non-valence-associated other) target-color baseline and for the two valence-associated target colors (green vs. red) dependent on their valence association (pleasant vs. neutral). (**b**) Relative RTs, and associated SEs, for the 'other' (i.e., non-valence-associated other) target-color baseline and for the two valence-associated target colors (green vs. red) dependent on their valence association (pleasant vs. neutral). (**c**) Correlation between the color-valence preference in the association phase and the target (facilitation) effect in the test phase, with the color of the individual participants' data points corresponding to the color association in the training session.*

Overall response accuracy was 92.5% in the test phase, ranging from 90.3% for the non-associated color target to 94.3% for the neutral-red target. A repeated-measures ANOVA of the mean SATO-corrected RTs with the factors Target-Valence association (pleasant, neutral, absent) and Exposure Duration (short vs. long) yielded a significant Target-Valence main effect, $F(2, 48) = 30.31$, $p < .001$, $\eta^2_p = 0.558$, $BF_{incl} > 100$, but no effect involving Exposure Duration (main effect, $F(1, 24) = 0.47$, $p = .50$, $\eta^2_p = 0.019$, $BF_{incl} = 0.317$; Target-Valence × Exposure-Duration interaction, $F(2, 48) = .96$, $p = .388$, $\eta^2_p = 0.039$, $BF_{incl} = 0.161$). As revealed by post-hoc Bonferroni-corrected comparisons, the Target-Valence effect was due to mean RTs being slower to targets appearing in a non-associated color (800 ms) relative to targets in a valence-associated color (pleasant: 723 ms, $t(24) = 6.09$, $p < .001$; neutral: 719 ms, $t(24) = 9.02$, $p < .001$; neutral vs. pleasant, $t(24) = 0.31$, $p = .76$).

Given the absence of Exposure-Duration effects, and our focus on the effects of color and color-valence association, we averaged the data across Exposure Duration for the mean (SATO-corrected) RTs (see Fig. 7a) and removed this factor in the analysis of the relative RTs (Fig. 7b). Concerning the relative RTs, Dunnett tests revealed that, compared to the baseline of the 'other' (non-valence-associated) target color(s), both the red and green colored targets were responded to substantially faster, with facilitation effects of 69 ms and 89.3 ms for green- and red-colored targets, respectively (*p*s < .001). Interestingly, the difference in facilitation between the two valence-associated target colors, of 20 ms, in the test phase was less than half the RT difference, of 53 ms, between the two targets in the association phase, where the latter difference can be taken as a measure of the baseline preference for the red over the green color. Excluding the ‘other’-color condition, a two-way ANOVA with the factors Target Color and Valence Association revealed only the Target-Color main effect to be significant, $F(1, 23) = 4.25$, $p = .045$, $\eta^2_p = 0.085$, $BF_{incl} = 1.223$, that is, RTs to red-colored targets were faster than RTs to green-colored targets; but there were no effects involving the Valence association (main effect: $F(1, 23) = 0.11$, $p = .75$, $\eta^2_p = 0.002$, $BF_{incl} = 0.243$; Valence × Color: $F(1, 23) = 0.16$, $p = .69$, $\eta^2_p = 0.004$, $BF_{incl} = 0.227$). Accordingly, the substantial gains produced by green- and red-colored targets, including the narrowing of the difference between the association and test phases, are likely reflecting a target-history effect (e.g., Sha & Jiang, 2016) – that is, a facilitation effect deriving from the valence-associated but task-irrelevant colors having been encountered as target colors in the training phase, where this history effect is itself not modulated by the color-valence association.[10]

Association/Test-phase correlation

Despite the lack of an effect of the valence association in the averaged RTs, there was again a strong correlation between the color-valence preference in the association phase and the valence-based facilitation in the test phase ($r = .57$, $p = .003$); see Fig. 7c. Corroborating the findings of Experiments 1 and 2, this correlation is indicative of a stable (pre-established) color-valence preference that carries through from the association to the test phase of the experiment.

Note, however, that the strength of the linear relationship between the color-valence preference in the association phase and the valence-based effects in the test phase was greater in Experiment 3 (linear-regression slope [±SE]: 0.405 [±0.12]) than in Experiments 1 and 2 (0.188 [±0.09] and 0.138 [±0.08]). Multi-linear regression analysis, with the regressors Color-Valence

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[10] Some of the gains in the test phase could also be driven by intertrial priming effects (e.g., Maljkovic & Nakayama, 1994), due to red and green target colors (each of which characterized the target on ⅓ of the trials) being more likely to repeat across trials than any of the 10 alternative colors (⅓ of trials combined). Indeed, re-analysis of the data revealed cross-trial facilitation of 20 and 27 ms when the green and, respectively, the red target color repeated (vs. changed) on consecutive trials. Interestingly, however, a facilitation effect of 20 ms was also evident for the alternative colors combined (i.e., irrespective of whether the specific alternative color repeated or changed), which appeared to be treated like one color category. This makes it hard to unequivocally interpret the facilitation for the green and red colors in terms of cross-trial color-*feature* priming. In any case, such cross-trial facilitation effects could at best explain a small fraction of the gains for green and red (of some 70 and 90 ms, respectively), especially also given that color feature (or category) changes were much more likely than repetitions.

Preference and Color Condition (color-in-target [Experiment 3] vs. color-in-distractor [Experiments 1 and 2]), revealed the regression slope, as a measure of the strength of the facilitation effect, to be significantly steeper (*p* = .037) when the critical color appeared in the target (0.405) rather than a distractor (0.164).

Discussion

Experiment 3 set out to test whether any color-emotion linkage established in the association phase would facilitate performance in the test phase if the happy- or, respectively, neutral-face-associated color appears (as an irrelevant feature) in the shape-defined target. In the association phase, red targets were responded to significantly faster than green targets; but there was no significant modulation of RTs by the differential (pleasant vs. neutral) valence associated with the two colors; this pattern is consistent with Experiments 1 and 2, as well as earlier reports (Anderson, 2016; Anderson, 2017; Kim & Anderson 2020). In the test phase, RTs to the shape-defined (diamond) target were greatly expedited if it possessed one of the colors that had previously been associated with happy- or neutral-face feedback, compared to a non-associated color. This shows that a previously (in the association phase) critical and emotionally rewarded target feature boosts search performance even when this feature is rendered non-critical for performing the task, in line with a general selection-history effect (Sha & Jiang, 2016); that is, the facilitation of shape-search by the two emotional-face-associated (as compared to non-associated) colors would be due to a persistent bias in the system in favor of the previously relevant colors (irrespective of their emotional-valence association), which boosts the priority of the shape (saliency) signal (cf. Krummenacher et al., 2001, 2002). Of note, though, red-colored targets were still responded to faster than green-colored targets in the test phase, indicating that a general selection-history effect was added to by the majority of participants' color-valence preference for red.

Critically, however, the mean facilitation effect was not modulated by the emotional valence paired with the accidental target color in the association phase (i.e., it was not greater for happy- vs. neutral-face-associated colors). However, a correlation analysis between the color-valence preference in the association phase and facilitation in the test-phase revealed a significant positive relationship, consistent with the findings of Experiments 1 and 2: those who showed an RT advantage (or, respectively, disadvantage) for the happy- relative to neutral-face-associated color in the association phase also showed an advantage (or, respectively, disadvantage) in the test phase. This again is as predicted if the congruency between the color-valence pairing and individuals' preference is the major factor determining the effect pattern in the test phase.

Omnibus analysis

The sample sizes of the above three experiments were calculated based on previous studies that reported a main effect of the valence-based manipulation. Given the inconsistent findings in the extant literature, the valence-based association and attentional-interference effects may be too small to be picked up by the sample size we originally calculated. In order to check whether there would be any consistent results across experiments, we pooled Experiments 1, 2, and 3 together, which yielded the sample size of 99. This omnibus analysis was performed on the relative RTs: by removing individual differences from the absolute RTs, the relative RTs are comparable across three experiments for both the association and test phases.

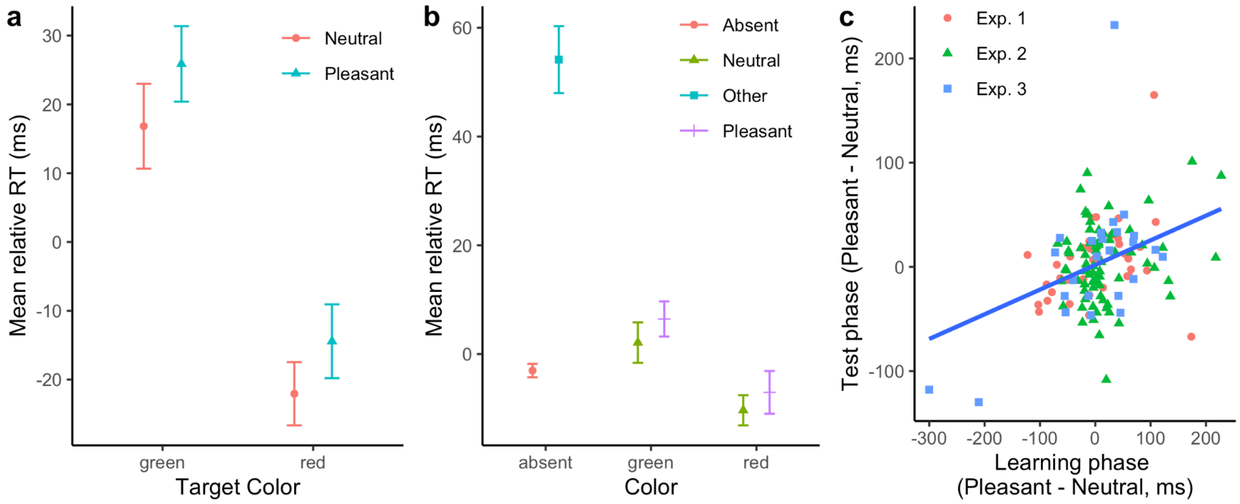

*Fig. 8 (**a**) Mean relative RTs, and associated SEs, for the training phase, collapsed across the three experiments, separately for the target color and valence association. (**b**) Mean relative RTs, and associated SEs, for the test phase, collapsed across the three experiments, separately for the distractor (Exps. 1 and 2) / target (Exp. 3) color and valence association. 'Absent' denotes the* *distractor-absent condition in Exps. 1 and 2, ‘Other’ the non-valence-associated color of the target in Exp. 3.* ***(c)*** *Correlation between the color-valence preference in the association phase and the distractor (interference; Experiments 1 and 2)/ target (facilitation; Experiment 3) effect in the test phase, with the color of the individual participants’ data points corresponding to the three experiments. The color-valence preference was calculated as the relative RT difference between the pleasant- and neutral-emotion-associated target conditions in the association phase, and the (facilitation) effect as the difference between the pleasant and neutral-emotion-associated distractor/target conditions in the test phase.*

Fig. 8a depicts the (relative) RTs as a function of the target color and the associated feedback valence in the *association* phase, showing a consistent facilitation of RTs by the red, but not the green, target color. Also, RTs tended to be somewhat slower to targets in the color associated with pleasant compared to neutral emotional feedback. However, a mixed-model ANOVA with the factors of Target Color and Color-Valence Association revealed only the Color main effect to be significant, $F(1, 270) = 51.01$, $p < .001$. The main effect of Valence Association remained non-significant, $F(1, 270) = 2.84$, $p = .093$, even with the pooled sample (of 99 participants). The Color × Valence interaction was also non-significant, $F(1, 270) = .015$, $p = .901$.

Fig. 8b depicts the attentional interference (Experiments 1 and 2)/ facilitation (Experiment 3) by the Color and Valence association in the *test* phase. Given that the (color) distractor-absent condition in Experiments 1 and 2 is different from the ‘Other’ (color) condition in Experiment 3, we restricted our analysis to the Distractor/Target Color and Valence Association deriving from the training phase. A mixed-model ANOVA of the relative RTs, with the factors Color and Valence, revealed the Color main effect to be significant, $F(1, 270) = 17.03$, $p < .001$, while there were no effects involving Valence (main effect, $F(1, 270) = 0.246$, $p = .62$; Color × Valence interaction, $F(1, 270) = .0014$, $p = .97$). Thus, again, there was a reliable effect of Color, but no Valence-relöated effect in the test phase.

Fig. 8c depicts the overall positive relationship between the color-valence preference in the association phase and the distractor (interference; Experiments 1 and 2)/ target (facilitation;

Experiment 3) effect in the test phase. The correlation analysis revealed a significant positive correlation, $r = 0.37$, $p < .001$, consistent across all three experiments.

Thus, the omnibus analysis revealed a consistent color effect and a positive correlation between the color-valence preference in the association phase and the distractor interference / target facilitation in the test phase, while any effects of the experimental color-valence association remained undetectable (in both the association and the test phases) even the increase of the sample size to 99.

General discussion

The present study aimed to re-evaluate the influence of learnt color-emotion associations in a value-driven attentional-capture (visual-search) paradigm, using happy and neutral faces (in Experiments 1 and 3) and, respectively, pleasant and neutral social-evocative pictures (in Experiment 2) as feedback stimuli in the learning (i.e., association) phase. A growing body of work employing variants of this paradigm has shown that previously neutral stimuli, such as arbitrary target colors, that are consistently followed by high-value (e.g., monetary reward feedback) in an initial association phase do later on, in a test phase in which color is task-irrelevant, interfere more with performance compared to trials on which the reward-associated color (distractor) is absent – an effect attributed to more robust attentional capture (Anderson et al., 2011; Le Pelley et al., 2015; Raymond & O'Brien, 2009; Sussman et al., 2013; Watson et al., 2019). However, there has been no consistent evidence of valence-modulated interference effects in *emotion*-associated attentional-capture paradigms that presented social-emotional (mainly face) pictures as reward stimuli in the association phase; in fact, significant valence-*dependent* attentional-capture effects turned out hard to demonstrate (e.g., Anderson, 2017; Kim & Anderson, 2020). Simple and clear manipulations of (high vs. low) monetary reward, most often signalled by written feedback (e.g., "10 cent"), would be understood in the same way by virtually all observers. In contrast, emotional photographs (e.g., of faces with a happy versus neutral expression) vary in manifold ways (e.g., gender, ethnicity, attractiveness, etc.). Even though these depictions can be summarily described on the basic emotional valence and arousal dimensions, this variability (across a range of other dimensions) may give rise to greater inter-individual variability in the color-to-emotional-reward associations that observers form in the association phase, which then impacts the valence-dependent attentional-interference/capture effects. Of note, also, what has been largely neglected in the literature is that certain colors themselves may have their own, distinct emotional associations (Jonauskaite, Althaus, et al., 2019; Jonauskaite et al., 2020; Maier et al., 2009). Yet, previous studies investigating experimentally manipulated color-emotion associations (Anderson et al., 2011; Anderson & Halpern, 2017; Cho & Cho, 2021; Qi et al., 2013; Sha & Jiang, 2016; Anderson, 2016, 2017; Anderson & Kim, 2018; Kim & Anderson, 2020) primarily used *red* and *green* as critical colors, for which pre-established associations, and subjective preferences, are likely to be particularly strong and which may therefore hamper the acquisition of any arbitrary associations meant to be formed in the experimental association phase. For instance, for some people, 'red' may be harder to associate with a positive or, respectively, neutral emotion than 'green', and vice versa for other people, so that acquired association effects may be hard to demonstrate in the data averaged across the two colors (as is typically the case in the literature). Given this, in the present experiments, albeit using the same critical colors (red and green), we set out to examine for valence-dependent modulations of attentional capture in the mean data *separately* for the two alternative colors, and under experimental conditions optimized to either acquire color-valence associations (e.g., using high-arousal feedback stimuli in the association phase) or permit attentional-capture effects to come to the fore (e.g., when having to perform the test task under speed stress, impeding distractor control processes, in the test phase). In addition to examining average data, in a correlation analysis, we determined individuals' color-valence preferences based on their performance in the association phase and examined whether this would predict the distractor-interference and, respectively, target-facilitation effects in the test phase.

Across all three experiments, in the average-based measures, we failed to find any significant emotional-feedback-dependent modulation of performance in the association phase and we found no valence-dependent modulation of either distractor-interference (Experiments 1 and 2) or target-facilitation (Experiment 3) effects in the test phase. This was the case even though we implemented conditions that were meant to be conducive for such effects to manifest, in particular: speed stress in the test phase by introducing a short (as well as a long) display exposure duration, and a high- (as well as a low-) arousal emotional-feedback condition in the association phase. Although we found RTs to be faster with brief than with long test displays, this effect of exposure duration did not interact with Valence (and we found no effects of the arousal manipulation). We conclude that any valence-dependent modulations of performance, as assessed in the average-based measures, must be rather weak (if existent at all).

However, there was a consistent color difference in the average-based measures: in the association phase, red targets were consistently responded to faster than green targets; and in the test phase, only green, but not red, distractors produced interference relative to the distractor-absent baseline condition (in which displays contained only non-associated colors) in Experiments 1 and 2, and red targets produced greater facilitation (relative to the baseline) than green targets in Experiment 3.

The comparable performance with pleasant- and neutral-valence feedback stimuli in the association phase may appear surprising, given that emotional stimuli are thought to be potent attractors of attention (Bradley et al., 2012; Dominguez-Borràs & Vuilleumier, 2013; Hinojosa et al., 2015) and preferred over neutral stimuli (Alpers, 2008; Calvo et al., 2007). Also, emotional stimuli ('distractors') have been reported to modulate the oculomotor system at an early stage of processing, attracting eye movements in an automatic and involuntary manner (Bucker et al., 2015; Le Pelley et al., 2015; Nissens et al., 2017; Watson et al., 2019). On the other hand, failures to find a color-valence association effect (i.e., faster RTs to pleasant- vs. neutral-valence-associated targets) in the association phase are actually not uncommon. That such failures appear to be particularly frequent in studies using emotional (Anderson, 2017; Anderson & Halpern, 2017; Cho & Cho, 2021; Kim & Anderson, 2020), rather than monetary, feedback may be due to large interindividual differences in how observers process, or 'respond' to, the emotional feedback stimuli. Alternatively, in contrast to monetary-reward feedback stimuli, the emotional-reward stimuli presented after the search-task response (and disappearance of the search display) may themselves be so engaging (or attention-attracting) that they are not consistently linked to the color of the search target (which, given the compound search task, is itself only search- but not directly response-relevant) in the association phase. Potentially even more importantly, observers may have relatively stable valence preferences, acquired over their lifetimes, for one over the other color, which they bring along to the experiment, and these pre-established preferences may be too strong to be modulable by the (incongruent) pairing of colors with pleasant- or neutral-emotion feedback in the association phase. In contrast, monetary-reward manipulations allow for more effective *ad-hoc* associative learning, as for most observers there would be no pre-established associations of particular colors with (high vs. low) monetary reward. For any of these reasons, it would not be surprising that we found no evidence of differential distractor interference or differential target facilitation (in terms of the mean relative RTs) between the pleasant- and neutral-valence conditions in the test phase.

Interestingly, though, one crucial finding obtained consistently across all experiments was that of a positive correlation between the color-valence preference in the association phase and the valence-related effect in the test phase, even though there were no differential effects in the average measures. Consistent with the conclusion above, the high variability evident in participants' color-valence preferences, with a near-equal spread from 'negative' to 'positive' biases (see Fig.s 3c, 5c, and 7c), suggests that the emotional-feedback manipulation was relatively weak as compared to the color-valence preference. Participants who exhibited no strong preference in a particular direction would have been shifted by the experimentally manipulated color-valence pairing in one or the other direction, but (as can be seen from the Fig.s) the data points are almost equally spread for participants near the zero preference point, and the positive correlation was mainly determined by those participants who revealed a pronounced color-valence preference (whether in the positive or negative direction) in the association phase of the experiment.

It is crucial to note that the positive correlation reflects a response-*facilitation* effect according to the in-/congruence of the color-valence preference with the emotional-feedback manipulation, rather than an *interference*, or attentional-capture, effect as found with monetary-reward manipulations (Anderson et al., 2011).[11] However, it remains unclear which processing stage(s) between attentional selection and response execution is (are) facilitated by the presence of the valence-preferred color even in a distractor. Quite possibly, the presence of such a valence-

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[11] Despite this, it appears that Anderson and colleagues did not pursue a correlation-based approach in their work on attentional capture by *emotion*-associated distractor stimuli.

preferred color is registered preattentively and provides a general boost to performance (i.e., expedites the operation of multiple stages) via activation of the (feature-unspecific) alerting system (e.g., Matthias et al., 2010; Weinbach & Henik, 2014), without giving rise to inadvertent attentional-capture if the color appears in a distractor rather than the target. The latter would be consistent with Treisman's 'feature integration theory' (cf. Treisman & Gelade, 1980), which assumes the possibility of detection without localization, that is: the presence of a (unique) feature may be registered (by some mechanism that operates spatially in parallel and pools activity across a particular feature map, e.g., the map for 'red') without giving rise to an attentional orienting, which would render the localization of this item. In Experiments 1 and 2, in which the critical color appeared invariably in a distractor (rather than the target, as in Experiment 3), orienting to color signals may have been proactively prevented by some color-based filtering mechanism (c.f. Liesefeld & Müller, 2021; Müller et al., 2009; Won et al., 2019, 2020; Zhang et al., 2021). Thus, even if the critical color did not generate a priority signal that summoned attention to its location ('attentional capture'), it may have been detected pre-attentively and triggered the emotional (color-valence) representation system, alerting the system to the presence of an emotionally/motivationally 'significant' item. This in turn might have produced a boost to the later, focal-attentional processing stages, including the analysis of the target (which, as a singleton item, does produce a strong priority signal and gets selected) for the response-relevant feature and selecting and executing the required motor response.

To justify the assumption of color-based filtering in the test phase, note that the heterogeneity of the item colors in the test display would give rise to 'spurious' local color-feature-contrast signals most likely at one or the other of the (multiple) non-target locations (e.g., Liesefeld et al., 2021)[12], which, when transferred to the priority map, may compete with the shape-driven target signal. To ensure efficient target selection in this situation, potentially distracting 'noise' signals from the color dimension may be generally suppressed or 'down-weighted', so that priority computation would be driven more or less exclusively by the shape

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[12] An example would be an item array (section) *v*-*w*-***x***-*y*-*z* in which the central (colored) item ***x*** happens to be flanked by items of a relatively distant color on the color circle. If the flankers on each side (*v*, *w*, and *y*, *z*) are similar in color, item ***x*** would produce a relatively strong local (color-) feature-contrast signal (and the immediate flankers *w* and *y* a somewhat weaker signal), due to the operation of lateral iso-feature suppression (e.g., Li, 2002).

contrast engendered by the target singleton (Liesefeld & Müller, 2021; Müller et al., 2009; Won et al., 2019, 2020; Zhang et al., 2021). Operating a strategy of color-signal suppression would be particularly beneficial to target detection if valence-preferred colors are perceptually more salient than the other colors as a result of long-term color-valence learning; for instance, the feature-coding system may have become more sensitive to valence-preferred colors, whether due to lower-level perceptual learning or to long-term-memory based biasing of the respective feature detectors. Thus, the down-scaling of color signals in the priority computation would curtail the potential of ('distractor') items appearing in the valence-preferred color to *capture attention* (due to the competition for selection being almost always resolved in favor of the unique shape signal), making it hard to demonstrate attentional-interference effects.

However, while down-weighting of color signals would arguably be beneficial when a potentially distracting, valence-preferred color invariably occurs in a 'distractor' item, it may limit performance when the critical color never occurs in a distractor, but is likely to appear in the target item instead, as in the present Experiment 3. In this case, the presence of a valence-preferred color in the target could provide a 'redundant' signal adding to the critical target (shape) signal in the computation of search priority (a "supra-dimensional" signal; e.g., Itti et al., 1998; Itti & Koch, 2000; Liesefeld & Müller, 2021; Wolfe, 2021) – expediting the allocation of attention to the response-critical item (e.g., Krummenacher et al., 2001, 2002; 2014). Thus, assuming that color signals are not down-weighted under these conditions, a differential facilitation effect by the valence-preferred (vs. the non-preferred) color would have been expected in Experiment 3. The results indeed revealed such an effect pattern, which was characterized by the highest positive correlation and the steepest regression slope in all three experiments – consistent with the idea that, in contrast to the 'distractor' Experiments 1 and 2, there was no suppression of color-saliency signals in the 'target' Experiment 3, allowing the effect of an increased saliency of the valence-preferred color ('red' for most of the observers, producing benefits of some 20 ms over above 'green') to come to the fore. This effect is likely the main factor generating the steepest regression slope in Experiment 3.

However, there was also very substantial facilitation if the target appeared in the non-preferred color ('green' for most observers). This suggests that the largest part of the facilitation is attributable to a classical search-history effect, that is, the fact that the two alternative (ie., the preferred or non-preferred) colors were target-defining in the association phase of the experiment (Sha & Jiang, 2016); in other words, owing to their target status in search history, detecting the ‘old’ red or green colored target items in the test phase was faster than the detecting the other, ‘new’ colored target items. Of note, even a search-history account would have to assume that color signals were suppressed in Experiments 1 and 2 (in which there was no evidence consistent with a search-history effect), but not in Experiment 3, and such an account would have to explain why, in Experiment 3, targets in the preferred color produced greater facilitation than those in the non-preferred color. The latter effect might be attributable to the preferred color being perceptually more salient (as a result of long-term color-valence learning), so that it adds a stronger (color) signal to the (in the test phase critical) target-*shape* signal, thereby boosting the target’s attentional selection priority. Alternatively, the color might provide a non-specific boost to target processing at multiple stages, through the same mechanism discussed above in relation to the ‘color-distractor’ Experiments 1 and 2. Further work, for instance, involving the analysis of ERP (event-related-potential) components thought to be diagnostic for pre-attentive target-selection and post-selective response-decision processes, is necessary to decide between these alternative accounts.

From a wider theoretical perspective, the color-valence effect may still be considered a kind of search-history effect, only that the acquisition of long-term color-valence associations (through lifelong learning prior to the experiment) has to be factored-in in what is meant by ‘search history’. Some theoretical accounts of attentional selection (Anderson et al., 2021; Awh et al., 2012) hold that search-history effects, including reward-based effects, form a third influence on priority computation, in addition to bottom-up and top-down influences. Some aspects of the present results would appear to challenge this notion. In particular, the influence of long-term color history is greatly reduced when a valence-preferred color appears in one of the non-targets (turning it into a ‘distractor’) as compared to when it appears in the target. As argued above, we take this to reflect the general down-weighting of color-saliency signals in the computation of attentional priority in the former, but not the latter, case. That is, long-term-history-associated distractor colors are scaled by the same suppression weight as any bottom-up-computed color-feature-contrast signal (cf. Liesefeld & Müller, 2021; Müller et al., 2009; Won et al., 2019, 2020; Zhang et al., 2021). This would not necessarily be the case if signals are contributed by an independent, 'lateral' influence on priority computation (unless one non-parsimoniously assumes that this lateral route is subject to the same down-modulations).

Conclusion

In sum, we re-investigated whether and under which conditions valence-dependent attentional interference/facilitation may be demonstrable experimentally. Our findings suggest valence-based association and interference/facilitation effects cannot be captured by the traditional averaging measures. We found no evidence of inadvertent valence-based attentional-capture effect, but rather a general valence-preferred facilitation effect likely operating via the alerting system, revealed by a consistent positive correlation between the valence-preference measured in the association phase and the valence-dependent performance modulation in the test phase, across three experiments. An effect of target selection history manifested only when the target-defining color in the association phase could appear (exclusively) in the target in the test phase, but not when it appeared in one of the non-target (i.e., the 'distractor') intem. This pattern likely reflects the suppression of color signals in the computation of attentional-selection priority in the latter case, curtailing the potential of 'distractors' to capture attention and interfere with performance. By contrast, not suppressing the previously searched for colors (along with other, spurious color signals) benefits performance when these colors appear in the target, even though they are not critical for singling out the target item. Nevertheless, while the colors reappearing in a 'distractor' were prevented from attracting an orienting response (diverting attention to a position away from the target), at least the valence-preferred color was registered by the system and caused a *facilitation* effect, where the facilitation was the greater the stronger the preference for the preferred (vs. the non-preferred color). This preference appeared to reflect stable, long-term acquired color-valence associations, which were not significantly modulated by the short-term experimental pairing of the colors with differently-valenced emotional feedback (in particular, feedback incongruent with the pre-established valence preference). This preference can itself be understood to reflect a long-term emotional-reward-history effect, enhancing the saliency of the preferred color either due to lower-level perceptual learning or to the top-down biasing by (acquired) long-term memory associations enhancing the sensitivity of the respective feature detectors.

There also appear to be a few guidelines that emerge from the present study for future work exploring for emotional-valence-modulated attentional-capture effects. In particular, future work should employ colors (other than red and green) for which observers have no strong pre-established preferences (the particular colors may have to be individualized for particular observers, rather than using the same colors for all observers). Use of such colors allow the effects of short-term valence-based manipulations to become demonstrable. Alternatively, one may focus on participants who do not show a strong preference for one or the other pre-selected (and across observers) fixed colors. Whichever approach is chosen, there appears a need for establishing observers' color-valence preferences prior to (or in any case: independently of) the experimental association phase (e.g., by means of appropriate psychometric tests), perhaps assessing both stable 'trait' measures as well as momentary 'state' fluctuations, both of which may impact the effects of the experimental color-valence manipulation.

Data

All data have been made publicly available at the Open Science Framework (OSF) and can be accessed at https://osf.io/4jgq2/?view_only=eaf6b5c89eeb44cfbddd8880dfcd389b.

References

Alpers, G. W. (2008). Eye-catching: right hemisphere attentional bias for emotional pictures. *Laterality*, *13*(2), 158–178.

Altman, N., & Krzywinski, M. (2015). Split plot design. *Nature Methods*, *12*(3), 165–166.

Anderson, B. A. (2013). A value-driven mechanism of attentional selection. *Journal of Vision*, *13*(3).

Anderson, B. A. (2016). Social reward shapes attentional biases. In *Cognitive Neuroscience* (Vol. 7, Issues 1-4, pp. 30–36). https://doi.org/10.1080/17588928.2015.1047823

Anderson, B. A. (2017). Counterintuitive effects of negative social feedback on attention. *Cognition & Emotion*, *31*(3), 590–597.

Anderson, B. A., & Halpern, M. (2017). On the value-dependence of value-driven attentional capture. *Attention, Perception & Psychophysics*, *79*(4), 1001–1011.

Anderson, B. A., & Kim, H. (2018). Relating attentional biases for stimuli associated with social reward and punishment to autistic traits. *Collabra: Psychology*, *4*(1). https://www.collabra.org/articles/119/

Anderson, B. A., Kim, H., Kim, A. J., Liao, M.-R., Mrkonja, L., Clement, A., & Grégoire, L. (2021). The Past, Present, and Future of Selection History. *Neuroscience and Biobehavioral Reviews*. https://doi.org/10.1016/j.neubiorev.2021.09.004

Anderson, B. A., Laurent, P. A., & Yantis, S. (2011). Value-driven attentional capture. *Proceedings of the National Academy of Sciences of the United States of America*, *108*(25), 10367–10371.

Arnell, K. M., Killman, K. V., & Fijavz, D. (2007). Blinded by emotion: target misses follow attention capture by arousing distractors in RSVP. *Emotion* , *7*(3), 465–477.

Awh, E., Belopolsky, A. V., & Theeuwes, J. (2012). Top-down versus bottom-up attentional control: a failed theoretical dichotomy. *Trends in Cognitive Sciences*, *16*(8), 437–443.

Behrens, T. E. J., Hunt, L. T., Woolrich, M. W., & Rushworth, M. F. S. (2008). Associative learning of social value. *Nature*, *456*(7219), 245–249.

Bourgeois, A., Chelazzi, L., & Vuilleumier, P. (2016). How motivation and reward learning modulate selective attention. *Progress in Brain Research*, *229*, 325–342.

Bradley, M. M., Keil, A., & Lang, P. J. (2012). Orienting and emotional perception: facilitation, attenuation, and interference. *Frontiers in Psychology*, *3*, 493.

Britton, J. C., Taylor, S. F., Sudheimer, K. D., & Liberzon, I. (2006). Facial expressions and complex IAPS pictures: common and differential networks. *NeuroImage*, *31*(2), 906–919.

Bucker, B., Belopolsky, A. V., & Theeuwes, J. (2015). Distractors that signal reward attract the eyes. *Visual Cognition*, *23*(1-2), 1–24.

Bucker, B., & Theeuwes, J. (2017). Pavlovian reward learning underlies value driven attentional capture. In *Attention, Perception, & Psychophysics* (Vol. 79, Issue 2, pp. 415–

428). https://doi.org/10.3758/s13414-016-1241-1

Calvo, M. G., Nummenmaa, L., & Hyönä, J. (2007). Short Article: Emotional and Neutral Scenes in Competition: Orienting, Efficiency, and Identification. *The Quarterly Journal of Experimental Psychology*, *60*(12), 1585–1593.

Cho, S. A., & Cho, Y. S. (2021). Uncertainty modulates value-driven attentional capture. *Attention, Perception & Psychophysics*, *83*(1), 142–155.

Compton, R. J. (2003). The Interface Between Emotion and Attention: A Review of Evidence from Psychology and Neuroscience. *Behavioral and Cognitive Neuroscience Reviews*, *2*(2), 115–129.

Desimone, R., & Duncan, J. (1995). Neural mechanisms of selective visual attention. *Annual Review of Neuroscience*, *18*, 193–222.

Dominguez-Borràs, J., & Vuilleumier, P. (2013). *Affective biases in attention and perception*. https://psycnet.apa.org/record/2013-03691-014

Donk, M., & van Zoest, W. (2008). Effects of salience are short-lived. *Psychological Science*, *19*(7), 733–739.

Eriksen, C. W. (1988). A source of error in attempts to distinguish coactivation from separate activation in the perception of redundant targets. *Perception & Psychophysics*, *44*(2), 191–193.

Ferrante, O., Patacca, A., Di Caro, V., Della Libera, C., Santandrea, E., & Chelazzi, L. (2018). Altering spatial priority maps via statistical learning of target selection and distractor filtering. *Cortex; a Journal Devoted to the Study of the Nervous System and Behavior*, *102*, 67–95.

Gaspelin, N., & Luck, S. J. (2018). Distinguishing among potential mechanisms of singleton suppression. *Journal of Experimental Psychology. Human Perception and Performance*, *44*(4), 626–644.

Geng, J. J. (2014). Attentional Mechanisms of Distractor Suppression. *Current Directions in Psychological Science*, *23*(2), 147–153.

Geyer, T., Müller, H. J., & Krummenacher, J. (2008). Expectancies modulate attentional capture by salient color singletons. *Vision Research*, *48*(11), 1315–1326.

Hinojosa, J. A., Mercado, F., Albert, J., Barjola, P., Peláez, I., Villalba-García, C., & Carretié, L. (2015). Neural correlates of an early attentional capture by positive distractor words. *Frontiers in Psychology*, *6*, 24.

Itti, L., & Koch, C. (2000). A saliency-based search mechanism for overt and covert shifts of visual attention. *Vision Research*, *40*(10-12), 1489–1506.

Itti, L., Koch, C., & Niebur, E. (1998). A model of saliency-based visual attention for rapid scene analysis. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, *20*(11), 1254–1259.

Izuma, K., Saito, D. N., & Sadato, N. (2008). Processing of social and monetary rewards in the human striatum. *Neuron*, *58*(2), 284–294.

Jonauskaite, D., Abdel-Khalek, A. M., Abu-Akel, A., Al-Rasheed, A. S., Antonietti, J.-P., Ásgeirsson, Á. G., Atitsogbe, K. A., Barma, M., Barratt, D., Bogushevskaya, V., Bouayed Meziane, M. K., Chamseddine, A., Charernboom, T., Chkonia, E., Ciobanu, T., Corona, V., Creed, A., Dael, N., Daouk, H., … Mohr, C. (2019). The sun is no fun without rain: Physical environments affect how we feel about yellow across 55 countries. *Journal of Environmental Psychology*, *66*, 101350.

Jonauskaite, D., Althaus, B., Dael, N., Dan-Glauser, E., & Mohr, C. (2019). What color do you feel? Color choices are driven by mood. *Color Research and Application*, *44*(2), 272–284.

Jonauskaite, D., Parraga, C. A., Quiblier, M., & Mohr, C. (2020). Feeling Blue or Seeing Red? Similar Patterns of Emotion Associations With Colour Patches and Colour Terms. *I-Perception*, *11*(1), 2041669520902484.

Kass, R. E., & Raftery, A. E. (1995). Bayes Factors. *Journal of the American Statistical Association*, *90*(430), 773–795.

Kim, A. J., & Anderson, B. A. (2020). Neural correlates of attentional capture by stimuli previously associated with social reward. *Cognitive Neuroscience*, *11*(1-2), 5–15.

Krummenacher, J., & Müller, H. J. (2014). Visual search for singleton targets redundantly defined in two feature dimensions: Coactive processing of color-motion targets? *Journal of Experimental Psychology. Human Perception and Performance*, *40*(5), 1926–1939.

Krummenacher, J., Müller, H. J., & Heller, D. (2002). Visual search for dimensionally redundant pop-out targets: parallel-coactive processing of dimensions is location specific. *Journal of Experimental Psychology. Human Perception and Performance*, *28*(6), 1303–1322.

Krummenacher, Müller, H. J., & Heller, D. (2001). Visual search for dimensionally redundant pop-out targets: evidence for parallel-coactive processing of dimensions. *Perception & Psychophysics*, *63*(5), 901–917.

Lang, P. J., Bradley, M. M., Cuthbert, B. N., & Others. (1997). International affective picture system (IAPS): Technical manual and affective ratings. *NIMH Center for the Study of Emotion and Attention*, *1*, 39–58.

Le Pelley, M. E., Pearson, D., Griffiths, O., & Beesley, T. (2015). When goals conflict with values: counterproductive attentional and oculomotor capture by reward-related stimuli. *Journal of Experimental Psychology. General*, *144*(1), 158–171.

Liesefeld, H. R., & Müller, H. J. (2021). Modulations of saliency signals at two hierarchical levels of priority computation revealed by spatial statistical distractor learning. *Journal of Experimental Psychology: General*, *150*(4), 710.

Liesefeld, H. R., Liesefeld, A. M., & Müller, H. J. (2021). Attentional capture: An ameliorable side-effect of searching for salient targets. *Visual Cognition*, *29*(9), 600-603.

Liesefeld, H. R., Liesefeld, A. M., & Müller, H. J. (2019). Distractor-interference reduction is dimensionally constrained. *Visual Cognition*, *27*(3-4), 247–259.

Li, Z. (2002). A saliency map in primary visual cortex. In *Trends in Cognitive Sciences* (Vol. 6, Issue 1, pp. 9–16). https://doi.org/10.1016/s1364-6613(00)01817-9

Lundqvist, D., Flykt, A., & Öhman, A. (1998). The Karolinska directed emotional faces (KDEF). *CD ROM from Department of Clinical Neuroscience, Psychology Section, Karolinska Institutet*, *91*(630), 2–2.

Maier, M. A., Barchfeld, P., Elliot, A. J., & Pekrun, R. (2009). Context specificity of implicit preferences: the case of human preference for red. *Emotion* , *9*(5), 734–738.

Maljkovic, V., & Nakayama, K. (1994). Priming of pop-out: I. Role of features. *Memory & Cognition*, *22*(6), 657–672.

Matthias, E., Bublak, P., Müller, H. J., Schneider, W. X., Krummenacher, J., & Finke, K. (2010). The influence of alertness on spatial and nonspatial components of visual attention. *Journal of Experimental Psychology. Human Perception and Performance*, *36*(1), 38–56.

Müller, Geyer, T., Zehetleitner, M., & Krummenacher, J. (2009). Attentional capture by salient color singleton distractors is modulated by top-down dimensional set. *Journal of Experimental Psychology. Human Perception and Performance*, *35*(1), 1–16.

Müller, H. J., & Rabbitt, P. M. (1989). Reflexive and voluntary orienting of visual attention: time course of activation and resistance to interruption. *Journal of Experimental Psychology. Human Perception and Performance*, *15*(2), 315–330.

Nissens, T., Failing, M., & Theeuwes, J. (2017). People look at the object they fear: oculomotor capture by stimuli that signal threat. *Cognition & Emotion*, *31*(8), 1707–1714.

Peirce. (2008). Generating Stimuli for Neuroscience Using PsychoPy. *Frontiers in Neuroinformatics*, *2*, 10.

Peirce, Gray, J. R., Simpson, S., MacAskill, M., Höchenberger, R., Sogo, H., Kastman, E., & Lindeløv, J. K. (2019). PsychoPy2: Experiments in behavior made easy. *Behavior Research Methods*, *51*(1), 195–203.

Peirce, & MacAskill, M. (2018). *Building Experiments in PsychoPy*. SAGE.

Qi, S., Zeng, Q., Ding, C., & Li, H. (2013). Neural correlates of reward-driven attentional capture in visual search. *Brain Research*, *1532*, 32–43.

Raymond, J. E., & O’Brien, J. L. (2009). Selective visual attention and motivation: the consequences of value learning in an attentional blink task. *Psychological Science*, *20*(8), 981–988.

RStudio Team (2020). RStudio: Integrated Development Environment for R. RStudio, PBC, Boston, MA URL. http://www.rstudio.com/

Sali, A. W., Anderson, B. A., & Yantis, S. (2014). The role of reward prediction in the control of attention. *Journal of Experimental Psychology. Human Perception and Performance*, *40*(4), 1654–1664.

Sauter, M., Hanning, N. M., Liesefeld, H. R., & Müller, H. J. (2021). Post-capture processes contribute to statistical learning of distractor locations in visual search. *Cortex; a Journal*

Devoted to the Study of the Nervous System and Behavior, *135*, 108–126.

Schlagbauer, B., Geyer, T., Müller, H. J., & Zehetleitner, M. (2014). Rewarding distractor context versus rewarding target location: a commentary on Tseng and Lleras (2013) [Review of *Rewarding distractor context versus rewarding target location: a commentary on Tseng and Lleras (2013)*]. *Attention, Perception & Psychophysics*, *76*(3), 669–674.

Sha, L. Z., & Jiang, Y. V. (2016). Components of reward-driven attentional capture. In *Attention, Perception, & Psychophysics* (Vol. 78, Issue 2, pp. 403–414). https://doi.org/10.3758/s13414-015-1038-7

Sussman, T. J., Heller, W., Miller, G. A., & Mohanty, A. (2013). Emotional distractors can enhance attention. *Psychological Science*, *24*(11), 2322–2328.

Theeuwes. (2019). Goal-driven, stimulus-driven, and history-driven selection. *Current Opinion in Psychology*, *29*, 97–101.

Theeuwes, J. (1992). Perceptual selectivity for color and form [Review of *Perceptual selectivity for color and form*]. *Perception & Psychophysics*, *51*(6), 599–606.

Treisman, A., & Gelade, G. (1980). A feature-integration theory of attention. *Cognitive Psychology*, *12*(1), 97–136.

Vuilleumier, P. (2015). Affective and motivational control of vision. *Current Opinion in Neurology*, *28*(1), 29–35.

Vuilleumier, P., & Huang, Y.-M. (2009). Emotional Attention: Uncovering the Mechanisms of Affective Biases in Perception. *Current Directions in Psychological Science*, *18*(3), 148–152.

Watson, P., Pearson, D., Most, S. B., Theeuwes, J., Wiers, R. W., & Le Pelley, M. E. (2019). Attentional capture by Pavlovian reward-signalling distractors in visual search persists when rewards are removed. *PloS One*, *14*(12), e0226284.

Weinbach, N., & Henik, A. (2014). Alerting enhances attentional bias for salient stimuli: evidence from a global/local processing task. *Cognition*, *133*(2), 414–419.

Wessa, M., Kanske, P., Neumeister, P., Bode, K., Heissler, J., & Schönfelder, S. (2010). EmoPicS: subjective and psychophysiological evaluation of new imagery for clinical biopsychological research. *Z. Klin. Psychol. Psychother. Suppl*, *1*, 11–77.

Wolfe, J. M. (2021). Guided Search 6.0: An updated model of visual search. *Psychonomic Bulletin & Review*, *28*(4), 1060-1092.

Won, B.-Y., Forloines, M., Zhou, Z., & Geng, J. J. (2020). Changes in visual cortical processing attenuate singleton distraction during visual search. *Cortex; a Journal Devoted to the Study of the Nervous System and Behavior*, *132*, 309–321.

Won, B.-Y., Kosoyan, M., & Geng, J. J. (2019). Evidence for second-order singleton suppression based on probabilistic expectations. *Journal of Experimental Psychology. Human Perception and Performance*, *45*(1), 125–138.

Zhang, B., Weidner, R., Allenmark, F., Bertleff, S., Fink, G. R., Shi, Z., & Müller, H. J. (2021). Statistical learning of frequent distractor locations in visual search involves regional signal suppression in early visual cortex. In *bioRxiv* (p. 2021.04.16.440127). https://doi.org/10.1101/2021.04.16.440127.

5.2. Influence of state anxiety on attentional capture by additional singleton: empirical evidence from dual-target attention paradigm

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Influence of state anxiety on attentional capture by additional singleton: empirical evidence from dual-target attention paradigm

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Highlights

We examined the link between state anxiety and goal-directed attention.

We used a novel dual-target visual search attentional paradigm.

State anxiety impaired attentional control due to high arousal.

The link between state anxiety and distractor interference is negative.

State anxiety modulates target eccentricity.

Credit Author Statement

Miloš Stanković: Investigation. Conceptualization, Methodology, Formal analysis, Writing - Original Draft, Writing - Review & Editing. **Fredrik Allenmark:** Conceptualization, Methodology, Formal analysis, Writing - Original Draft, Writing - Review & Editing. **Zhuanghua Shi:** Conceptualization, Methodology, Formal analysis, Writing - Original Draft, Writing - Review & Editing.

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Abstract

While there is some evidence that anxiety affects stimulus-driven attentional capture and disturbs goal-directed attentional control by increasing distractibility of physically salient distractors (e.g., red items, threat-cues) or narrowing spatial attention, recent behavioral studies have revealed a multilayer association between state-dependent (e.g., situational) anxiety and attentional performance. Despite this, less is known about how state-dependent anxiety modulates cognition resulting in impairment/facilitation of attentional performance. We explored behavioral mechanisms underlying attentional control related to state-dependent anxiety by a novel dual-target attentional paradigm, using a sample of 31 healthy university students. This paradigm included visual search of two non-emotional shape items (i.e., two circles among diamonds and vice versa), in the presence or absence of a salient distractor (i.e., a red item) in half of the trials. Additionally, spatial narrowing was examined by visual-search displays presented centrally or peripherally. State-dependent anxiety, evidenced by self-reported inventory, was experimentally induced by displaying a short movie with anxiety-inducing or neutral content followed by a dual-target attentional paradigm. At the group-level analysis we revealed participants were faster and more accurate in the distractor-absent than the distractor-present trials, and faster in central compared to peripheral presentations. However, in general, participants' overall speed and accuracy were comparable for the high vs. low anxiety sessions. Crucially, though, at the individual-level analysis, we revealed that state-dependent anxiety modulates attentional control abilities by impairing accuracy but reducing overall distractor interference. These findings provide solid evidence that visual-search of non-emotional items under state anxiety affects attentional control by impairing effectiveness while reducing irrelevant distractor capture.

Key works: anxiety, attentional selection, goal-directed attention; distractor; visual search

Introduction

Our attention can be easily oriented toward potentially dangerous stimuli or objects in social (e.g., an angry face) and/or physical reality. Alerting and orienting attention activate upon perception and fast evaluation of detected threat-related cues (Ghassemzadeh et al., 2019), triggering behavioral and cognitive resources such as attentional vigilance (LeDoux, 1996), and facilitating the efficiency of goal-directed[13] attentional control (Kim et al., 2021) to promote survival and well-being. Threat-related cues that trigger behavioral and attentional resources are often preceded by fear-emotion (Ghassemzadeh et al., 2019), providing automatic (fast) response. Attention automatically orients to fearful or threatening stimuli (Vuilleumier, 2005), whereas a goal-directed search for a threat target (e.g., snakes or spiders) among heterogeneous non-threat distractors (flowers or mushrooms) facilitates reaction time (RT) (Öhman et al., 2001). Whereas emotion of fear causes immediate response to conditioned or unconditioned stimuli (Ghassemzadeh et al., 2019) by directing attention toward threat (Öhman et al., 2001; Vuilleumier, 2005), anxiety causes distant and uncertain harm response (LeDoux & Pine, 2016). Thus, little is known whether the same behavioral mechanisms underlie attention bias in anxiety; moreover, whether anxiety impairs or facilitates goal-directed attentional control. Previous literature is inconsistent since some theoretical accounts, such as Attentional Control Theory (ACT), hold that orienting toward threatening stimuli in anxious individuals occurs due to a decrease in goal-driven attentional control (Eysenck & Derakshan, 2011), and increases distractibility (stimulus-driven attention) (Eysenck et al., 2007; Moser et al., 2012a). Moreover, in contrast, a recent study (Kim et al., 2021) using electric shock conditioning, reported higher efficiency of goal-directed attentional control under threat, suggesting that mild threat in somewhat beneficial for participants in optimizing their visual search, resulting in fewer missed targets; however, it is still unknown under which conditions anxiety may modulate goal-driven attentional control, subsequently impairing or even enhancing behavioral performance. In line

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[13] Goal-directed versus stimulus-driven attention (Jan Theeuwes & Failing, 2020, for a review) in the literature is also sometimes referred to as top-down versus bottom-up process (Corbetta & Shulman, 2002; Stigchel et al., 2009), or endogenous versus exogenous attention (Carrasco, 2011; Posner, 1980). Goal-directed attention is a voluntary process in which particular object, location or feature relevant for current behavioral goals is selected internally and focused upon (Katsuki & Constantinidis, 2014,for a review), whereas stimulus-driven visual attention is an automatic process out of voluntary control often reflecting phenomena of 'attentional capture' upon exposure of a salient object (Neumann, 1984; Jan Theeuwes & Failing, 2020, for a review).

with ACT, prior work by Moser et al., (2012b) supports the notion arguing that trait anxiety is related to increased attentional distraction (i.e., attentional capture) by the color singleton in an additional singleton task[14]. In addition, using a modified additional singleton paradigm and fear-conditioning, Schmidt et al., (2015) paired an irrelevant non-target distractor (e.g., orange or blue diamond) with an aversive stimulus (i.e., electric shock), whereas no conditioning was used with the other and found more attentional capture of fear-paired stimuli than neutral ones. Of note, searching for a target coupled with an aversive stimulus (conditioned or unconditioned) by Schmidt et al. (2015) is somewhat different from searching for a neutral stimulus under emotions of fear or anxiety (LeDoux & Pine, 2016), given that the former is an immediate anxiety conditioning while the latter is state-dependent performance. Inconsistency in the literature extends to a variety of attentional tasks such as Stroop task demonstrating performance improvement (Hu et al., 2012) or impairment (Choi et al., 2012) due to a threat of electric shock, or antisaccade task[15] (Cornwell et al., 2012), demonstrating that threat-induced anxiety impairs responding for anti-saccades, but improves stimulus-driven responses (pro-saccades). In parallel, neurological studies have demonstrated enhanced bottom-up over top-down attentional control in high-anxiety (Bishop, 2009), or in acute stress (Arnsten, 2009), due to reduced frontal cortex activity, whereas reduction of attentional control may be compensated by enhanced activity of brain circuits involved in attentional control (Osinsky et al. 2012; Basten et al. 2011).

The controversial impacts of anxiety on task performance can be partly attributed to the complex relation between the anxiety state and performance. Recent work has shown an inverted U-shape relation between anxiety and task performance: when both anxiety and task-demands are high, attentional performance is less vulnerable since top-down control competes for cognitive resources with bottom-up signals, whereas low task-demands are followed by high-anxiety, that results in attentional distraction and performance reduction since bottom-up

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[14] The additional singleton paradigm by Jan Theeuwes (1992), typically used for examination of stimulus-driven attentional capture, in which observers search for a task-relevant unique shape (i.e., a singleton) with the presence of a task-irrelevant but physically salient distractor (i.e., a color singleton). A common finding is that the singleton distractor is hard to be suppressed, causing attentional capture (i.e., distractor-interference) manifested by a higher error rate and/or prolonged latency of RT.

[15] An antisaccade paradigm was often used in anxiety-attention research. In this paradigm, participants are instructed to execute eye-movements (saccades) either towards or away from an abruptly exposed stimulus display (Hallett, 1978).

mechanisms dominate in anxiety (Vytal et al., 2012). Enhanced top-down attentional employment, for example by demanding attentional tasks, may reallocate attentional resources towards task-demands, thereby decreasing anxiety (King & Schaefer, 2011).

Attentional impairment and facilitation by anxiety has been interpreted by the attentional spatial narrowing account (Derryberry & Reed, 1998; Najmi et al., 2012), which assumes impairment and facilitation come from 'narrowing' spatial attention to smaller sets of items toward central compared to peripheral visual field under extremely high anxiety/stress conditions (Janelle et al., 1992). For example, driving a car in an anxious state leads to slower and less accurate evaluating and processing of the task-relevant information for driving performance that is received from the periphery of the visual field (Janelle et al. 1992). Some early theoretical accounts proposed that anxiety/stress may narrow spatial attention (Easterbrook, 1959), in such a way by 'narrowing' attentional deployment from peripheral visual areas to central view-point to enhance processing of the central information. However, this potentially reduces the ability to have wider attentional control of the observed stimuli, and may cause greater error rate in doing peripheral tasks. In line with this, previous studies (Chandrakumar et al., 2020; Rogé et al., 2003), with non-anxious individuals, reported that lower alertness (means low anxiety!) leads to a narrowing of spatial attention[16], thereby deteriorating the ability to detect stimuli in the peripheral compared to central presentations. Thus, attentional improvement under anxiety/negative arousal, for instance in Stroop tasks (Robinson et al., 2013) or in the contextual cueing (Zinchenko et al., 2019) or color-dot-detection (Sussman et al., 2013) task, may occur since attention restricts to peripheral distracting cues, due to attentional narrowing. Taking together, extensive research is needed to explore effects of induced- or threat-anxiety on goal-driven attention, since anxiety characterized by the subjective experience of anxious affect, physical changes and anxious thoughts (American Psychiatric Association, 2015), is reported to affect cognition by impairing episodic memory (Airaksinen et al., 2005).

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[16] Another concept similar to spatial narrowing and important for attentional control and related stimulus-driven selection is the 'attentional window'. Attentional capture by an irrelevant, but salient distractor, can be less prominent if it occurs around a small attentional window, whereas when the attentional window is wide, the presented items are processed in parallel across the visual field, providing that salient items capture attention regardless of visual search goals (see Belopolsky & Theeuwes, 2010). While the attentional window is a perceptual phenomenon, attentional narrowing refers to emotional components related to attention.

To re-evaluate whether state anxiety affects goal-driven attentional control, we experimentally manipulated anxiety/arousal by presenting a short movie with ‘anxiety-inducing content’ prior and during the experimental testing, and a movie with ‘relaxing-content’ as the control condition. State anxiety level was evidenced by the State-Trait Anxiety inventory (STAI; Spielberger et al., 1983). Since anxiety highly depends on intra-individual personality differences (Stojiljković & Stanković, 2018), a repeated-measure experimental design was established by including two experimental sessions (induced-anxiety vs. neutral). Goal-driven attentional control was measured by a novel dual-target attention paradigm involving visual search for two equal, pop-out/group search, targets (i.e., two diamonds among circles vs. two circles among diamonds) with a color singleton (i.e., salient red circle or diamond) as task-irrelevant distractor, introduced in half of the trials.

The present study aimed to examine a) whether goal-directed visual search for two targets (i.e., dual-target) is affected by experimentally induced state anxiety due to impairment/ facilitation of top-down attentional control, b) whether goal-directed visual search for two targets is affected by the presence of a physically salient distractor (i.e., a red item) modulated by state anxiety due to enhancement/reduction of bottom-up attentional capture, c) whether goal-directed visual search with central and peripheral exposure is affected by state anxiety due to reduction/ facilitation of spatial attentional narrowing. Thus, we investigated whether goal-directed over stimulus-driven attentional capture is modulated by experimentally induced state anxiety. We hypothesized that increased personal state anxiety would impair goal-directed visual search for two targets (i.e., high error rate and prolonged RTs) due to reduction of top-down attention; and facilitate stimulus-driven attentional capture (i.e., distractor interference) of distractors (i.e., red item) due to enhancement of bottom-up attention. Furthermore, we hypothesized that personal state anxiety would enhance spatial ‘narrow’ attention in such a way as to improve the visual search for two targets in the central presentations to peripheral presentations, and to reduce distractor interference in central than peripheral presentations. Since ACT proposed that anxiety impairs efficiency (i.e., RT) more than effectiveness (e.g., accuracy, quality of performance) (Shi et al., 2019), we collected both RT and accuracy data.

Method

Participants

A total of 31 (11 males) healthy university students (*Mean* age = 26.06, *SD* = 3.95 years) participated in this study for compensation of 9 Euro per hour or student credit. We recruited participants through a public announcement. Exclusion criteria for participation were color blindness, or respectively, a diagnosis of a neurological or psychiatric disorder. A power analysis of the sample size was performed *a priori* by G*Power 3.1 (Faul et al., 2007), based on the effect size of $r = 0.43$, obtained in relatively similar research, using an additional singleton paradigm and correlation with trait anxiety (Moser et al., 2012a). For the protocol of power analyses, using power (1-ß) = 0.80, an alpha level of .05, and Effect size |ρ| of .43, the recommended sample size was 29 participants. The present study was approved by the Ethics Board of the LMU Faculty of Psychology and Educational Sciences whereas participants signed informed consent.

Apparatus and stimuli

Participants were seated comfortably at 70 cm in front of a monitor placed at participants' eye level, using a chin-rest to ensure stable and precise reception of visual stimuli from the monitor. The search display consisted of a central (radius of 4° at the viewing distance) or peripheral (radius of 6.9°) imaginary ring of eight items spaced equidistantly around a fixation dot (subtending 0.2° × 0.2° of visual angle), each with a vertical or horizontal line (subtending 1.6° × 0.3°) inside, followed by a dot mask (subtending 7° × 7°). Eight visual items (item size: 2.5° × 2.5° in diameter) were two diamonds among six circles or two circles among six diamonds. In line with prior studies (e.g. Allenmark et al., 2019; Wang & Theeuwes, 2018; Zhang et al., 2019), target items were shape swapped across trials, in 50% of the trials participants searched for two circles among diamonds, otherwise they searched for two diamonds among circles. We applied random shape swapping across trials to encourage a dimension search, rather than a feature search, strategy to increase a chance of stimulus-driven attentional capture by the distractor (Bacon & Egeth, 1994). The central and peripheral search arrays were equal in set-up parameters, except for the radius size. The color of the targets and non-targets search items were green, whereas the distractor item was red, presented on 50% of the all trials.

The luminance of green or red stimuli was 14 cd/m^2, presented on a black monitor background of 0.2 cd/m^2, registered by a Luminance and Color Meter (CS-100A).

For temporary induction or reduction of state anxiety, we used short movies with anxious- and neutral-content as in a prior study (Stanković & Nešić, 2020). A stressful movie contained a total of 6 minutes of unpleasant and fearful sequences from the movie—The Shallows (2016) (https://www.imdb.com/title/tt4052882/), including disturbing scenes of a shark attack on a surfer, anticipation of the attack, psychological tension, and scenes of the surfer's injuries caused by the shark. A neutral movie contained a total of 6 minutes of relaxing sequences taken from a National Geographic documentary—The Great Wall of China (https://www.youtube.com/user/NationalGeographic/videos), depicting the architecture of the Great Wall and people's relaxed daily lives. Stimuli presentation was performed on a color-calibrated (120 cd/m^2 D65 whitepoint) 24" TFT-LCD monitor (ASUS VG248QE, screen resolution 1920 × 1080 pixels, frame rate 120 Hz), supported by PsychoPy (Peirce et al., 2019) platform.

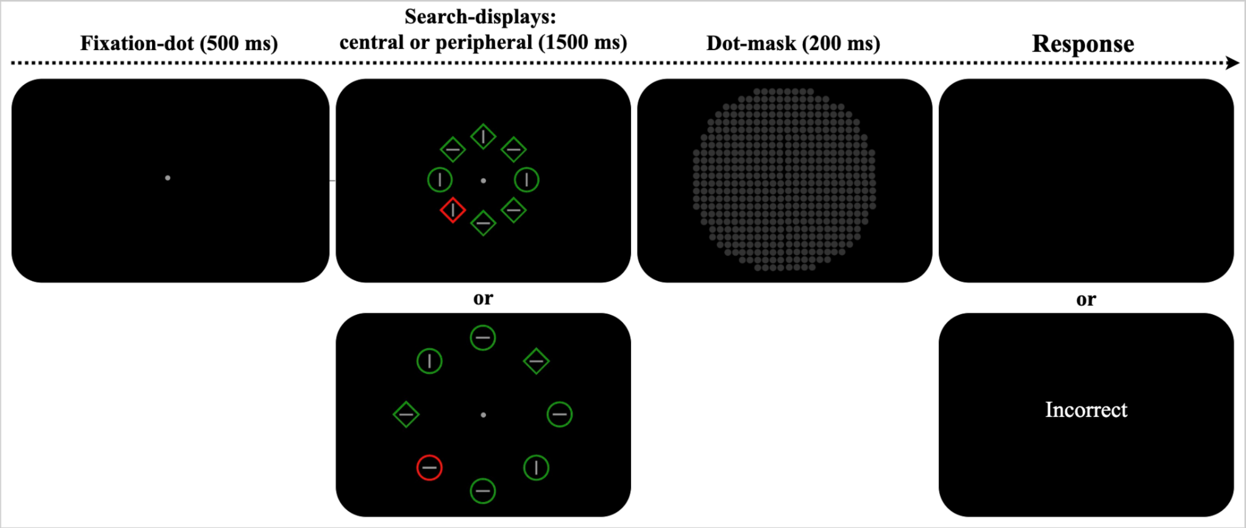
Psychological measurements

The State-Trait Anxiety inventory (STAI; Spielberger et al., 1983). The STAI is a widely used measure of state and trait anxiety (form Y-1, Y-2, respectively); the state anxiety (..'how you feel right now, that is, at this moment') form contains 20 items (e.g., I am worried), rated on a 4-point scale (e.g., 'Not at all' to 'Very much so), and the trait-anxiety (...'how you generally feel?) form contains 20 items (e.g., I feel nervous and restless), rated on a 4-point scale (e.g, 'Almost Never' to 'Almost Always'). Participants self-reported their emotional state. Normative scores ranged from 20 - 80; the higher scores demonstrated a higher level of state or trait anxiety, whereas the *cut-off* for clinically significant indicator of state anxiety was 40 units (Spielberger et al. 1983). Internal consistency Alpha (a), obtained on the first experimental session, in our sample was $a = .889$ for state anxiety, and $a = .896$ for trait-anxiety.

Procedure

The experiment was conducted in a sound-attenuated and dimly lit laboratory cabin. Participants filled both forms of the STAI inventory as baseline, then performed a practice-session (100 trials) of the dual-target attention task. Next, participants were exposed to the first part of a short (3 minutes) movie (i.e., anxiety-inducing or neutral-content) and subsequently they continued with the dual-target attention task. Halfway through the experimental task participants were exposed to the second sequel of the short movie (3 minutes), then filled the state anxiety inventory again and completed the rest of the trials (Figure 1). Total state anxiety score was calculated by subtracting STAI values of posttest from baseline.

Fig.1 Dual-target attention paradigm example.



Note. *The search-display started with a fixation-dot on the screen, randomly followed by eight items two of which were unique shape targets (two diamonds among six circles or two circles among six diamonds), covered by a mask. Incorrect response was followed by text message ('Incorrect') feedback, whereas correct response was followed by blank display. In this example, an upward central search-display shows two target (i.e., dual target) circles among homogeneous diamonds that are pop-out/group in the visual search, whereas downward peripheral search-display shows two target diamonds among circles. Both central and peripheral presentations include a red item distractor.*

Presentation trials started with a fixation-dot in the center of the monitor for 500 ms, followed by a visual search-display containing eight items for 1500 ms, immediately covered by a dot-mask for 200 ms. Participants were instructed to fixate their gaze on the fixation-dot at the beginning of the trial and, upon the onset of the display, search for two unique shape targets, either two diamonds among circles or two circles among diamonds. Participants had to report if the lines inside the two unique shapes were ‘same’ (i.e., both lines vertically or horizontally oriented) by pressing the ‘J’ key using their right-hand index finger, or the ‘different’ (i.e., one line is vertical the other one is horizontal, or reverse) by pressing the ‘F’ key using their left-hand index finger, as fast and accurately as possible. Depending on the participant's speed, the visual search display lasted for a maximum of 1500 ms or terminated upon the response-button press. Incorrect response was followed by 500 ms of text message feedback (‘Incorrect’), whereas correct responses led to a blank screen of 500 ms. The inter-trial interval (ITI) lasted 500 ms. Participants' RTs data over each trial were registered from the onset of the search array until a response-button press.

The experiment was separated by 7 to 10 days apart into two separate sessions: ‘anxiety session’ included induction of state anxiety, by presenting a short movie with anxious-content, and another included presentation of a neutral movie[17] to maintain a relaxed emotional state of participants. The order of the sessions was counterbalanced across the participants whereas participants were randomly assigned into the sessions. The dual-target attention task included 35 blocks, 25 trials per each block, followed by a short pause. Experiment lasted for 1.3 hours per session.

Data processing and statistical analysis

To establish baseline experimental effects between anxiety- and neutral-sessions, we conducted analyses of variance (ANOVAs), including mean RT and accuracy as dependent variable; and Sessions (anxiety vs. neutral), Distractor (present vs. absent), Target Eccentricity (center vs. peripheral) and Identity (same vs. different) as within-subject factors. Statistically significant ($p < .05$) F-values were followed by Bonferroni post-hoc correction tests for multiple comparisons. The values below 0.33 indicate the null hypothesis, whereas the values greater than 3 are in favor of the alternative hypothesis (Kass & Raftery, 1995). Furthermore, we explored

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[17] Two participants reported that they had seen the sequences of the stressful movie on popular media before the experiment, whereas none of the participants had seen the sequences of the neutral movie.

intra-individual differences in regard to attention performance by applying a forward stepwise multiple regression analysis model using state and trait anxiety as predictors; Sessions, Distractor, Target Eccentricity and Identity as factors; and the visual search performance as criterion which was mean RT, accuracy, distractor interference speed (ms) and accuracy (%). We used unstandardized regression coefficient (B) and standardized regression coefficient (β) for computation of regression analyses. Distractor interference was indexed by speed (ms) [distractor-present minus distractor-absent trials] and by accuracy (%) [distractor-absent minus distractor-present presentation]. Practice session trials and RT's outliers below 150 ms and above 3000 ms (on average, 3%), response-error trials, were excluded from statistical analysis. Statistical analyses were conducted using R software (RStudio Team, 2020).

Results

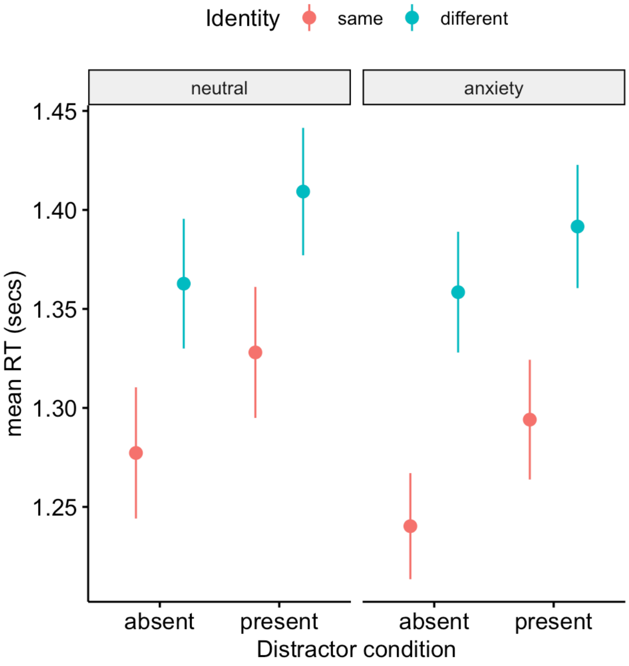
Anxiety measures

The average trait-anxiety of the participants was 39.5 (range: 23 - 60), almost reaching the *cut-off* (40 units) level for clinical anxiety (Spielberger et al., 1983). State anxiety was calculated as follows [posttest – pretest-state (i.e., baseline) anxiety], indicating positive sign as index of induced anxiety and negative sign as indicator of induced neutral/relaxation state. Paired *t*-test indicates that the induced state anxiety was statistically greater in the anxiety- compared to the neutral-session, *mean difference* = 15, *SD* = 9.83, vs. *mean difference* = -2.31, SD = 5.95, respectively; $t(1, 30) = -7.74$, $p < .001$.

Mean reaction times and accuracy

The average accuracy was 88.5% and the mean correct RT was 1333 ms. Participants were slightly faster in anxiety- compared to neutral-sessions (mean RT ± *SE*: 1317 ± 38 ms vs. 1348 ± 38 ms), but comparable in accuracy (*M* ± *SE*: 88.4% ± 0.4% vs. 88.6% ± 0.4%).

Figure 2. Identity in regard to Distractor conditions separately for the neutral and anxiety sessions.



Note. *Mean RT for Identity (same: vertical/vertical or horizontal/horizontal; or different: vertical/horizontal) in regard to Distractor (present and absent), separately for Session condition (anxiety and neutral). The error bars represent 1 standard error.*

Figure 2 shows the mean RTs for the different conditions. We performed repeated-measures ANOVAs separately for the mean RTs and the accuracy, including Sessions (anxiety vs. neutral), and Distractor (present vs. absent), Target Eccentricity (center vs. peripheral), and Identity (same vs. different) as within-subject factors. For RTs we failed to find the difference between two anxiety sessions, $F(1, 30) = 0.201$, $p = .657$, $\eta_p^2 = .007$, $BF_{incl} = 0.07$; but all other main effects were significant: Distractor, $F(1, 30) = 59.76$, $p < .001$, $\eta_p^2 = .67$, $BF_{incl} = 2.47$; Target Eccentricity, $F(1, 30) = 35.46$, $p < .001$, $\eta_p^2 = .54$, $BF_{incl} = 1.79$; Identity, $F(1, 60) = 112.33$, $p < .001$, $\eta_p^2 = .79$, $BF_{incl} > 100$. The responses were faster in the distractor-absent relative to the distractor-present condition (1310 ms vs. 1356 ms, respectively, a typical distractor interference of 50 ms), in the center relative to the peripheral presentations (1310 ms vs. 1356 ms, respectively, again a 50 ms central benefit), and in reporting the same identity relative to the different identity (1290 ms vs. 1380 ms, respectively). Moreover, there was a significant Target Eccentricity × Identity interaction, $F(1, 30) = 11.24$, $p < .001$, $\eta_p^2 = .27, BF_{incl}$= 0.152. The rest of the interactions were all non-significant, Fs (1, 30) < 3.3, ps > .08, BFs_{incl}< 0.141.

For accuracy we only revealed a statistically significant main effect of Distractor, $F(1, 30) = 27.86$, $p < .001$, $\eta_p^2 = 0.481$, BF_{incl}= 52.34; responses were more accurate to the distractor-absent compared to the distractor-present presentations (89.4% vs. 87.6%, respectively). All the other two-way (*ps* > .053, *BFs* < 0.019) or three-way interactions (*ps* > .314, *BFs* < 0.001) were statistically non-significant. Perceptually, this suggests a strong interference effect on attentional selection by a physical salient distractor.

Thus, the main manipulation - anxiety - turned out to be non-significant for the mean RTs and accuracy, albeit the self-evaluation showed the significant difference. There are two possible interpretations of obtained group-level results: One possibility is that the movie-induced anxiety may vanish quickly. Another possibility is that each individual participant may have different anxiety states for the movie-induced anxiety. Thus, the averaging measure across participants may not pick the relation between the state anxiety and the search performance. In order to investigate this, we further conducted linear regression analyses.

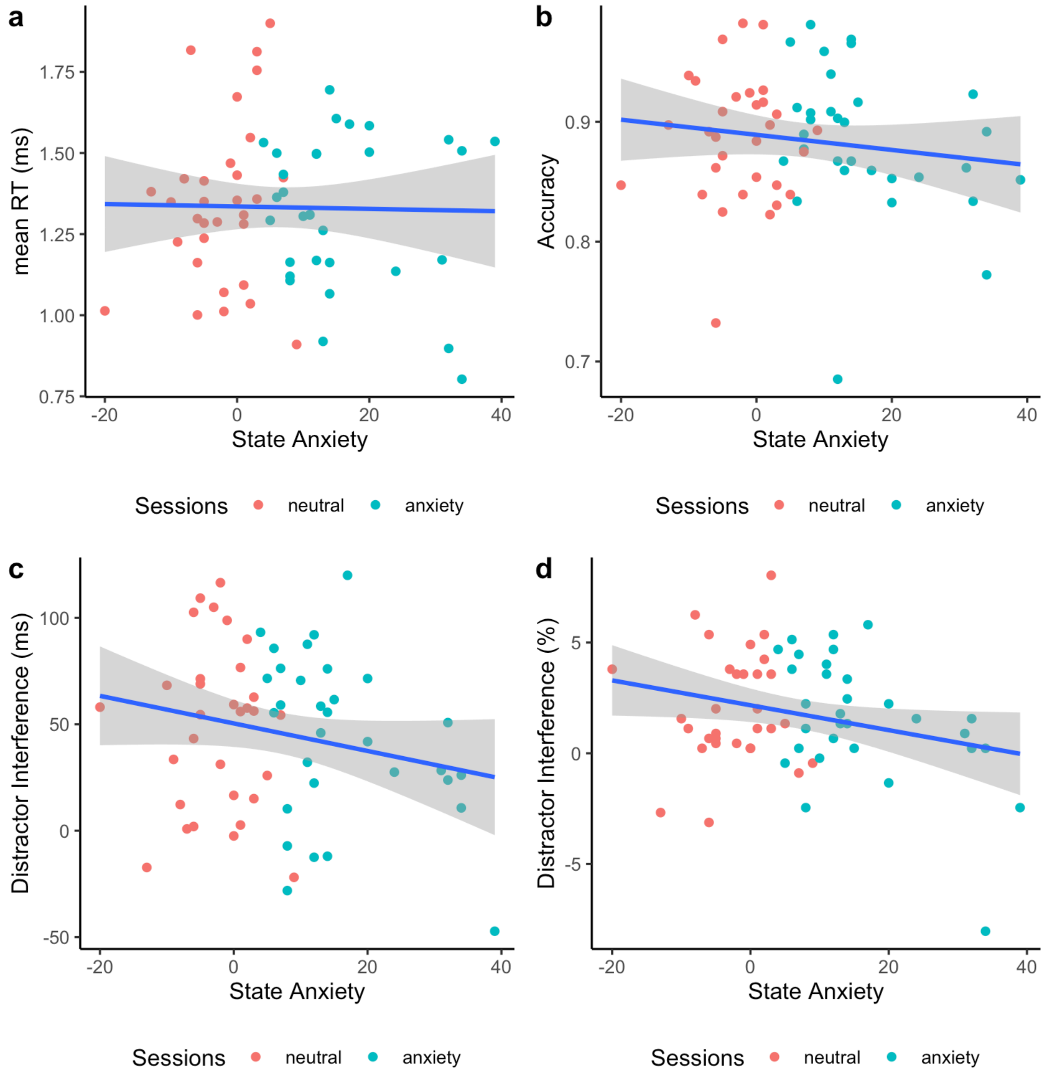
Relation between distractor interference and individual state of anxiety

To test whether intra-individual state anxiety score may have linear relation to the visual search performance we applied a *forward stepwise regression analysis model*. In particular, we estimate whether intra-individual state and trait anxiety (predictor variables) may predict overall accuracy, RT, accuracy and distractor interference (%, ms) (criterion variable), using Session, Distractor, Target eccentricity and Identity (factor variables) for regression models. Regression model demonstrated that state and trait anxiety were non-significant predictors or the participants' RT, including factor of Session ($p < .05$), Target Eccentricity and Identity were statistically significant factors (overall model: $R^2 = 0.05$, $F(3, 495) = 9.23$, $p < .001$). This confirms mean differences for these factors in regard to RT but without contributing to the regression model through influence of main predictors of state and trait anxiety. By contrast, regression model (overall model: $R^2 = 0.07$, $F(4, 495) = 8.77$, $p < .001$) involving Accuracy as criterion demonstrated state that a statistically significant predictors were State anxiety, B = -0.001, S.E < 0.001, β = 0.28, *t* = -4.15, *p* < .001, Trait anxiety, B = -0.001, S.E < 0.001 , β = -0.15, *t* = -3.40, *p* < .001, including factors of Distractor, B = -0.02, S.E = 0.02, β = -0.13, *t* = -3.09, *p* = .002, and Session, B = 0.03, S.E = 0.02, β = 0.19, *t* = 2.95, *p* = .003, whereas Identity and Target eccentricity were non-significant (p < .05). This suggests increased individual state together with trait anxiety reduced participants' visual search performance. As Fig. 3-b depicts, accuracy negatively correlates with state anxiety, that is, lower participants accuracy performance is associated with higher individual state anxiety, principally in the anxiety experimental session. Effect of the distractor was examined deeper through the following analysis including distractor interference.

Regression model demonstrated that the distractor interference of RT (ms) was predicted a statistically significant (overall model: R^2 = 0.04, *F*(4, 247) = 4.54, *p* = .012) by the individual State anxiety, B = -0.71, S.E = 0.31, β = -0.14, *t* = -2.31, *p* = .022, and Trait anxiety, B = -0.99, S.E = 0.46, β = -0.13, *t* = -2.14, *p* = .034, whereas the factors of Session, Target eccentricity and Identity were all non-significant (p < .095). Also, the distractor interference in accuracy (%) was predicted significantly (overall model: R^2 = 0.04, *F*(4, 247) = 2.69, *p* = .032) by individual State anxiety, B = -0.06, S.E = 0.02, β = -0.15, *t* = -2.37, *p* = .019, whereas Trait anxiety was non-significant (*p* = .486), including the factors of Session, Target eccentricity and Identity (*p* < .137). As Figure 3c-d depicts, distractor interference negatively correlates with individual state anxiety demonstrating that higher personal anxiety is associated with less distractor interference. Although both sessions (Anxiety vs. Neutral) showed comparable distractor interference (due to large variability), the negative linear trends are visible.

Thus, we revealed through linear regression analysis that Sessions factor may have diminished mean differences at group-level analysis, that is, exposure to aversive movie did not differ much from neutral movie; however, personal sensitivity to anxiety clearly affects the visual search in the dual-target task. Hence, increased anxiety reduced distractor interference in both speed or accuracy response.

Figure 3. Relations between RT, accuracy, distractor interference and state anxiety



Note. *Correlations between participants visual search performance and their individual state anxiety score in the anxiety (red dots) and neutral (green dots) session separately for a) mean RT, b) accuracy, c) distractor interference (expressed in ms) indexed as differences between distractor-present and the distractor-absent presentations, d) distractor interference (expressed as %) indexed as differences between distractor-absent and distractor-present presentation. State anxiety was calculated by subtracting self-reported measures recorded after exposure of the second part (middle of the testing) of the movie and pretest (i.e., baseline).*

Discussion

In the present study we investigated whether goal-directed visual search for two targets is affected by experimentally induced state anxiety due to facilitation/impairment of top-down attentional control. Furthermore, we investigated whether goal-directed visual search is affected by the appearance of a physically salient distractor (i.e., red item) during induced anxiety-anxiety: in particular, whether state anxiety enhances/reduces bottom-up attention resulting in less/more prominent distractor interference in the visual search. Finally, in addition, we examined whether spatial attentional narrowing is affected by state anxiety due to facilitation/ impairment of top-down attentional control.

At a group level-analysis between the anxiety and neutral session we failed to find any evidence of goal-directed attention facilitation or impairment affected by experimentally induced state anxiety, since obtained results demonstrated a similar pattern of behavioral performance for both RT and accuracy. Hence, exposure to non-threatening, but at some point aversive movie scenes, at a group-level failed to produce a greater effect on the visual search task. Possible interpretation suggests that the movie-induced anxiety vanishes quickly, since nowadays the average individual may be desensitized at some point to aversive movie experience.

Crucially, we demonstrated large intra-individual differences in sensitisation on state anxiety in a way that some participants reported high while others reported low or no induced anxiety upon ‘stressful’ movie viewing. Along these lines, at individual-level analysis we revealed that the increased level of anxiety induced by aversive short film presentation was linearly negatively correlated with the goal-directed ability to search for targets. State-dependent emotional fluctuation toward anxiety interferes with attentional control of goal-directed visual search by affecting behavioral performance (speed and accuracy) in line with recent findings (Shi et al., 2019).

Interestingly, we revealed that distractor interference (ms) was predicted negatively by state and trait anxiety whereas distractor interference, related to accuracy, was negatively predicted by state anxiety. Although our findings demonstrated that goal-directed performance impair by state and trait anxiety, results related to distractor interference showed a different behavioral pattern. We demonstrated state and trait anxiety reduce goal-directed attention, but not necessarily favoring stimulus-driven attention. It seems that under anxiety the difference between distractor-present and distractor-absent presentations become less prominent, resulting in decrease of distractor interference related to speed and accuracy. Hence, attentional effectiveness and efficiency decreased due to emotions of anxiety; however, mental distress optimized top-down and bottom-up modes leading to less distractor interference. For example ACT holds anxiety as critical emotional factor deterioration top-down favoring bottom-up attention (Derakshan and Eysenck 2009; Eysenck and Derakshan 2011), that is, deficit in goal-directed attention a leading to greater sensitivity of distractor interference (Osinsky et al. 2012). Task-irrelevant but physically salient distractor stimuli (e.g., red color) interfered less with dual-target search in high-level anxious participants demonstrating enhanced top-down attention. In consistency, a recent study (Kim et al., 2021) reported on higher efficiency of goal-directed attention control under threat (i.e., electric shock): visual search of affectively neutral stimuli was facilitated by the threat. Thus, experimentally induced state anxiety may increase vigilance, response alertness and decrease distractor interference, possibly indicating biologically determined mechanisms for survival related to threatening stimuli (Ghassemzadeh et al., 2019; Vuilleumier, 2005). Increased internal anxiety/arousal-state stimulated attention vigilance resulting in higher efficiency of goal-directed attentional control (Kim et al., 2021), in line with our findings; however, in contrast, an earlier study by Moser and colleagues (2012b), using an additional singleton paradigm[18] (2012b), reported a correlation between the personality trait of anxiety and enhanced attentional distraction by physically salient stimuli, but noting that their study did not account for anxiety manipulation. Thus, since we explored influence of state anxiety on non-threatening stimuli (e.g., shape-search) via dual-target paradigm favoring goal-directed over stimulus-driven mode, at a speculative level in comparison with Moser's (2012b) findings, we assumed that greater task-demands in our experiment leads to attention facilitation due to low anxiety impact that is even stimulative. Goal-directed attention employment in dual-target task may reallocate cognitive resources towards task-demands causing anxiety reduction (King & Schaefer, 2011), become even more vigilant operating faster and more accurately since

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[18] An additional singletop paradigm was mainly used for exploring stimulus-driven attention (Jan Theeuwes & Failing, 2020, for a review).

they refocusing these emotional arousal into the demanding dual-target task[19]. However, we found that induced state anxiety influenced speed and response accuracy and was attributed to suppression of distractor interference. Such relations between anxiety and task performance have been recently reported (King & Schaefer, 2011; Vytal et al., 2012), demonstrating less vulnerability of attentional performance when the participant performs a demanding task that occupies executive resources. In contrast to the ACT, we found increased state anxiety affected goal-directed visual search for the two targets due to attentional control impairment, in particular facilitating top-down attention; simultaneously decreased distractor interference. ACT assuming that state anxiety would impair efficiency of inhibitory functions that have been used to resist interference from distractors and task-irrelevant stimuli (Eysenck & Derakshan, 2011), in such a way that anxious participants fail to suppress the distractor (i.e., task-irrelevant information) due to lack of attentional control. By contrast, however, we demonstrated possible improved vigilance in such a way to reduce distractor effects, and improve efficiency of goal-directed attention consistent with recent work (Kim et al., 2021). In addition, ACT assumed high anxiety might trigger compensatory mechanisms to reduce distractor interference by employing additional cognitive resources (Eysenck & Derakshan, 2011), but it is unlikely that higher anxiety was linked with this compensatory function, since additional resources must be covered by triggering internal or external (e.g., reward) motivation, that we did not provide as a feedback in our experiment. An alternative interpretation of this inconsistency is that ACT might be applied for low demanding cognitive tasks that operate in extreme stress conditions. In addition, we revealed the speed performance advantage of the same orientation lines versus the different orientation line trials, which is in line with prior studies (Osinsky et al., 2012).

Furthermore, as we expected, we revealed at group-level analyses that the both anxiety- and neutral sessions were more accurate and faster in central compared to peripheral presentations, which has been reported in the recent visuospatial detection task (Chandrakumar et al., 2020). Interestingly, Chandrakumar et al., (2020) suggested that spatial narrowing to the center of the visuospatial field is due to decreased alertness in certain intervals of time required

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[19] For illustration purposes, overall RT for dual-target paradigm was 1330 ms, whereas in comparison average overall RT in an additional singleton paradigm using eight items was below 600 ms (J. Theeuwes, 1992)

for task performance. Taken together, state anxiety affects effectiveness and efficiency of attention that results in less distractibility in central (RT) and peripheral (error rates) presentations.

Further studies should explore whether increased anxiety magnitude to higher aversive levels would reduce attentional control, in lines proposed by ACT. Of note, inconsistent with ACT, we did not observe that state-dependent effects such as anxiety modulate attentional control by affecting efficiency more than effectiveness (Eysenck & Calvo, 1992; Shi et al., 2019). State anxiety affected both response time and accuracy at the intra-individual level.

In conclusion, using a novel dual-target attention paradigm, obtained findings provide strong evidence of modulating influence of intra-individual differences in attentional control mechanisms: in particular, state-dependent train anxiety affects goal-directed attention for pop-out/group visual search for two items by impairing accuracy but decreasing distractor interference. Although at group-level analysis participants were faster and more accurate in the distractor-absent than the distractor-present trials, we failed to evidence differentiation among experimental anxiety sessions. State-dependent and personal trait anxiety predicted fewer participants' accuracy indicating emotional interference on goal-directed attentional control. These findings provide strong evidence for the emotional component involved in visual cognition by modulating attentional control behavior.

Reference

Airaksinen, E., Larsson, M., & Forsell, Y. (2005). Neuropsychological functions in anxiety disorders in population-based samples: evidence of episodic memory dysfunction. *Journal of Psychiatric Research*, *39*(2), 207–214. https://doi.org/10.1016/j.jpsychires.2004.06.001

Allenmark, F., Zhang, B., Liesefeld, H. R., Shi, Z., & Müller, H. J. (2019). Probability cueing of singleton-distractor regions in visual search: the locus of spatial distractor suppression is determined by colour swapping. In *Visual Cognition* (pp. 1–19). https://doi.org/10.1080/13506285.2019.1666953

American Psychiatric Association. (2015). *Anxiety Disorders: DSM-5® Selections*.

American Psychiatric Pub. https://play.google.com/store/books/details?id=VHqcCgAAQBAJ

Arnsten, A. F. T. (2009). Stress signalling pathways that impair prefrontal cortex structure and function. *Nature Reviews. Neuroscience*, *10*(6), 410–422. https://doi.org/10.1038/nrn2648

Bacon, W. F., & Egeth, H. E. (1994). Overriding stimulus-driven attentional capture. *Perception & Psychophysics*, *55*(5), 485–496. https://doi.org/10.3758/bf03205306

Belopolsky, A. V., & Theeuwes, J. (2010). No capture outside the attentional window. *Vision Research*, *50*(23), 2543–2550. https://doi.org/10.1016/j.visres.2010.08.023

Bishop, S. J. (2009). Trait anxiety and impoverished prefrontal control of attention. *Nature Neuroscience*, *12*(1), 92–98. https://doi.org/10.1038/nn.2242

Carrasco, M. (2011). Visual attention: the past 25 years. *Vision Research*, *51*(13), 1484–1525. https://doi.org/10.1016/j.visres.2011.04.012

Chandrakumar, D., Dorrian, J., Banks, S., Keage, H. A. D., Coussens, S., Gupta, C., Centofanti, S. A., Stepien, J. M., & Loetscher, T. (2020). The relationship between alertness and spatial attention under simulated shiftwork. *Scientific Reports*, *10*(1), 14946. https://doi.org/10.1038/s41598-020-71800-6

Choi, J. M., Padmala, S., & Pessoa, L. (2012). Impact of state anxiety on the interaction between threat monitoring and cognition. *NeuroImage*, *59*(2), 1912–1923. https://doi.org/10.1016/j.neuroimage.2011.08.102

Corbetta, M., & Shulman, G. L. (2002). Control of goal-directed and stimulus-driven attention in the brain. *Nature Reviews. Neuroscience*, *3*(3), 201–215. https://doi.org/10.1038/nrn755

Cornwell, B. R., Mueller, S. C., Kaplan, R., Grillon, C., & Ernst, M. (2012). Anxiety, a benefit and detriment to cognition: behavioral and magnetoencephalographic evidence from a mixed-saccade task. *Brain and Cognition*, *78*(3), 257–267. https://doi.org/10.1016/j.bandc.2012.01.002

Derakshan, N., Ansari, T. L., Hansard, M., Shoker, L., & Eysenck, M. W. (2009). Anxiety, inhibition, efficiency, and effectiveness. An investigation using antisaccade task.

Experimental Psychology, *56*(1), 48–55. https://doi.org/10.1027/1618-3169.56.1.48

Derryberry, D., & Reed, M. A. (1998). Anxiety and attentional focusing: trait, state and hemispheric influences. *Personality and Individual Differences*, *25*(4), 745–761. https://doi.org/10.1016/S0191-8869(98)00117-2

Easterbrook, J. A. (1959). The effect of emotion on cue utilization and the organization of behavior. *Psychological Review*, *66*(3), 183–201. https://doi.org/10.1037/h0047707

Eysenck, M. W., & Calvo, M. G. (1992). Anxiety and Performance: The Processing Efficiency Theory. *Cognition and Emotion*, *6*(6), 409–434. https://doi.org/10.1080/02699939208409696

Eysenck, M. W., & Derakshan, N. (2011). New perspectives in attentional control theory. *Personality and Individual Differences*, *50*(7), 955–960. https://doi.org/10.1016/j.paid.2010.08.019

Eysenck, M. W., Derakshan, N., Santos, R., & Calvo, M. G. (2007). Anxiety and cognitive performance: attentional control theory. *Emotion* , *7*(2), 336–353. https://doi.org/10.1037/1528-3542.7.2.336

Faul, F., Erdfelder, E., Lang, A.-G., & Buchner, A. (2007). G*Power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods*, *39*(2), 175–191. https://doi.org/10.3758/bf03193146

Ghassemzadeh, H., Rothbart, M. K., & Posner, M. I. (2019). Anxiety and Brain Networks of Attentional Control. *Cognitive and Behavioral Neurology: Official Journal of the Society for Behavioral and Cognitive Neurology*, *32*(1), 54–62. https://doi.org/10.1097/WNN.0000000000000181

Hallett, P. E. (1978). Primary and secondary saccades to goals defined by instructions. *Vision Research*, *18*(10), 1279–1296. https://doi.org/10.1016/0042-6989(78)90218-3

Hu, K., Bauer, A., Padmala, S., & Pessoa, L. (2012). Threat of bodily harm has opposing effects on cognition. *Emotion* , *12*(1), 28–32. https://doi.org/10.1037/a0024345

Janelle, C. M., Singer, R. N., & Mark Williams, A. (1992). External Distraction and Attentional Narrowing: Visual Search Evidence. *Journal of Sport and Exercise Psychology*, *21*(1), 70–91. https://doi.org/10.1123/jsep.21.1.70

Kass, R. E., & Raftery, A. E. (1995). Bayes Factors. *Journal of the American Statistical Association*, *90*(430), 773–795. https://doi.org/10.1080/01621459.1995.10476572

Katsuki, F., & Constantinidis, C. (2014). Bottom-up and top-down attention: different processes and overlapping neural systems. *The Neuroscientist: A Review Journal Bringing Neurobiology, Neurology and Psychiatry*, *20*(5), 509–521. https://doi.org/10.1177/1073858413514136

Kim, A. J., & Anderson, B. A. (2020). Threat reduces value-driven but not salience-driven attentional capture. *Emotion* , *20*(5), 874–889. https://doi.org/10.1037/emo0000599

Kim, A. J., Lee, D. S., & Anderson, B. A. (2021). The influence of threat on the efficiency of goal-directed attentional control. *Psychological Research*, *85*(3), 980–986. https://doi.org/10.1007/s00426-020-01321-4

King, R., & Schaefer, A. (2011). The emotional startle effect is disrupted by a concurrent working memory task. *Psychophysiology*, *48*(2), 269–272. https://doi.org/10.1111/j.1469-8986.2010.01062.x

LeDoux, J. E. (1996). The Emotional Brain Simon Schuster. *New York*, *384*.

LeDoux, J. E., & Pine, D. S. (2016). Using Neuroscience to Help Understand Fear and Anxiety: A Two-System Framework. *The American Journal of Psychiatry*, *173*(11), 1083–1093. https://doi.org/10.1176/appi.ajp.2016.16030353

Moser, J. S., Becker, M. W., & Moran, T. P. (2012a). Enhanced attentional capture in trait anxiety. *Emotion* , *12*(2), 213–216. https://doi.org/10.1037/a0026156

Moser, J. S., Becker, M. W., & Moran, T. P. (2012b). Enhanced attentional capture in trait anxiety. *Emotion* , *12*(2), 213–216. https://doi.org/10.1037/a0026156

Najmi, S., Kuckertz, J. M., & Amir, N. (2012). Attentional impairment in anxiety: inefficiency in expanding the scope of attention. *Depression and Anxiety*, *29*(3), 243–249. https://doi.org/10.1002/da.20900

Neumann, O. (1984). Automatic Processing: A Review of Recent Findings and a Plea for an Old Theory. In W. Prinz & A. F. Sanders (Eds.), *Cognition and Motor Processes* (pp. 255–293). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-69382-3_17

Öhman, A., Flykt, A., & Esteves, F. (2001). Emotion drives attention: Detecting the snake in the grass. *Journal of Experimental Psychology. General*, *130*(3), 466–478. https://doi.org/10.1037/0096-3445.130.3.466

Osinsky, R., Gebhardt, H., Alexander, N., & Hennig, J. (2012). Trait anxiety and the dynamics of attentional control. *Biological Psychology*, *89*(1), 252–259. https://doi.org/10.1016/j.biopsycho.2011.10.016

Peirce, Gray, J. R., Simpson, S., MacAskill, M., Höchenberger, R., Sogo, H., Kastman, E., & Lindeløv, J. K. (2019). PsychoPy2: Experiments in behavior made easy. *Behavior Research Methods*, *51*(1), 195–203. https://doi.org/10.3758/s13428-018-01193-y

Posner, M. I. (1980). Orienting of Attention. In *Quarterly Journal of Experimental Psychology* (Vol. 32, Issue 1, pp. 3–25). https://doi.org/10.1080/00335558008248231

RStudio Team (2020). RStudio: Integrated Development Environment for R. RStudio, PBC, Boston, MA URL. http://www.rstudio.com/

Robinson, O. J., Vytal, K., Cornwell, B. R., & Grillon, C. (2013). The impact of anxiety upon cognition: perspectives from human threat of shock studies. *Frontiers in Human Neuroscience*, *7*, 203. https://doi.org/10.3389/fnhum.2013.00203

Rogé, J., Pébayle, T., El Hannachi, S., & Muzet, A. (2003). Effect of sleep deprivation and driving duration on the useful visual field in younger and older subjects during simulator driving. *Vision Research*, *43*(13), 1465–1472. https://doi.org/10.1016/s0042-6989(03)00143-3

Schmidt, L. J., Belopolsky, A. V., & Theeuwes, J. (2015). Attentional capture by signals of threat. *Cognition & Emotion*, *29*(4), 687–694. https://doi.org/10.1080/02699931.2014.924484

Shi, R., Sharpe, L., & Abbott, M. (2019). A meta-analysis of the relationship between anxiety and attentional control. *Clinical Psychology Review*, *72*, 101754. https://doi.org/10.1016/j.cpr.2019.101754

Spielberger, C. D., Gorsuch, R. L., Lushene, R., Vagg, P. R., & Jacobs, G. A. (1983). Consulting Psychologists Press; Palo Alto, CA: 1983. *Manual for the State-Trait Anxiety Inventory. [Google Scholar].*

Stanković, M., & Nešić, M. (2020). Functional brain asymmetry for emotions:

psychological stress-induced reversed hemispheric asymmetry in emotional face perception. *Experimental Brain Research. Experimentelle Hirnforschung. Experimentation Cerebrale*. https://doi.org/10.1007/s00221-020-05920-w

Stigchel, S. V. der, Van der Stigchel, S., Belopolsky, A. V., Peters, J. C., Wijnen, J. G., Meeter, M., & Theeuwes, J. (2009). The limits of top-down control of visual attention. In *Acta Psychologica* (Vol. 132, Issue 3, pp. 201–212). https://doi.org/10.1016/j.actpsy.2009.07.001

Stojiljković, J., & Stanković, M. (2018). Depressive state and social anxiety in adolescents: the role of family interactions. *The American Journal of Family Therapy*. https://www.tandfonline.com/doi/abs/10.1080/01926187.2018.1506269

Sussman, T. J., Heller, W., Miller, G. A., & Mohanty, A. (2013). Emotional distractors can enhance attention. *Psychological Science*, *24*(11), 2322–2328. https://doi.org/10.1177/0956797613492774

Theeuwes, J. (1992). Perceptual selectivity for color and form [Review of *Perceptual selectivity for color and form*]. *Perception & Psychophysics*, *51*(6), 599–606. https://doi.org/10.3758/bf03211656

Theeuwes, J., & Failing, M. (2020). *Attentional Selection: Top-Down, Bottom-Up and History-Based Biases*. Cambridge University Press. https://play.google.com/store/books/details?id=Y732DwAAQBAJ

Vuilleumier, P. (2005). How brains beware: neural mechanisms of emotional attention. In *Trends in Cognitive Sciences* (Vol. 9, Issue 12, pp. 585–594). https://doi.org/10.1016/j.tics.2005.10.011

Vytal, K., Cornwell, B., Arkin, N., & Grillon, C. (2012). Describing the interplay between anxiety and cognition: from impaired performance under low cognitive load to reduced anxiety under high load. *Psychophysiology*, *49*(6), 842–852. https://doi.org/10.1111/j.1469-8986.2012.01358.x

Wang, B., & Theeuwes, J. (2018). Statistical regularities modulate attentional capture. *Journal of Experimental Psychology. Human Perception and Performance*, *44*(1), 13–17. https://doi.org/10.1037/xhp0000472

Zhang, B., Allenmark, F., Liesefeld, H. R., Shi, Z., & Muller, H. (2019). Probability cueing of singleton-distractor locations in visual search: priority-map-or dimension-based inhibition? *Journal of Experimental Psychology. Human Perception and Performance*. https://doi.org/10.1037/xhp0000652

Zinchenko, A., Geyer, T., Müller, H. J., & Conci, M. (2019). Affective modulation of memory-based guidance in visual search: Dissociative role of positive and negative emotions. In J. Emotion (Ed.), *No Pagination Specified*. https://doi.org/10.1037/emo0000602

5.3. Goal-directed attentional control and response inhibition under induced state anxiety: an EEG investigation

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Goal-directed attentional control and response inhibition under induced state anxiety. EEG investigation

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Abstract

While a growing body of literature has demonstrated that goal-directed attentional control is impaired by trait anxiety (e.g., worry) due to the reduction of top-down attention and decreased ability to focus on the task-relevant and inhibit irrelevant stimuli (i.e., inhibition function), recent behavioral studies have provided inconsistent evidence. The present study, using a sample of healthy university students, investigated the neuropsychological (i.e., EEG) and behavioral mechanisms underlying attentional control under state-dependent anxiety, with a novel dual-target attentional paradigm in which observers visually searched for two (dual) targets (e.g., two circles among four diamonds or reverse) on the display, whereas in half of the presentations a psychically salient distractor was introduced (i.e., a red item). We hypothesized that induced anxiety would modulate event-related potential waveforms (e.g., Ppc, N2pc, PD) during time-locked visual search presentations. Although results failed to support hypotheses related to attentional modulation of N2pc component in the visual search of task-relevant items, or PD component for distractor suppression, we revealed prominent attentional modulation of Ppc component by dual-target task. The elicited Ppc during the early visual processing showed that the emotion of anxiety modulates focusing on the task-relevant stimuli and the inhibition response of irrelevant non-targets in the dual-target attentional paradigm. Behaviorally, attentional control was modulated by individual anxiety since more anxious participants responded less accurately during the visual search. The present study provided strong empirical behavioral and neurpsyhiolocal evidence that observers in the anxiety session demonstrated impaired attentional control related to goal-directed attention and response inhibition in the visual search of dual-target.

Introduction

In everyday life, human attention is biased by potentially threatening situations or objects that may harm a person's physical or mental integrity. This is the biological preposition of attentional vigilance (J. E. LeDoux, 1996), activating upon the perception of threat-related cues (Ghassemzadeh et al., 2019), to promote survival and well being, promoting efficiency of goal-directed attentional control (Kim et al., 2021). Alerting and orienting attention toward threat-related cues are triggered by cognitive evaluation of danger, usually preceded by the emotion of fear (Ghassemzadeh et al., 2019), enabling fast behavioral response (Vuilleumier, 2005). Here, previous studies have pointed out the emotion of fear that results in immediate response to conditioned or unconditioned stimuli (Ghassemzadeh et al., 2019), whereas anxiety results in response to distant and uncertain harm (Joseph E. LeDoux & Pine, 2016). Thus, threat-related cues that may harm a person's integrity would immediately cause the emotion of fear after attentional detection proceeded with the fight or flight mode (McCarty 2016), whereas anxiety is more related to uncertain danger since anxiety is characterized by a person's subjective experience of anxious affect, physical changes, and anxious thoughts (American Psychiatric Association, 2015). Since previous literature provides strong evidence that the so-called 'emotional brain' includes broad neuronetwork of key brain regions of the amygdala, the prefrontal cortex (PFC), the hypothalamus, and the anterior cingulate cortex (ACC) (Dalgleish 2004), recent views highlight its influence on emotional attention (for a review, Vuilleumier 2005). Neuroanatomical perspectives of the emotional brain in immediate fear condition include a direct versus indirect sensory pathway whereby a threatening stimulus reaches the amygdala as a crucial structure in evaluating and providing the fight or flight response (Vuilleumier 2005). In particular, by a direct sensory pathway from the thalamus to the amygdala (e.g., an automatic rapid emotional reaction the so-called 'short route'), and by an indirect pathway from the thalamus via the cortex to the amygdala (e.g., cognitive assessment, the so-called 'long route') (LeDoux and Pine 2016; Garrido et al. 2012). Along these lines, it is still unknown to what extent the maintained state or trait anxiety may bias neurological and behavioral attentional control mechanisms. Attentional control, viewed as the ability to focus and swift attention in a flexible manner, mainly operates between goal-driven and stimulus-driven attention and their interaction.

Previous literature contradicts this since there are at least two opposite lines of research in regard to the influence of anxiety on attentional control.

The first line of research, such as the Attentional Control Theory (ACT) referring to the link between anxiety and attention (Eysenck et al. 2007; Moser et al. 2012), proposes that state or trait anxiety impairs attentional control performance. Anxious individuals would allocate their attention to threat-related stimuli reducing the attentional focus on the task-relevant stimuli unless it includes threatening stimuli. The ACT proposes that mechanisms underlying anxiety tend to reduce attentional control and increase attention toward threat-related stimuli. Thus, stimulus-driven attention would predominate goal-driven attention in anxious but mentally healthy individuals by impairing efficiency (e.g., response speed) and effectiveness (e.g., accuracy, quality of performance) (Eysenck et al. 2007). Negative effects of anxiety on performance are predicted to be greater on processing efficiency than effectiveness (Shi et al., 2019); moreover, high anxiety individuals may compensate for poorer behavioral performance, for example, in the visual search task, by investing 'compensatory cognitive effort' (Berggren and Derakshan 2013). The ACT relies on an influential paper by Miyake et al., (2000) proposing three main executive functions: *shifting* (e.g., shifting between tasks, operations, or mental sets); updating (e.g., information updating and monitoring; working memory); inhibition (e.g., focussing attention to task-relevant and inhibiting irrelevant stimuli). This influential paper on attentional control[20] mechanisms affected the ACT in referring to the link between anxiety and cognitive performance (Eysenck et al. 2007). The second line of research has demonstrated that anxious individuals may even outperform non-anxious individuals in a variety of tasks such as detection of facial expression emotion (Byrne and Eysenck 1995), the Stroop task (Hu et al. 2012; Robinson et al. 2013), or a color-dot task (Sussman et al. 2013). Anxious individuals compared to non-anxious ones may perform equally (Blankstein et al. 1990), whereas exposure to threatening conditions such as electric shock even facilitates attentional performance (i.e.,

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[20] The term the *attentional control i*s widely used in a variety of science contexts, such as that attentional control involves two main modes of top-down and bottom-up attention (Awh et al. 2012), often referred to as goal-driven and stimulus-driven attention (Theeuwes and Failing 2020). However, although the ATC refers to those attentional modes, fundamental constructs rely on attentional control within anxiety and cognitive performance (Eysenck et al. 2007), preferring the use of main cognitive sub-components of inhibition, switching and updating (Shi et al. 2019; Miyake et al. 2000) to describe the theory.

visual search task) under threat (Kim et al., 2021). Taken together, previous behavioral studies have demonstrated controversial findings since little is yet known whether anxiety impairs or facilitates attentional control, in particular, goal-directed attention during the visual search task. In parallel, neuroimaging findings failed to contribute to resolving a current issue of attentional control and anxiety since recent studies have shown increased recruitment of neural control mechanisms in high-anxious individuals (Basten et al. 2011; Telzer et al. 2008), whereas some studies found the opposite results (Bishop 2009).

Attentional control and anxiety: empirical evidence of EEG

There is now ample evidence that event-related potentials (ERPs) can reflect cognitive processes of attentional selection, particular for those early components, such as Ppc, posterior-contralateral negativity (PCN/N2pc), and distractor positivity (PD). For example, the P1 onset of 80-90 ms, peak 125 ms, reflects attention-sensitive components (Mangun 1995; Hillyard and Anllo-Vento 1998), and the early contralateral positivity (Ppc, also known as P1pc) 50-125ms after target onset (Verleger et al. 2012). Early studies reported that P1 is sensitive for low-level visual features such as color, luminance, contrast, or spatial frequencies of stimulus, and is often used as early face categorization (Herrmann et al. 2005; Itier and Taylor 2004), reflecting early sensory processing of the occipital and inferotemporal cortex (Luck et al. 1994). Visual Ppc roughly coincided with the P1 component evoked by the presented stimuli (Verleger et al. 2012).

N2pc, also referred to as the PCN[21], is observed at the posterior scalp sites contralateral to an attended object, reflecting the lateralized focusing of attention (Luck 2014). The N2pc is a subcomponent of the posterior N2 belonging to the so-called lateralized components that is characterized by increased negative deflection arising between 175 and 300 ms post-stimulus onset over posterior electrodes such as PO7 and PO8 contralateral to the attended hemifield (Luck and Hillyard 1994). The N2pc is considered an ERP lateralized component that represents the spatial deployment of attentional selection, by which the observer’s attention can be directed.

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[21] There is inconsistency in scientific terminology related to the N2pc component. Namely, some researchers found that instead of the N2pc, the PCN abbreviation would be more appropriate due to a more precise meaning. However, we found that the N2pc abbreviation has a practical advantage over the PCN since number 2 describes its latency in the current waveform; it is the second negative deflection that occurs for about 200 ms. Along these lines, the N2pc has a direct informative advantage over the PCN, thus it will be used in further discussion of the present dissertation.

As such, the N2pc revealed a significant shift of attention toward threat in the dot probe task (Kappenman et al. 2015), and N2pc should be able to capture an attentional bias to treat even when its not evidenced behaviorally, which is likely linked with timing since behavioral response occur several hundred milliseconds afterwards (Kappenman et al. 2014).

Interestingly, both N2pc and Ppc are attention-sensitive components, however, early study by Wauschkuhn et al., (1998) demonstrated dissociation between N2pc and Ppc, in particular: visual display of stimuli which consist a gray circle presented opposite to a colored circle (red, blue), serving across different blocks as target (i.e., colored-circle or gray-circle), demonstrated that N2pc was always negative contralateral to the relevant circle whereas Ppc was always positive contralateral to the colored circle. This was affected simply by color salience or maybe by the change of the color across trials (blue or red, whereas gray was presented in each trial) (for discussion see, Verleger et al. 2012).

In addition to the N2pc, extensive literature has demonstrated that the distractor positivity (PD) is a component occurring in the visual search involving the suppression of an object (Luck 2014). The Pd is the neurological signature of distractor suppression mechanisms that occurs due to the presentation of task-irrelevant stimuli. The Pd component consists of a more positive voltage over the contralateral hemisphere to a distractor compared to the ipsilateral hemisphere, whereas the scalp distribution is very similar to the N2pc (Luck 2014). Furthermore, Hickey (2009) demonstrated that the Pd component was eliminated in cases of visual search where participants search for presence/detection rather than discrimination of identity since this type of task presumably decreases the requirement to actively suppress a potential distractor.

Study rationale

To re-evaluate whether state anxiety influences attentional control, in particular, goal-driven attention, we used an experimental method of induced anxiety by displaying a short movie with anxiety-inducing content prior to and during the experimental testing, whereas a neutral emotional state was maintained by presenting a movie with ‘relaxing-content’ as a control condition. The level of state anxiety was registered by the State-Trait Anxiety Inventory (STAI; Spielberger et al., 1983). Goal-driven attention was measured by the dual-target task including a visual search for two equal, pop-out/group search targets (i.e., two circles among diamonds or two diamonds among circles). In half of the trials, the color singleton (i.e., a red item) was introduced to examine the effect of state anxiety on stimulus-driven attention. This paradigm required maintaining high attentional vigilance during the visual search, which can be demanding since prior work showed that increased anxiety limited the full range of attentional capacity. ACT predicted greater negative effects of anxiety on efficiency than the effectiveness of behavioral performance (Shi et al., 2019), thus both accuracy and RT were collected.

The present EEG study sought to investigate neural and behavioral (i.e., accuracy and RT) mechanisms underlying goal-directed attentional control under experimentally induced state anxiety/arousal, and personality trait anxiety, using a dual-target attention paradigm. In particular, the main aims of the study were to examine: 1) whether induced state, and personality trait anxiety modulate neural (e.g., Ppc, N2pc) and behavioral goal-driven attention in the dual-target visual search task due to facilitation or impairment of top-down attentional control, 2) whether induced state, and personality trait anxiety modulate neutral (e.g., Pd) and behavioral stimulus-driven attention under a physically salient distractor (i.e., a red item) due to the facilitation of bottom-up attentional capture, 3) whether induced state, and personality trait anxiety modulate neutral (e.g., Ppc) No-go response due to the reduction of inhibition function. Thus, we re-evaluated the relationship between emotions and attentional control mediated by intra-individual differences of vulnerability to anxiety.

Method

Participants

A total of 20 healthy university students participated in the Experiment (13 females; *mean* age = 26, *SD* = 3.27, years), while two of them were excluded only from EEG data recordings due to large eye-blink artifacts that compromised their data. We recruited our participants via a public announcement and they received monetary compensation or student credits upon request. The exclusion criteria were color blindness, absence of psychiatric/ neurological disorders whereas the inclusion criteria were adults up to 35 years of age. Participants were asked to refrain from the consumption of caffeine for at least 2 hrs prior to the experiment, and abstain from consuming drugs/alcohol on the day of the experiment, with a recommendation to obtain a regular portion of sleep the night before the recording. The present study was approved by the Ethics Board of the LMU Faculty of Psychology and Educational Sciences and in accordance with the declaration of Helsinki. Participants signed informed consent. The required sample size for this study was estimated *a priori by G*Power* 3.1 (Faul et al., 2007), based on the effect size |ρ| of 0.54 from our previous study (Stanković et al., in revision), with an alpha level of .05 and using power (1-ß) = 0.90.

Apparatus and stimuli

Participants were placed comfortably at 70cm in front of a presentation monitor positioned at the participant's eye level using a chin-rest to provide stable perception of the presented stimuli. The search display consisted of a central (radius of 3.3° at the viewing distance) imaginary ring of six stimuli (stimuli size: 1.7° × 1.7° in diameter) equidistantly surrounding a fixation-dot (subtending 0.2° × 0.2° of visual angle). A horizontal or vertical line (subtending 1.6° × 0.3°) was placed inside each item. Six of the displayed stimuli were distributed in the imaginary circle of 12, 2, 4, 6, 8, and 10 o'clock positions.

Targets and non-targets were always green, whereas irrelevant distractors were red. Their luminance, measured by the Chroma Meter (Konica Minolta CS-100A), was equalized at 10 cd/m^2, and 12 cd/m^2 for bars/fixation dot, presented on a black screen background of 0.20 cd/m^2. Based on prior experiments (e.g. Allenmark et al., 2019; Wang & Theeuwes, 2018; Zhang et al., 2019), the targets were shape swapped across trials; half of the search displays promoted two circles among four diamonds and vice versa.

State anxiety was induced temporarily by a short movie with anxiety-inducing content (anxiety session), otherwise, neutral content was presented (neutral session). A stressful movie included unpleasant and fearful scenes from The Shallows (2016) (https://www.imdb.com/title/tt4052882/), such as a shark attack on a surfer, anticipation of the attack, the surfer's injuries scenes, and psychological tension. A neutral movie included scenes from a National Geographic documentary—The Great Wall of China (https://www. youtube.com/user/NationalGeographic/videos), mainly displaying the architecture of the Great Wall and people's daily lives. Both sequences of the movies taken from popular media have been previously successfully implemented in neutral versus anxiety induction (Stanković & Nešić, 2020) + Stanković, Allenmark, and Shi (under review). The duration of the short movies was 6 minutes.

Visual stimuli presentation, data collection of the individual participant's RTs and accuracy was performed by an open-source platform PsychoPy (Peirce et al., 2019), using a presentation computer with a color-calibrated (120 cd/m² D65 whitepoint) 24" TFT-LCD monitor (ASUS VG248QE, screen resolution 1920 × 1080 pixels, frame rate 120 Hz).

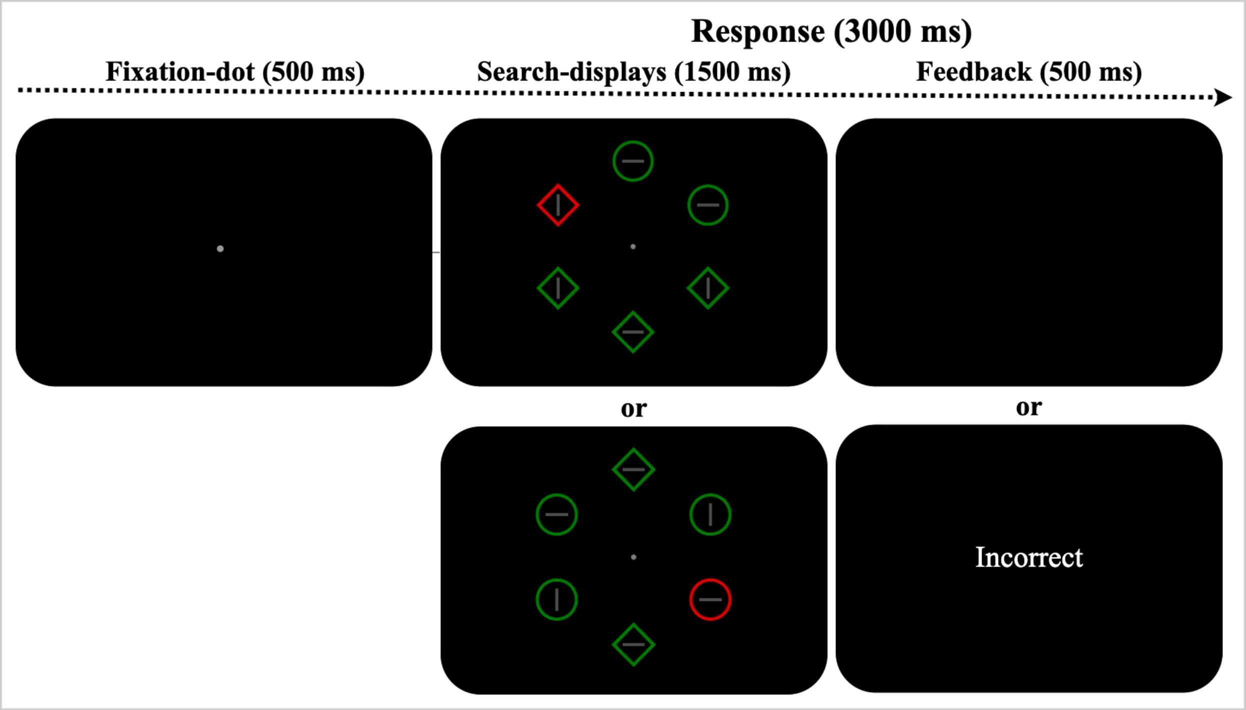
The State-Trait Anxiety Inventory (STAI; Spielberger et al. 1983), is a widely used inventory of state and trait anxiety (form Y-1, Y-2, retrospectively). STAI is a self-reported inventory. The state anxiety form (..'how you feel right now, that is, at this moment') includes 20 items (e.g., I am worried), rated on a 4-point scale (e.g., 'Not at all' to 'Very much so), and the trait anxiety form (...'how you generally feel?) includes 20 items (e.g., I feel nervous and restless), rated on a 4-point scale (e.g, 'Almost Never' to 'Almost Always'). The norms range from 20 to 80; the greater scores indicate a higher level of either state or trait anxiety, whereas the cut-off for clinical anxiety is a score above 40 units (Spielberger et al. 1983). Internal consistency Alpha (*a*) in our sample was: a = 0.91 for trait anxiety, whereas a = 0.88 for state anxiety (baselines) in the first and a = 0.93 in the second experimental session.

Procedure

The experiment was conducted in a sound-attenuated and dark laboratory cabin. The experimental procedure timeline was the following: the participant filled the STAI (state-trait) inventory (emotional baseline), then the experimenter managed EEG cap preparation by actiCap Control System, followed by instructions about the dual-target attention task and a practice session. Following the experimental procedures from a previous behavioral study by Stanković, Allenmark, and Shi (under review), where the dual-target attention paradigm was implemented for the first time, participants were exposed to the first part of a short (3 minutes) movie (i.e., anxiety-inducing or neutral-content), and continued with the visual-search task immediately afterward. To maintain neutral- or anxiety-induction as constant as possible, the second part of the movie was played halfway through the task, followed again with STAI inventory (i.e., state anxiety) screening. Individual state anxiety scores were calculated by subtracting scores obtained in the baseline and the scores registered by the follow-up presentation of the second sequel of the movie. There were two experimental sessions (neutral, anxiety) separated by a time interval of seven to ten days to minimize the transfer effects. The sessions were counterbalanced across participants in such a way that half of the participants were randomly assigned to the 'neutral session', and the other half to the 'anxiety session'.

As can be seen from Fig. 1 presentation trials began with a fixation-dot at the screen center for 500 ms; next, a visual-search display of six items appeared for 1500 ms. We instructed participants to fixate their gaze on the fixation-dot and, upon the onset of the display, search for two unique shape targets (circles or diamonds), and when they find it, to report the orientation of the lines inside the targets by pressing the 'F' key using their left-hand index finger if two lines were horizontal, or pressing the 'J' key using their right-hand index finger if two lines were vertical, or press nothing if one of the lines was horizontal and the other was vertical. No-go trials occur in 30%, whereas 70% (35% for both vertical and horizontal orientation lines) remain for all response-present trials. In line with prior EEG studies (Kappenman et al. 2014; Luck 2014) maintaining eye fixation in the center of the screen was critical to avoid potential contamination of the EEG recordings and examined attentional lateralized components. For incorrect responses, a feedback white text message “Incorrect' was provided for 500 ms, whereas correct responses were followed by a blank screen for the same duration. Participants were instructed to respond as fast and accurately as possible, whereas depending on response speed, the display was either terminated upon the response-button press or lasted for 1500 ms, including the predicted additional response time of 1500 ms. Psychopy registered RT from search display presentation appearance till the response-button press. The intertrial interval lasted for 500 ms. Stimuli were presented randomly.

Figure 1. Dual-target attention task illustration.



Note. *The search-display began with a fixation-dot, followed by six items, two of which were unique shape targets, and four homogeneous non-targets (i.e., two diamonds among four circles or two circles among four diamonds). Two targets (i.e., a dual-target) are pop-out/group in the visual-search display. For incorrect responses a feedback message 'incorrect' was provided, whereas correct responses were followed by a blank screen, both followed by the interstimulus intervals. State anxiety was evidenced using the STAI before the first and after the second part of a short movie. In the current example, the upper slide of the search-display shows two target circles among four diamonds, the lines inside are horizontal, whereas the lower slide shows two target diamonds; the lines inside are horizontal. In both slides the task-irrelevant distractor was located at lateral sites.*

A task-irrelevant distractor (i.e., a red item) was presented in 50% of the trials. Shape swapping was performed across trials (two diamonds among circles and vice versa) to facilitate pop-out/group detection rather than a feature search, thus maximizing the attentional capture effect by the distractor (Bacon and Egeth 1994; Allenmark et al. 2019). One experimental session contained 35 blocks in the task, 30 trials per each block, preceded by 5 blocks of practice-trials. The blocks included a short rest of the length decided by participants, however, usually about 30 seconds was sufficient. The duration of each experimental session was approximately 2.5h.

Data processing and statistical analysis

We excluded practice trials, outliers (less than 150 ms or greater than 3000 ms). After analyzing the accuracy, we also excluded those error responses to calculate the mean RTs. We applied analysis of variance (ANOVA) for correct responses that included Session (anxiety vs. neutral), Distractor (present vs. absent), and Response-type (No-go vs. Go) as within-subject factors, followed up by the Bonferroni test for multiple comparisons if *F*-values were statistically significant ($p < .05$). For RTs, ANOVA included Session and Distractor as within-subject factors for the Go trials. In addition to a given effect size (partial eta-squared η^2_p), we reported Bayesian ANOVAs, by default settings (i.e., r-scale fixed effects = 0.5, r-scale random effects = 1, r-scale covariates = 0.354). Bayes factors for main and interaction effects are 'inclusion' (BF_{incl}), calculated 'across matched models'. Bayes factors are quantification evidence for the alternative relative to the null hypothesis. Values below 0.33 indicate support for the null hypotheses, whereas values greater than 3 indicate strong support for the alternative hypothesis (Kass and Raftery 1995). Furthermore, we performed the multiple regression analyses between state-anxiety for given individual and distractor interference calculated as the distractor-absent minus distractor-present trials, using unstandardized regression coefficient (B) and standardized regression coefficient (β). We used both correct (accuracy) trials, averaged accuracy across conditions, and RTs. For RT, 'No-go' responses were excluded from the conditions. Statistical analyses were performed by R (RStudio Team, 2020).

EEG recordings and data preprocessing

Electrophysiological (EEG) signals were recorded using 64-channel BrainAmp amplifiers (Brain Products, Munich, Germany). EEG signals were recorded *online* with a 0.1 Hz to 250 Hz band-pass filter. Electrode positions matched the International 10-20 System (for more detail see American Electroencephalographic Society, 1994), using adjusted electrode impedance below 15 Ω during the actiCAP preparation, maintained during pause intervals if necessary. An additional electrode was attached to the inferior orbit of the left eye to register the vertical electrooculogram

(VEOG), whereas the FCz electrode was used as an *online* reference during EEG data acquisition. Afterwards, the average of left and right mastoids (average mastoid reference) was readjusted in *offline* re-referenced channels for the EEG preprocessing. Those signals were re-sampled to 256 Hz. A High-Pass Filter (HPF) was applied at 1 Hz to limit low-frequency artifacts, followed by the *cleanline* plugin application to remove line noise set up at 50Hz-100Hz. Bad channels from the continuous EEG data were identified using a component spectra and a map tool to eliminate apparent noise (e.g., electromyographic burst, discontinuity), while EEG artifacts (e.g., blinking, movements) were removed by visual inspection by the experimentator. Independent Component Analysis (ICA) of the continuous EEG data was performed using a *runica* algorithm (512 steps, convergence bound 1 = 10-7) to remove large, non-structural artifacts (e.g., eye blinks). A 30 Hz low pass IIR filter was applied to the EEG continuous data, which were then segmented into 1200 ms epochs (- 200ms to + 800ms) per trial, calculated from search array onset. *Baseline correction* was computed to these segmented epochs for 200 ms pre-stimulus intervals.

We computed difference waves over electrodes PO7/PO8 by subtracting the ipsilateral from contralateral waveforms (relative to the lateralized two-targets/distractor), and averaging the resulting lateralized ERPs across both left and right hemifield trials[22].

EEG analysis

The EEGs were averaged into ERPs, separately for each condition and every participant, after the offline incorrect responses were removed. Local peak amplitudes of the N2*pc* and PD were computed separately for the anxiety and the neutral condition for the following search-display presentations: a) lateral two-targets (2 and 4 or 8 and 10 o'clock positions), absent-distractor, b) lateral two-targets, midline distractor (12 or 6 o'clock position), c) lateral distractor (2, 4, 8 or 10 o'clock position), midline two-targets (12 and 6 o'clock positions). A computed *t*-test for independent samples was used to compare different-waveforms of ERPs between anxiety and neutral sessions. A paired t-test was used to compare grand-average waveforms of contralateral and ipsilateral waveforms separately for the neutral and anxiety session. Time

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[22] Formula: [(PO8 – PO7 [left two-targets]) + (PO7 – PO8 [right two-targets])/2])

windows for computing the local peak amplitudes (between two fixed latencies) of the N2pc (230-290 ms), P_d (250-290 ms) were established in line with recent studies exploring these components (Hickey et al. 2009; Dodwell et al. 2021), and Ppc (90-120ms) component (Mangun 1995; Itier and Taylor 2004). The EEG data were processed using EEGLAB (Delorme and Makeig 2004), and open-source matlab toolbox ERPLAB (Lopez-Calderon and Luck 2014).

Results

Anxiety measurement

The average trait anxiety evidenced in our participants was 41.1 (range: 32 - 62), close to the cut-off (40 units) as indicated for clinical anxiety (Spielberger et al. 1983). Induced state anxiety was statistically significantly higher in the anxiety session in comparison with the neutral session[23], *mean difference* = 15.2, *SD* = 12.8, vs. *mean difference* = -1.35, *SD* = 10.5, respectively; $t(1) = -4.26, p < .001$.

Behavioral results - mean reaction times and accuracy

Overall response accuracy was 90.1% (range: 73.2% - 100%) followed by the mean RT of 1290 ms. Participants responded numerically faster in the anxiety- relative to the neutral-session (mean RT ± *SE*: 1278 ± 40 ms vs. 1309 ± 40 ms), but were comparable in accuracy (*M* ± *SE*: 89.7% ± 11% vs. 90.5% ± 9%). Thus, distributions of attentional performance between neutral and anxiety sessions in regard to RTs and accuracy significantly overlapped. To examine the baseline effects of anxiety and neutral sessions, we computed ANOVAs separately for response accuracy and RT. The ANOVA conducted for accuracy included Sessions (anxiety vs. neutral), Distractor (present vs. absent), and Response-type (Go vs. No-go) as within-subject factors. For the Go-trial mean RTs, the ANOVA including factors of Sessions (anxiety vs. neutral), and Distractor (present vs. absent), as within-subject factors, failed to show any significant main effects of Session, $F(1, 19) = 1.25, p = .277, \eta_g^2 = 0.06, BF_{incl} = 0.98$; Distractor, $F(1, 19) = 2.84, p = .109, \eta_g^2 = 0.13, BF_{incl} = 0.33$, nor their interaction, $F(1, 19) = 3.71, p =$

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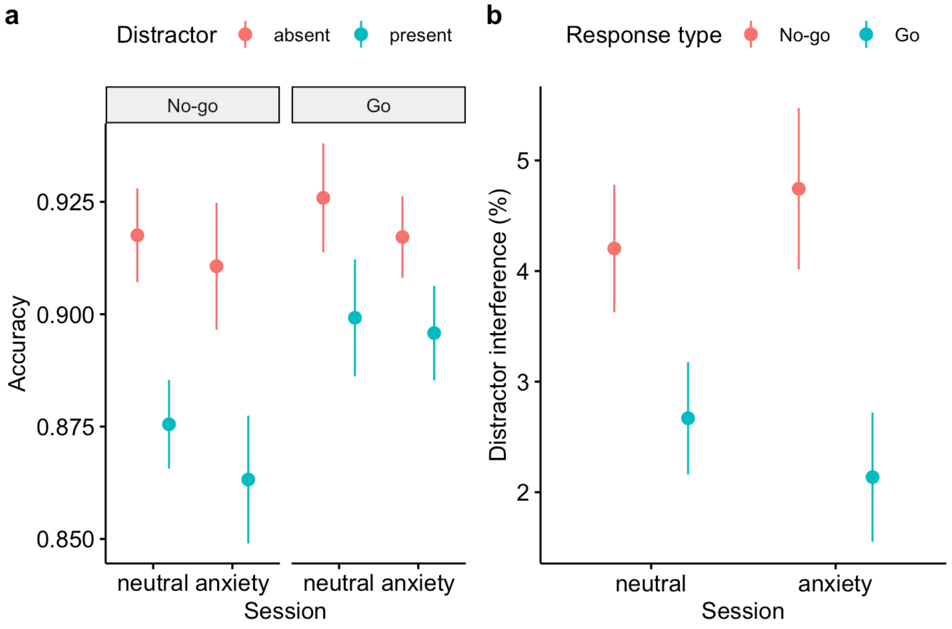
[23] We estimated state anxiety by substracing posttest from pretest state anxiety (i.e., baseline). Positive sign indexed level of induced anxiety, whereas negative sign indexed state anxiety reduction.

.069, $\eta_g^2 = 0.16$, $BF_{incl} = 0.33$. Though the mean RTs were comparable across conditions, accuracies were quite different across conditions.

For accuracy, the ANOVA including factor of Sessions (anxiety vs. neutral), Distractor (present vs. absent), and Response-type (Go vs. No-go) as within-subject factors, demonstrated main effect of Distractor, $F(1, 19) = 122.01$, $p < .001$, $\eta_g^2 = 0.86$, $BF_{incl} > 100$; more accurate responses were evidenced for distractor-absent compared to distractor-present trials (91.8% vs. 88.3%, respectively). Main effects of Session, $F(1, 19) = 0.75$, $p = .398$, $\eta_g^2 = 0.04$, $BF_{incl} = 0.42$, was non-significant but with a slightly numerical advantage of neutral over the anxiety session (90.5% vs. 89.7%, respectively), whereas marginal significance was found for Response-type, $F(1, 19) = 3.84$, $p = 0.07$, $\eta_g^2 = 0.16$, $BF_{incl} = 11.87$, demonstrated numerically more accurate Go compared to No-go responses (91% vs. 89.2%, respectively), suggesting inhibiting response was more difficult than the go trials.

Fig. 2 depicts a statistically significant two-way interaction between Response-type and Distractor, $F(1, 19) = 11.98$, $p = 0.003$,$\eta_g^2 = 0.39$, $BF_{incl} = 0.96$, showing the distractor interference (Distractor Present vs. Absent) was significantly different between the Go trials (Interference: 2.4%) and the No-Go trials (Interference: 4.5%). A post-hoc comparison showed that it was mainly due to the significant lower accuracy in the No-go distractor-present condition (86.9%) as compared to the No-go distractor-absent condition (91.4%, $t(1, 39) = 9.70$, $p < .001$), and to the Go distractor-present condition (89.8%, $t(1, 39) = -3.57$, $p < .001$). This suggests that the presence of a distractor in the No-go trials was hard to inhibit responses as compared to those Go-trials (see Figure 2b). However, the other interactions, including the interactions with the anxiety, were statistically non-significant (*ps* > 0.354, *BFs* < 0.35).

Figure 2. Interaction between Response-type and Distractor separately for the neutral and anxiety sessions



Note. a) Mean response accuracy for Response-type (Go and No-go) and Distractor (present and absent), separately for the neutral and the anxiety session, b) distractor interference (%) for neutral and anxiety session in regard to Response-type. The error bars represent 1 standard error.

Relation between overall accuracy, RT, distractor interference and individual state and trait of anxiety

Similar to the previous studies, we failed to find any significant manipulation of anxiety on the group level (Kappenman et al. 2014; Kappenman et al. 2015). However, the previous study showed a negative linear relation between the state anxiety and the visual search performance (Moser et al. 2012). Thus, here we further performed multiple regression analysis to estimate whether intra-individual state anxiety may predict overall accuracy, RT, and distractor interference (i.e., ms and %). We calculated forward stepwise regression analysis for overall participants' accuracy and RT separately for the distractor-absent and the distractor-present trials, including state and trait anxiety as predictor variables, and Session and Response Type as factors. Again, we used distractor interference as criteria, state and trait anxiety scores as predictor variables, and Session, and Response type as factors. Distractor interference was calculated separately for speed (ms) and accuracy (%).

For RTs, the forward stepwise regression analysis model including state and trait anxiety as predictors and Session and Distractor as factors (overall model: $R^2 = 0.07$, $F(1, 79) = 5.89$, $p = .017$), demonstrated that RT was predicted by State anxiety, B = -0.004, S.E = 0.001, $\beta = -0.26$, $t = -2.42$, $p = .018$. We then calculated the distractor interference based on the difference between the distractor present vs. absent, and conducted a linear regression to the state anxiety, B = -1.01, S.E = 0.49, $\beta = -0.32$, $t = -2.07$, $p = .045$, (overall model: $R^2 = 0.10$, $F(1, 39) = 4.30$, $p = .045$), whereas the factors of trait anxiety and Session were failed to be included in the regression. This suggests that participants' speed was facilitated by state anxiety in such a way that individual RT was faster when state anxiety was higher and vice versa. Moreover, state anxiety modulated the association between the distractor-present and the distractor absent trials by the slowed effect of distractor interference. Higher state anxiety influences less distractor interference upon relative optimisation of individual speed response related either with the distractor present or distractor absent trials.

For accuracy, the forward stepwise regression analysis model including state and trait anxiety as predictors and Session, Distractor and Response type as factors (overall model: $R^2 = 0.32$, $F(4, 159) = 18.02$, $p < .001$), also demonstrated that accuracy was predicted by State anxiety, B = -0.001, S.E < 0.001, $\beta = -0.250$, $t = -3.75$, $p < .001$, Trait anxiety, B = -0.002, S.E < 0.001, $\beta = -0.39$, $t = -5.87$, $p < .001$, Distractor, B = -0.03, S.E = 0.007, $\beta = -0.31$, $t = -4.67$, $p < .001$, and Response type, B = 0.02, S.E = 0.02, $\beta = 0.16$, $t = 2.42$, $p = .017$. There was a statistically significant main interaction between State anxiety and Response type, B = -0.001, S.E < 0.001, $\beta = -0.22$, $t = -2.77$, $p = .006$, and also between Trait anxiety and Response type, B = -0.002, S.E = 0.001, $\beta = -0.85$, $t = -3.40$, $p = .001$. Moreover, further linear regression analysis showed that Distractor interference (%) was predicted significantly by Response type, B = -2.07, S.E = 0.60, $\beta = -0.36$, $t = -3.45$, $p = .001$ (overall model: $R^2 = 0.13$, $F(1, 79) = 11.90$, $p < .001$), whereas State anxiety, Trait anxiety, and Session was non-significant predictors. This suggests that participants' accuracy was modulated by state and trait anxiety in such a way that the higher state or trait anxiety was associated with lower accuracy and vice versa. Also, participants with higher state and trait anxiety responded less accurately in the No-go than Go trials. In addition, distractor interference (ms) was higher in No-go compared to Go condition.

EEG results

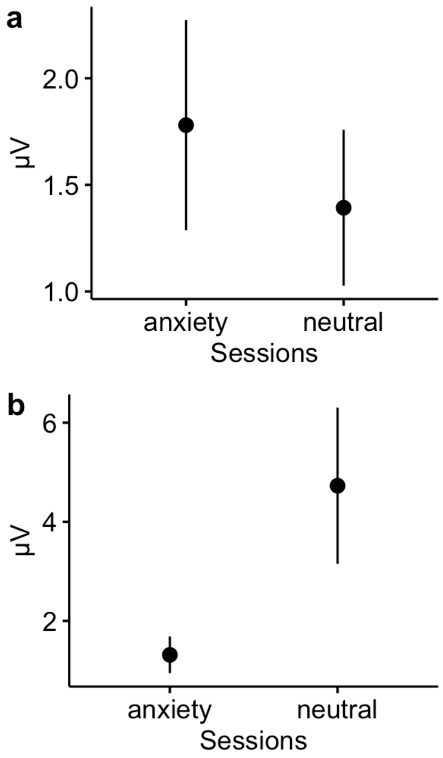
Dual-target selection for distractor-absent trials: Ppc

In order to focus on the neuropsychological mechanisms underlying goal-directed attention during dual-target visual search, we calculated *difference-waveform* as contralateral minus ipsilateral wave, comparing the anxiety and neutral sessions separately for the Go and No-go conditions. We then searched for the local peak amplitudes near in between 90 - 120 ms for the Ppc amplitudes. Then, we computed multiple regression analysis predicting Ppc based on state and trait anxiety separately for the Go and No-go condition.

Difference-waveform was tested separately for the response-type conditions, comparing the neutral and the anxiety session. Considering the Go condition (see Figure 3a), an independent t-test demonstrated the local-peak amplitude did not differentiate between the anxiety and the neutral session (*M* = 1.78 vs. 1.39 µV, respectively; *t*(34) = 0.63, *p* = .532, *d* = 0.211, BF_{10} = 0.38), whereas in the No-go condition (see Figure 3b), the local-peak amplitude of difference-waveform Ppc was statistically greater in the anxiety compared to the neutral session (*M* = 1.31 vs. 4.73 µV, respectively; *t*(34) = 2.11, *p* = .043, *d* = 0.702, BF_{10} = 1.72). Thus, the obtained result supports the hypothesis based on prior literature (Eysenck et al. 2007) that differentiating the neutral and anxiety conditions in regard to inhibition function, that is, stress diminished individual ability to inhibit irrelevant and focus on the task-relevant information.

Multiple regression analysis showed state and trait anxiety, involving the factor of Session, was a non-significant predictor of *difference-waveform* Ppc for Go (*p*s < .151), or No-go condition (*p*s < .209). Hence, individual state or trait anxiety was not associated with the Ppc component.

Figure 3. Difference-waveforms Ppc between the neutral and the anxiety session for the No-go and Go responses



Note. Difference-waveform Ppc between the anxiety and the neutral session separately for a) No-go and b) Go responses.

Dual-target selection for distractor-absent trials: N2pc

Similar to Ppc, we calculated the difference between contralateral minus ipsilateral waves, and then searched for the N2pc peaks in between 230-290 ms for the target-only trials. Considering *difference-waveforms* for the Go trials an independent *t*-test demonstrated no difference between the anxiety and the neutral session for the N2pc (M = -1.03 µV, M = -1.98 µV, respectively; $t(34) = 1.24$, $p = .225$, $d = 0.41$, $BF_{10} = 0.582$). Also, in the No-go trials there was no significant difference between anxiety and neutral sessions in the N2pc (M = -2.25 µV, M = -0.06 µV, respectively; $t(34) = 1.33$, $p = .192$, $d = 0.44$, $BF_{10} = 0.64$).

Multiple regression analysis demonstrated that state and trait anxiety, involving the factor of Session, was a non-significant predictor of *difference-waveform* N2pc for Go (ps < .216), or No-go condition (ps < .169). Individual state or trait anxiety is not linked to the N2pc component.

Dual-target selection for distractor-present trials: PD

To examine the *PD* component, we calculated the difference between contralateral minus ipsilateral waves for only distractor-present presentations separately for Go and No-go trials. No difference was found between the anxiety and the neutral sessions in regard to difference-waveforms (p*s* > .173, BF*s* < 0.68).

Multiple regression analysis showed state and trait anxiety, involving the factor of Session, was a non-significant predictor of *difference-waveform* PD for Go (*p*s < .110), or No-go condition (*p*s < .416).

Discussion

The present EEG study investigated neural and behavioral mechanisms underlying goal-directed attention under experimentally induced state anxiety due to the facilitation/impairment of top-down attentional control using a novel dual-target attention paradigm. In particular, we investigated whether the anxiety and the neutral session differ in the individual neuropsychological local peak-amplitude in a visual dual-target presented laterally with absent-distractor trials (Ppc and N2pc) and a dual-target presented on the midline with a lateral distractor (PD). In addition, the association between emotions and attentional control was examined by including intra-individual differences in their relationship. As such, the correlations between state/trait anxiety and ERPs was estimated.

Behaviorally, at a *group-level* analysis we found no evidence that participants' mean RT and accuracy differ across the neutral and the anxiety sessions. Hence, personal trait anxiety and a response to state-dependent anxiety can affect obtained group results since posible anxiety resistance or overreacting may diminish mean differences between the anxiety and neutral session. As such, we focus on individual state and trait anxiety based on prior study (Moser et al. 2012). In line with a wider range of previous behavioral findings (Zhang et al. 2019; Allenmark et al. 2019; Goschy et al. 2014), we found distractor interference in the dual-target visual search for accuracy but not for RT; participants responded faster and more accurately in the distractor-absent than the distractor-present trials. Dual-target visual search was affected by a task-irrelevant and physically salient red item. In general, participants responded numerically less accurately in the No-go than the Go trials, but the obtained finding was marginal; however, this behavioral pattern was not related with the anxiety or the neutral session. Thus, participants' inhibition (e.g., No-go responses) function in the anxiety session demonstrated a uniform pattern as in the neutral session. Moreover, significant interaction between Distractor condition and Response-type was evidenced, since participants responded less accurately in the No-go distractor-present trials than the No-go distractor absent condition and the Go distractor-present condition. This suggests that exposure of the physically salient distractor during the dual-target visual search, highly interfered with responses in the No-go trials compared to Go-trials trials. In line with Miyake et al. (2000) concept of executive functions, the ACT proposes greater vulnerability of inhibition function in high anxiety individuals (Eysenck et al. 2007; Eysenck and Derakshan 2011). We failed to find *a group-level* evidence between the anxiety and neutral session in regard to inhibition response; however, involving state and trait anxiety revealed a link emphasizing intra-individual differences. Thus, at a *group-level* analysis the obtained findings are more in line with theoretical accounts that suggest equal performance by non-anxious and anxious individuals (Blankstein et al. 1990). Of note, the ACT discussed the very high or even extreme levels of stress influence into attentional mechanisms, whereas we employed an aversive movie that may have affected arousal at first and just partially modulated emotions of anxiety.

At an *intra-individual-level* of analysis, involving the association between personality trait, state anxiety and attentional performance in the visual search, demonstrated significant correlations. We found that RT was facilitated by state anxiety, thus participants responded faster when they gained higher state-dependent anxiety, in line with prior study (Moser et al. 2012) reported less accurately responses associated with the high anxiety traits. Typically, visual search studies (Jia et al. 2013) reported response facilitation due to increased anxiety or even arousal, psychological tension boost motor response, but without decreasing response accuracy. Interestingly, increased state anxiety leads to less distractor interference (ms). Possibly less distractor interference was caused due to relative optimisation of the participants motor response; overall facilitated speed under increased state anxiety resulted in both distractor-present and distractor-absent condition response facilitation. As such, distractor interference related by accuracy did not show influence of state anxiety, so may be more motor response rather than attentional mechanisms. Critically, regression analyses provide behavioral evidence that both state and trait anxiety may impaired goal-directed attention by reducing overall accuracy performance in the visual dual-target search.

In line with ACT (Eysenck et al. 2007; Eysenck and Derakshan 2011) holding that increased anxiety would sensitize human perception for a physically salient distractor by attentional capture/interference due to reduced inhibition function, we found significant interaction between participants' state and trait anxiety and response type. Hence, higher anxiety influences less accurate response inhibition, whereas lower anxiety leads to higher attentional performance related to inhibition response. However, ACT assumes that impairment of inhibition response is related to bottom-up domination in anxious individuals (Shi et al., 2019), we find no evidence that involves personal anxiety level. As such, it seems that some individuals are resistant to aversive visual stimulation, whereas in some anxiety elicits impairment of goal-directed visual search for dual-target visual search due to top-down reduction. Nevertheless, at a *group-level* analysis a distractor affects response inhibition as we discussed earlier.

Overall, ERPs results were consistent to some extent with behavioral findings. In addition to behavioral findings that failed to demonstrate anxiety-neutral valence differentiation at *group-level* analyses, but highly promoting the association between attentional control and intra-individual emotional vulnerability such as trait and state anxiety, ERPs provided additional evidence of neural mechanisms underlying the anxiety-attention relationship. As pointed out by Luck (2014) increased arousal typically associated with higher sensory responsiveness, thus can affect attention-sensitive component P1, and related derivatives such as Ppc that occurred with positive-going phase of P1 (Verleger et al. 2012). Critically, the Ppc component significantly differed between the anxiety and the neutral session in the No-go (i.e., response inhibition) condition, supporting theoretical account of the ACT pointing out impairment of inhibition function in anxious individuals (Shi et al. 2019; Eysenck et al. 2007; Eysenck and Derakshan 2011). Along these lines, larger sensory responsiveness due to increased arousal in the anxiety session potentially caused significant Ppc deflection. Behaviorally, the anxious individuals show less flexibility at adjusting the visual task demands (Pacheco-Unguetti et al. 2012), and decreased regulation of attentional control mechanisms (Derryberry and Reed 2002). Since greater attentional control is required for the response inhibition in the task, evidenced differences between the anxiety and the neutral session in the Ppc deflection provide neurophysiological evidence in favor of attentional control bias in anxiety. Increased attentional alertness in anxiety may decrease ability to regulate inhibition of the motor responses since attentional focus is relocated toward threat. Both behavioral and EEG results supporting the ACT refers to attentional control and inhibition.

Early studies (Luck et al. 1994) reported that P1 reflects the *cost of attention*, a shift that occurs from a particular attended location toward a target-relevant location, whereas N1 reflects the *benefit of attention* in which the attended location matches with real stimuli display. Luck (1990) indicated that the P1 component is enhanced in response to attended unilateral stimuli, representing a suppression of non-target locations, or facilitation of early sensory processing for search stimuli presented to a location where the observer already focuses his attention. However, in the dual-target task, locations of targets are equally relevant for a successful task accomplishment. As such, in the dual-target search Ppc may reflect early processing of identifying the first target item in the visual field and subsequent perceptual action toward the second item. Hence, the Ppc deflection in response to dual-target, instead of the *cost of attention* for unattended spatial locations as defined in early studies for the P1 component (Luck et al. 1994), the Ppc may actually reflect early targets detection.

We found neither the N2pc nor P_D was significant. Although typical attentional components include the N2pc and P_D (Gaspar et al. 2016; Dodwell et al. 2021), the N2pc was attenuated under strong Ppc deflection elicited by demanding attentional deployment for multiple objects. Hence, the obtained time-locked ERPs matched the expected N2pc waveforms, however, the N2pc was attenuated due to early covert attention from one searched object toward the next one. Although we failed to evidence differentiation in the behavioral (i.e., RT, accuracy) performance between anxiety and neutral sessions, we revealed that Ppc differs for the time-locked No-go trials. In an induced anxiety state, an observer's attentional performance related to inhibition function is affected at an early level of neurophysiology processing, although this is not evidenced at the behavioral level. This neuropsychological-behavioral dissociation is not unusual for EEG studies keeping in mind that Ppc occurred hundreds of milliseconds before actual participants' motor response. Prior studies (Luck and Kappenman 2011; Kappenman et al. 2014) have, for example, reported dissociation between the N2pc and RT-based measures. Along these lines, our findings confirmed the ACT demonstrating a different pattern in early attentional processing under the emotion of anxiety.

In sum, the present study demonstrated behavioral association between attentional control mechanisms and personal state and trait anxiety. Attentional control is modulated by increased anxiety in such a way to impaired accuracy and facilitated speed response. Increased state anxiety and personal trait anxiety affects No-go trials by impairing participants' inhibition responses. In line with behavioral findings, ERPs demonstrated that in the anxiety session the elicited Ppc was modulated by attentional covert toward the early visual processing of dual-target in the Go condition. Attentional control related to response inhibition was impaired in the anxiety compared to the neutral session since Ppc differs across sessions for the No-go condition. Taken together, state-dependent and personality trait anxiety modulates behavioral and neurophysiological attentional control mechanisms related to reduction of goal-directed attention and inhibition response.

References

Allenmark, F., Zhang, B., Liesefeld, H. R., Shi, Z., & Müller, H. J. (2019). Probability cueing of singleton-distractor regions in visual search: the locus of spatial distractor suppression is determined by colour swapping. In *Visual Cognition* (pp. 1–19). https://doi.org/10.1080/13506285.2019.1666953

American Electroencephalographic Society Guidelines in Electroencephalography, Evoked Potentials, and Polysomnography. (1994). Raven Press. https://play.google.com/store/books/details?id=HncZHQAACAAJ

American Psychiatric Association. (2015). *Anxiety Disorders: DSM-5® Selections*. American Psychiatric Pub. https://play.google.com/store/books/details?id=VHqcCgAAQBAJ

Awh, E., Belopolsky, A. V., & Theeuwes, J. (2012). Top-down versus bottom-up attentional control: a failed theoretical dichotomy. *Trends in Cognitive Sciences*, *16*(8), 437–443. https://doi.org/10.1016/j.tics.2012.06.010

Bacon, W. F., & Egeth, H. E. (1994). Overriding stimulus-driven attentional capture. *Perception & Psychophysics*, *55*(5), 485–496. https://doi.org/10.3758/bf03205306

Basten, U., Stelzel, C., & Fiebach, C. J. (2011). Trait anxiety modulates the neural efficiency of inhibitory control. *Journal of Cognitive Neuroscience*, *23*(10), 3132–3145. https://doi.org/10.1162/jocn_a_00003

Berggren, N., & Derakshan, N. (2013). Attentional control deficits in trait anxiety: Why you see them and why you don't. In *Biological Psychology* (Vol. 92, Issue 3, pp. 440–446). https://doi.org/10.1016/j.biopsycho.2012.03.007

Bishop, S. J. (2009). Trait anxiety and impoverished prefrontal control of attention. *Nature Neuroscience*, *12*(1), 92–98. https://doi.org/10.1038/nn.2242

Blankstein, K. R., Flett, G. L., Boase, P., & Toner, B. B. (1990). Thought listing and endorsement measures of self-referential thinking in test anxiety. *Anxiety Research*, *2*(2), 103–112. https://doi.org/10.1080/08917779008249329

Byrne, A., & Eysenck, M. W. (1995). Trait anxiety, anxious mood, and threat detection. *Cognition and Emotion*, *9*(6), 549–562. https://doi.org/10.1080/02699939508408982

Dalgleish, T. (2004). The emotional brain. *Nature Reviews. Neuroscience*, *5*(7), 583–589. https://doi.org/10.1038/nrn1432

Delorme, A., & Makeig, S. (2004). EEGLAB: an open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. *Journal of Neuroscience Methods*, *134*(1), 9–21. https://doi.org/10.1016/j.jneumeth.2003.10.009

Dodwell, G., Liesefeld, H. R., Conci, M., Müller, H. J., & Töllner, T. (2021). EEG evidence for enhanced attentional performance during moderate-intensity exercise. *Psychophysiology*, *58*(12), e13923. https://doi.org/10.1111/psyp.13923

Eysenck, M. W., & Derakshan, N. (2011). New perspectives in attentional control theory. *Personality and Individual Differences*, *50*(7), 955–960. https://doi.org/10.1016/j.paid.2010.08.019

Eysenck, M. W., Derakshan, N., Santos, R., & Calvo, M. G. (2007). Anxiety and cognitive performance: attentional control theory. *Emotion* , *7*(2), 336–353. https://doi.org/10.1037/1528-3542.7.2.336

Faul, F., Erdfelder, E., Lang, A.-G., & Buchner, A. (2007). G*Power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods*, *39*(2), 175–191. https://doi.org/10.3758/bf03193146

Garrido, M. I., Barnes, G. R., Sahani, M., & Dolan, R. J. (2012). Functional evidence for a dual route to amygdala. *Current Biology: CB*, *22*(2), 129–134. https://doi.org/10.1016/j.cub.2011.11.056

Gaspar, J. M., Christie, G. J., Prime, D. J., Jolicœur, P., & McDonald, J. J. (2016). Inability to suppress salient distractors predicts low visual working memory capacity. *Proceedings of the National Academy of Sciences of the United States of America*, *113*(13), 3693–3698. https://doi.org/10.1073/pnas.1523471113

Ghassemzadeh, H., Rothbart, M. K., & Posner, M. I. (2019). Anxiety and Brain Networks of Attentional Control. *Cognitive and Behavioral Neurology: Official Journal of the Society for Behavioral and Cognitive Neurology*, *32*(1), 54–62. https://doi.org/10.1097/WNN.0000000000000181

Herrmann, M. J., Ehlis, A.-C., Ellgring, H., & Fallgatter, A. J. (2005). Early stages (P100) of face perception in humans as measured with event-related potentials (ERPs). *Journal of Neural Transmission* , *112*(8), 1073–1081. https://doi.org/10.1007/s00702-004-0250-8

Hickey, C., Di Lollo, V., & McDonald, J. J. (2009). Electrophysiological indices of target and distractor processing in visual search. *Journal of Cognitive Neuroscience*, *21*(4), 760–775. https://doi.org/10.1162/jocn.2009.21039

Hu, K., Bauer, A., Padmala, S., & Pessoa, L. (2012). Threat of bodily harm has opposing effects on cognition. *Emotion* , *12*(1), 28–32. https://doi.org/10.1037/a0024345

Itier, R. J., & Taylor, M. J. (2004). N170 or N1? Spatiotemporal differences between object and face processing using ERPs. *Cerebral Cortex* , *14*(2), 132–142. https://doi.org/10.1093/cercor/bhg111

Kappenman, E. S., Farrens, J. L., Luck, S. J., & Proudfit, G. H. (2014). Behavioral and ERP measures of attentional bias to threat in the dot-probe task: poor reliability and lack of correlation with anxiety. *Frontiers in Psychology*, *5*, 1368. https://doi.org/10.3389/fpsyg.2014.01368

Kass, R. E., & Raftery, A. E. (1995). Bayes Factors. *Journal of the American Statistical Association*, *90*(430), 773–795. https://doi.org/10.1080/01621459.1995.10476572

Kim, A. J., Lee, D. S., & Anderson, B. A. (2021). The influence of threat on the efficiency of goal-directed attentional control. *Psychological Research*, *85*(3), 980–986. https://doi.org/10.1007/s00426-020-01321-4

LeDoux, J. E. (1996). The Emotional Brain Simon Schuster. *New York*, *384*.

LeDoux, J. E., & Pine, D. S. (2016). Using Neuroscience to Help Understand Fear and Anxiety: A Two-System Framework. *The American Journal of Psychiatry*, *173*(11), 1083–1093. https://doi.org/10.1176/appi.ajp.2016.16030353

Lopez-Calderon, J., & Luck, S. J. (2014). ERPLAB: an open-source toolbox for the analysis of event-related potentials. *Frontiers in Human Neuroscience*, *8*, 213. https://doi.org/10.3389/fnhum.2014.00213

Luck, S. J. (2014). *An Introduction to the Event-Related Potential Technique, second edition*. MIT Press. https://play.google.com/store/books/details?id=y4-uAwAAQBAJ

Luck, S. J., Hillyard, S. A., Mouloua, M., Woldorff, M. G., Clark, V. P., & Hawkins, H. L. (1994). Effects of spatial cuing on luminance detectability: psychophysical and electrophysiological evidence for early selection. *Journal of Experimental Psychology. Human Perception and Performance*, *20*(4), 887–904. https://doi.org/10.1037//0096-1523.20.4.887

Luck, S. J., & Kappenman, E. S. (2011). *The Oxford Handbook of Event-Related Potential Components*. Oxford University Press. https://play.google.com/store/books/details?id=gItoAgAAQBAJ

Mangun, G. R. (1995). Neural mechanisms of visual selective attention. *Psychophysiology*, *32*(1), 4–18. https://doi.org/10.1111/j.1469-8986.1995.tb03400.x

McCarty, R. (2016). Chapter 4 - The Fight-or-Flight Response: A Cornerstone of Stress Research. In G. Fink (Ed.), *Stress: Concepts, Cognition, Emotion, and Behavior* (pp. 33–37). Academic Press. https://doi.org/10.1016/B978-0-12-800951-2.00004-2

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex “Frontal Lobe” tasks: a latent variable analysis. *Cognitive Psychology*, *41*(1), 49–100. https://doi.org/10.1006/cogp.1999.0734

Moser, J. S., Becker, M. W., & Moran, T. P. (2012). Enhanced attentional capture in trait anxiety. *Emotion* , *12*(2), 213–216. https://doi.org/10.1037/a0026156

Peirce, Gray, J. R., Simpson, S., MacAskill, M., Höchenberger, R., Sogo, H., Kastman, E., & Lindeløv, J. K. (2019). PsychoPy2: Experiments in behavior made easy. *Behavior Research Methods*, *51*(1), 195–203. https://doi.org/10.3758/s13428-018-01193-y

Robinson, O. J., Vytal, K., Cornwell, B. R., & Grillon, C. (2013). The impact of anxiety upon cognition: perspectives from human threat of shock studies. *Frontiers in Human Neuroscience*, *7*, 203. https://doi.org/10.3389/fnhum.2013.00203

Shi, R., Sharpe, L., & Abbott, M. (2019). A meta-analysis of the relationship between anxiety and attentional control. *Clinical Psychology Review*, *72*, 101754. https://doi.org/10.1016/j.cpr.2019.101754

Spielberger, C. D., Gorsuch, R. L., Lushene, R., Vagg, P. R., & Jacobs, G. A. (1983). Consulting Psychologists Press; Palo Alto, CA: 1983. *Manual for the State-Trait Anxiety Inventory. [Google Scholar]*.

Stanković, M., & Nešić, M. (2020). Functional brain asymmetry for emotions: psychological stress-induced reversed hemispheric asymmetry in emotional face perception. *Experimental Brain Research. Experimentelle Hirnforschung. Experimentation Cerebrale*. https://doi.org/10.1007/s00221-020-05920-w

Sussman, T. J., Heller, W., Miller, G. A., & Mohanty, A. (2013). Emotional distractors can enhance attention. *Psychological Science*, *24*(11), 2322–2328. https://doi.org/10.1177/0956797613492774

Telzer, E. H., Mogg, K., Bradley, B. P., Mai, X., Ernst, M., Pine, D. S., & Monk, C. S. (2008). Relationship between trait anxiety, prefrontal cortex, and attention bias to angry faces in children and adolescents. *Biological Psychology*, *79*(2), 216–222. https://doi.org/10.1016/j.biopsycho.2008.05.004

Theeuwes, J. (1991). Cross-dimensional perceptual selectivity. *Perception & Psychophysics*, *50*(2), 184–193. https://doi.org/10.3758/bf03212219

Theeuwes, J., & Failing, M. (2020). *Attentional Selection: Top-Down, Bottom-Up and History-Based Biases*. Cambridge University Press. https://play.google.com/store/books/details?id=Y732DwAAQBAJ

Vuilleumier, P. (2005). How brains beware: neural mechanisms of emotional attention. In *Trends in Cognitive Sciences* (Vol. 9, Issue 12, pp. 585–594). https://doi.org/10.1016/j.tics.2005.10.011

Wang, B., & Theeuwes, J. (2018). Statistical regularities modulate attentional capture. *Journal of Experimental Psychology. Human Perception and Performance*, *44*(1), 13–17. https://doi.org/10.1037/xhp0000472

Zhang, B., Allenmark, F., Liesefeld, H. R., Shi, Z., & Muller, H. (2019). Probability cueing of singleton-distractor locations in visual search: priority-map-or dimension-based inhibition? *Journal of Experimental Psychology. Human Perception and Performance*. https://doi.org/10.1037/xhp0000652.

5.4. Functional brain asymmetry for emotions: Psychological stress-induced reversed hemispheric asymmetry in emotional face perception

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Functional brain asymmetry for emotions: Psychological stress-induced reversed hemispheric asymmetry in emotional face perception

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Abstract

Empirical evidence demonstrated functional brain (mostly right-biased) asymmetry for emotion perception, whereas recent studies indicate that acute stress may modulate left and/or right hemisphere activation. However, it is still unknown whether emotion perception can be influenced by stress-induced hemispheric activation since behavioral studies report inconsistent or even contradictory results. We sought to reevaluate this gap. Eighty-eight healthy Caucasian university students participated in the study. In half of the randomly selected participants, acute psychological stress was induced by displaying a brief stressful movie clip (the stress condition), whereas the other half was shown a neutral movie clip (the non-stress condition). Prior to (the baseline) and following the movie clip display an emotion perception task was applied by presenting an emotional (happy, surprised, fearful, sad, angry, or disgusted) or neutral face to the left or right visual field. We found a more accurate perception of emotional and neutral faces presented to the LVF (the right hemisphere) in the baseline. However, we revealed that after watching a neutral movie clip, behavioral performance in emotional and neutral face perception accuracy became relatively equalized for both visual fields, while after watching a stressful movie clip the RVF (the left hemisphere) even became dominant in emotional face perception. We propose a novel hemispheric functional-equivalence model: the brain is initially right-biased in emotional and neutral face perception by default; however, psychophysiological activation of a distributed brain-network due to watching neutral movie clips redistributes hemispheric performance toward relative equivalence. Moreover, even reversed hemispheric asymmetry may occur.

Keywords: stress; emotion perception; functional brain asymmetry; hemispheric dominance; hemispheric functional-equivalence model

Introduction

A growing body of evidence suggests that stress may modulate functional brain asymmetry (FBA). Stress may affect the functional activity of the left hemisphere (LH) and/or the right hemisphere (RH) due to hormonal effects (e.g., glucocorticoids; Ocklenburg et al., 2016; Ströckens et al., 2013). This modulation of FBA by stress causes changes in cognitive abilities (e.g., attention), emotions (e.g., emotion perception), and/or physiological condition (e.g., cortisol levels) in individuals. Stress modulates emotion perception ability (Barel & Cohen, 2018; Daudelin-Peltier et al., 2017; Domes & Zimmer, 2019). Acute stress may result in greater involvement of the RH (although not always) - FBA decreases in dominant RH, whereas increases in dominant LH (Ocklenburg et al., 2016). Furthermore, stress affects the interhemispheric transfer of information important for emotion perception (Brüne, Nadolny, Güntürkün, & Wolf, 2013), thus suggesting a close association of stress and emotional processing with FBA. Since Ekman, in his pioneering work (Ekman, 1970; Ekman & Friesen, 1971), proposed that facial expressions represent basic emotions of happiness, surprise, fear, sadness, anger, and disgust, this conceptual framework has become broadly accepted worldwide in research on emotion perception. The facial expression of happiness is characterized by positive valence, whereas facial expressions of fear, sadness, anger, and disgust are of negative valence. A partial exception is the facial emotion of surprise typically interpreted as a "cognitive" emotion that may be experienced as pleasant or unpleasant depending on the observer's beliefs (Baron-Cohen et al., 1993). Numerous studies have shown an association of FBA with basic emotion perception. In pioneering research, Mills observed the association of a unilateral right-sided lesion with a decrease in emotional expression (Mills, 1912a, 1912b), indifference, or mania (Denny-Brown, Meyer, & Horenstein, 1952). There are at least four suggested models of FBA in basic emotion perception. The most prominent is the Right-Hemisphere Hypothesis (RHH) suggesting the RH dominance for the perception of all emotions (Adolphs, Damasio, Tranel, & Damasio, 1996; Alves, Aznar-Casanova, & Fukusima, 2009; Borod et al., 1998; Bourne & Hole, 2006; Gainotti, 2019b). The Valence-Specific Hypothesis (VSH) implies the RH dominance for the perception of facial expressions of negative emotions (fearful, sad, angry, disgusted), whereas the LH dominance for the perception of facial expressions of positive emotions (happy, surprised) (Davidson et al., 1987; Prete, Laeng, & Tommasi, 2014; Wedding & Stalans, 1985). The Modified Valence-Specific Hypothesis (MVSH) integrates RHH and VSH implying simultaneous operations in both hemispheres during emotion perception i.e. the RH posterior dominance for the perception of emotional facial expressions followed by a frontal valence-specific involvement (Killgore & Yurgelun-Todd, 2007). The Motivation Model (MM) is an approach/withdrawal model implying the LH dominance for the perception of approach-related emotions (e.g., happiness, anger), whereas the RH dominance for the perception of withdrawal-related emotions (e.g., fear) (Davidson, 1992; Poole & Gable, 2014). The suggested models are entirely or at least partly contradictory. Thus, in recent years, there has been a tendency to integrate the existing models. Additionally, there are other less-known FBA models proposing that the RH processes negative and positive emotions by default, whereas the LH mediates in high-level processing of emotional information (Shobe, 2014); information from the RH is shared with the LH via the corpus callosum, whereas the LH further integrates emotion perception into a unique emotional experience.

However, data from FBA behavioral studies on emotion perception are inconsistent. A growing number of studies have demonstrated that none of the proposed models (RHH, VSH, MVSH, and MM) is replicable in studies conducted on healthy individuals (Demaree, Everhart, Youngstrom, & Harrison, 2005; Prete et al., 2018; Stanković, Nešić, et al., 2019; Stanković & Nešić, 2019) or clinical samples (Stanković, et al., 2015). Data from a recent EEG auditory study (Papousek et al. 2012) support the unsustainability of the existing FBA models, demonstrating a change in lateralization as a function of emotional states; the left-right activation pattern changes depending on a negative (shift to the right activation) or positive emotional stimulus (shift to the left activation). Arnsten (2009) indicated that exposure to even mild acute stress causes a switch from prefrontal cortex regulation to rapid emotional response of the amygdala and related subcortical structures of the brain. The amygdala and related subcortical structures play a key role in the perception of emotions, primarily fear (Guex et al., 2020; Skiba & Vuilleumier, 2020). A distributed neural brain-network in neutral face perception includes the inferior occipital and fusiform cortex, whereas emotional face perception also involves the amygdala (Gainotti, 2019a; Vuilleumier & Pourtois, 2007), orbitofrontal, cingulate, superior temporal sulcus, somatosensory and insula cortex (Krolak-Salmon et al., 2004; Winston et al., 2003). This strongly suggests that the brain is a multi-layered and highly integrated system in emotional and neutral face perception that is not limited by lateralization. A functional component of the involvement of both hemispheres in emotional processing in a perception task leads to goal achievement in a relevant task due to self-preservation and well-being. A recent magnetoencephalographic (MEG) study (Kajal et al., 2020) using a task of facial expression perception has demonstrated that the right-hemispheric fronto-parietal network is more active in accurate emotional face perception, whereas the left frontal and right parietal regions are more active during inaccurate emotional face perception. This suggests that the brain may be biased toward the RH predominance in emotional and neutral face perception; however, increased task requirements cause increased engagement of both hemispheres. Early research provided empirical evidence that a demanding task requirement (i.e., the perception of physical features and identities of letters) enhances behavioral performance due to the distribution of processing between the hemispheres (Banich & Belger, 1990). The aforementioned FBA models somewhat exclude the possibility of modulating the lateralization of emotion perception by external factors. However, recent studies have provided evidence that mental performance of the hemispheres may be modulated by certain techniques, such as the possibility of enhancing local attentional performance by a unilateral right-hand contraction due to the LH activation (Stanković & Nešić, 2018), although such hand contraction has no effect on perception accuracy of emotional (happy and sad) and neutral faces presented bilaterally (Stanković & Nešić, 2019), or demonstrated that psychological stress conditions may cause a valence-specific pattern of FBA in an emotional attention task (Brüne et al., 2013). However, little is known about whether acute psychological stress modulates FBA in the perception of emotional faces in such a way that exposure to psychological stress would result in increased behavioral efficiency due to the functional redistribution of processing between the hemispheres.

The present study was designed to diminish this gap; hence, the crucial question investigated was whether there is evidence that the left-right bias in emotional and neutral face perception could be redistributed across hemispheres under induced psychological stress. Recent behavioral studies are inconsistent due to demonstrating faster recognition of an angry face with the RH, whereas of a happy face with the LH under acute stress conditions (Brüne et al., 2013). Acute psychological stress impairs the recognition of facial expressions of disgust (Daudelin-Peltier et al., 2017) and fear (Barel & Cohen, 2018), whereas improves the recognition of happy, surprised, angry, and neutral faces (Barel & Cohen, 2018; Domes & Zimmer, 2019) while some studies found no effect on sadness and disgust recognition (Barel & Cohen, 2018).

The present study aimed to examine a) whether the perception accuracy of emotional and neutral faces is higher in the left visual field (LVF) or the right visual field (RVF); b) individual differences in the perception accuracy of emotional and neutral faces presented to the LVF and the RVF prior to and following exposure to a short psychologically stressful or neutral movie clip.

We hypothesized a more accurate perception of emotional and neutral faces in LVF presentations compared with RVF presentations in the baseline. This is in line with previous studies demonstrating the RH dominance for emotional face perception (Adolphs et al., 1996; Alves et al., 2009; Borod et al., 1998; Bourne & Hole, 2006; Gainotti, 2019b). Furthermore, we hypothesized a more accurate perception of emotional and neutral faces presented to the LVF than the RVF in the non-stress condition while in the stress condition perception accuracy of LVF and RVF presentations would be relatively equalized. A recent study has demonstrated the RH predominance in accurate emotional face perception, whereas the involvement of the LH in inaccurate perception (Kajal et al., 2020). Moreover, increased task requirements lead to the redistribution of processing between the hemispheres (Banich & Belger, 1990; Hughes & Rutherford, 2013). We expected that psychological stress induction would result in functional redistribution in emotional and neutral face perception between both hemispheres; hence, the initial RH advantage would be redistributed, consequently resulting in relatively equalized performance of both hemispheres.

We used The Half Visual Field (HVF) methodology for a brief presentation of basic facial expressions (happy, surprised, fearful, sad, angry, and disgusted) and neutral faces to reevaluate the potential influence of psychological stress in emotion perception. The HVF methodology is based on the neurophysiological principle that a stimulus presented briefly in the LVF will be initially processed by the RH, while a stimulus presentation in the RVF will be initially processed by the LH (Bourne, 2006).

Methods

Participants

A total of 88 (47 female) healthy Caucasian students of the Faculty of Medicine (aged 20 to 27 years; *M* = 20.95, *SD* = 1.22) participated in this study voluntarily. The total number of participants was estimated using a statistical power analysis program G*Power (Faul et al., 2007) based on the average effect size of Cohen *d* = 0.8. The inclusion criteria were normal or corrected-to-normal vision and the absence of neurological and psychiatric disorders. All participants were right-handed as assessed by the Edinburgh Handedness Inventory-Short Form (Veale, 2014) since lateralization patterns are more consistent in right-handed individuals than in left-handers (Bourne, 2006).

Stimuli and instruments

Karolinska Directed Emotional Faces (KDEF; Lundqvist et al., 1998). A total of 48 color photographs of male and female facial expressions of emotions (fearful, angry, disgusted, sad, happy, and surprised; 8 photographs for each face) and 48 neutral faces were taken from the KDEF set.

State-Trait Anxiety Inventory (FormY-1; Spielberger, 1983). Anxiety Inventory contains 20 items ranked on a Likert type scale ranging from 1 – Not At All; 2 – Somewhat; 3 – Moderately So; 4 – Very much So. Participants responded to inventory items indicating their current emotional state. Normative scores ranged from 20 to 80; the higher score indicated greater anxiety. The internal consistency coefficient of Cronbach's α of the state-trait anxiety inventory obtained in our sample was $\alpha = .923$.

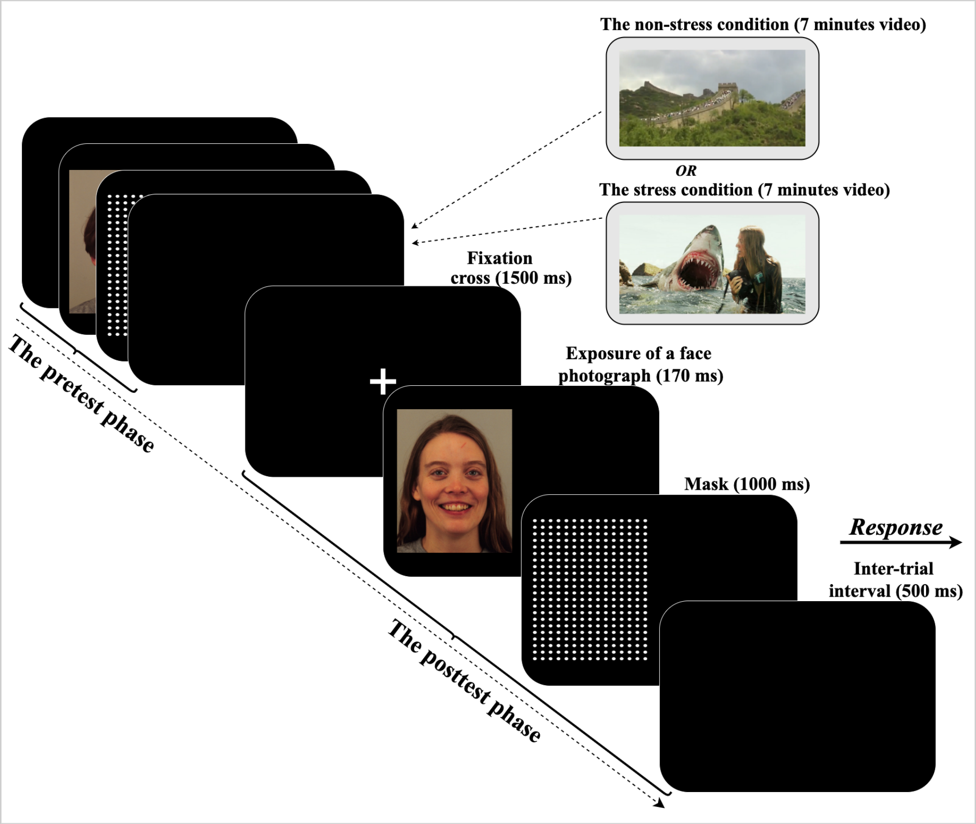
Psychological-stress scale. Psychological-stress scale is a self-assessment instrument used to examine the levels of participants's psychological stress (1 – not at all stressful to 7 – very stressful) of movie clips shown between the pretest and the posttest phase of the experiment.

Edinburgh Handedness Inventory-Short Form (Veale, 2014). Participants should respond to four statements indicating preferences in the use of hands in certain activities or with certain objects (Writing, Throwing, Toothbrush, and Spoon) on a Likert type scale – “always right”, “usually right”, “both equally”, “usually left” and “always left”. Cronbach’s α of this inventory obtained in our sample was $\alpha = .902$.

Procedure

The experiment was conducted at the laboratory of the Physiology Department, at the Faculty of Medicine, University of Nis, Serbia. A repeated measures design with independent conditions (stress and non-stress) was applied. The experimental procedure started with a pretest phase (including measurements of anxiety, blood pressure (BP), and an emotional and neutral face perception task), followed by displaying a movie clip and ended with a posttest phase (including measurements of anxiety, BP and an emotional and neutral face perception task). We first examined participants' anxiety using the State-Trait Anxiety Inventory and registered BP (systolic and diastolic) in the pretest phase. BP was registered using a digital automatic upper arm BP monitor (Omron M6 Comfort). Participants completed the emotion perception task afterward. After the pretest, participants were exposed to a movie clip, followed by repeated measurements of anxiety, BP, and the emotional and neutral face perception task in the posttest phase (Fig. 1)

Fig. 1. Experimental procedure flow.



Participants' physiological (BP) and psychological (current anxiety) values were registered in the pretest (baseline) phase. Participants were instructed to direct their gaze to a fixation cross followed by a randomly displayed face left or right of the fixation cross. Next, the face was covered by a mask, whereas participants were instructed to respond, whether a displayed face was emotional or neutral. There was a brief pause immediately after the completed pretest phase followed by a displayed stressful or neutral movie clip (rated on a self-assessment psychological-stress scale). In the posttest phase, BP and current anxiety were registered once more and the emotional and neutral face perception task was repeated afterward.

The stress condition was accomplished by presenting participants with a short movie clip with stressful content as in previous studies (Cook & Crewther, 2012), whereas participants in the non-stress condition watched a movie clip with neutral content. Half of the randomly selected participants (*n* = 44) were presented with a video sequence with stressful content taken from the movie „The Shallows„ (2016) (https://www.imdb.com/title/tt4052882/?ref_=vi_close). This movie clip depicted disturbing scenes of a shark attacking a female surfer, the anticipation of the attack, injuries caused by the attack, and scenes of other surfers suffering from a shark attack. The other half of the participants were presented with a sequence taken from a National Geographic documentary - The Great Wall of China (https://www.youtube.com/user/NationalGeographic/videos), depicting everyday life and architectural scenes. Both movie clips were of equal duration of 7 minutes. We used an additional psychological-stress scale after the movie clips were presented to examine the level of psychological stress of a video sequence in the stress and the non-stress condition in the posttest phase. The experimental procedure lasted approximately 45 minutes per participant; after the completed pretest phase followed by a brief rest (up to 2 minutes), participants were presented with a movie clip, whereas the emotion perception task was applied immediately afterward.

Participants were seated at a fixed position with a viewing distance of 600 millimeters in front of a color computer monitor (17' ASUS 1366 x 768 resolution) set up at eye level. Participants were asked to direct their gaze at the center of the monitor displaying a fixation cross (1,500 ms), followed by face photographs (170 ms) appearing to the left or right of the fixation cross, covered by a mask afterward (1,000 ms). Participants were instructed to press the right arrow key using their right-hand middle finger as quickly and as accurately as possible if an emotional facial expression appeared on the monitor or press the left arrow key with the right-hand index finger if a neutral face was displayed. Responses were followed by an inter-trial interval (ITI) (500 ms).

Photograph stimuli (70 millimeter width and 80 millimeter height) were displayed at an angle of 6.5° left or right of the fixation cross. The position angle of the displayed photographs in the visual field was calculated using the following formula: $B = A * W / D$, where W is the stimulus width or height in millimeters, D is the distance between the monitor and eyes in millimeters, and B is the visual angle in minutes, if a constant is $A = 3{,}438$ or in degrees, if $A = 57.3$ (American Clinical Neurophysiology Society, 2006). The face perception task included 48 trials in the pretest and 48 trials in the posttest phase (96 trials in total), with 12 practice trials excluded from the statistical analysis. A total of 48 emotional faces (fearful, angry, disgusted, sad, happy, and surprised; 8 photographs for each face) and 48 neutral faces displayed in the experiment were balanced both according to the gender of the person depicted and HVF. The randomization of stimuli was applied in the experiment. We used the same face perception task in the pretest and the posttest phase; however, none of the face photographs appeared twice. Dependent variables were defined by response accuracy registered from the moment of ending face photographs exposure to the moment of responding by pressing a response key. Responses from emotional and neutral face perception tasks in the pretest and the posttest phase were averaged by the number of trials (48); hence, dependent variables ranged from 0 to 1. An open-source software PsychoPy2 (J. Peirce et al., 2019; Peirce, 2008) was used to run the experiment.

Statistical analysis

For testing participants' psychological and physiological state, emotion perception in the pretest (baseline) phase, and emotion perception in the posttest phase, we ran three separate analyses of variance (ANOVA) for repeated measures. The posttest self-assessment of psychological stress induced by a displayed movie clip (stressful or neutral) was tested using Independent Samples t-test. We applied the Bonferroni post-hoc test for multiple comparisons only if the main effect or the main interaction was statistically significant. Partial eta-squared (η_p^2) and Cohen's *d* were used to test effect size. We used response accuracy as the dependent variable. We performed statistical analyses using JASP (Version 0.13.1; JASP Team (2020).

Results

The assessment of participants' psychological and physiological state in the pre/posttest phase

For testing participants’ current anxiety, we applied 2 x 2 x 2 ANOVA for repeated measures; the Test phase (pretest vs. posttest anxiety) as a within-subject factor and Conditions (stress vs. non-stress) x Gender (male vs. female) as between-subject factors. The one-way ANOVA showed no significant main effect of the Test phase, $F(1, 86) = 2.64$, $p = .108$, $\eta_p^2 = 0.030$, regarding current anxiety. The two-way ANOVA showed a statistically significant main interaction between the Test phase and Conditions, $F(1, 86) = 16.77$, $p < .001$, $\eta_p^2 = 0.166$; in the stress condition anxiety was higher in the posttest phase than in the pretest phase, $t(1, 43) = 4.00$,

$p < .001$, Cohen's $d = 0.426$; additionally, in the posttest phase, anxiety was higher in participants in the stress condition than in the non-stress condition, $t(1, 86) = 4.26$, $p < .001$, Cohen's $d = -0.454$. The two-way ANOVA showed a statistically significant main interaction between the Test phase and Gender, $F(1, 86) = 5.10$, $p = .027$, $\eta_p^2 = 0.06$; in females anxiety was higher in the posttest, $M = 38.51$, $SD = 13.26$, than in the pretest, $M = 33.81$, $SD = 9.37$, $t(1, 86) = 2.85$, $p = .033$, Cohen's $d = 0.304$. Our data showed that in the pretest phase current anxiety was, $M = 33.98$, $SD = 10.84$, in the stress condition and $M = 32.98$, $SD = 7.21$, in the non-stress condition. In the posttest phase, current anxiety was, $M = 40.52$, $SD = 12.70$, in the stress condition and M = 30.36, SD = 8.34, in the non-stress condition. Normative values ranged from 20 to 80 (Spielberger, 1983), commonly classified as low anxiety (20-37), moderate anxiety (38-44), and high anxiety (45-80). Hence, participants in the non-stress condition demonstrated low current anxiety, whereas moderate anxiety was recorded after stress-induction in the stress condition.

For testing participants' BP, we applied 2 x 2 x 2 x 2 ANOVA for repeated measures; BP (systolic and diastolic) x the Test phase (pretest vs. posttest) as within-subject factors and Conditions (stress vs. non-stress) x Gender (male vs. female) as between-subject factors. The one-way ANOVA showed a statistically significant main effect of BP, $F(1, 86) = 2857.64$, $p < .001$, $\eta_p^2 = 0.97$; the values of systolic BP were higher, $M = 113.08$, $SD = 1.03$, compared with diastolic BP, $M = 73.52$, $SD = 8.87$. The two-way ANOVA showed no significant main effect of the Test phase, $F(1, 86) = 3.29$, $p = .073$, $\eta_p^2 = 0.04$. The two-way ANOVA showed a statistically significant main interaction between BP and Gender, $F(1, 86) = 53.20$, $p < .001$, $\eta_p^2 = 0.39$. The two-way ANOVAs showed no statistically significant main interactions between the Test phase and Conditions, $F(1, 86) = 2.77$, $p = .100$, $\eta_p^2 = 0.03$, the Test phase and Gender, $F(1, 86) = 0.20$, $p = .880$, $\eta_p^2 = 0.00$, BP and Conditions, $F(1, 86) = 0.99$, $p = .989$, $\eta_p^2 = 0.00$, or between the Test phase and BP, $F(1, 86) = 0.01$, $p = 0.930$, $\eta_p^2 = 0.00$.

In addition, the posttest self-assessment of psychological stress induced by a displayed movie clip was tested using the Independent Samples t-test (stress vs. non-stress). Table 1 shows a statistically significant difference between the stress and the non-stress condition in the assessment of psychological-stress scale regarding a movie clip.

Table 1. t-test analysis of self-assessment after watching movie clips in stress and non-stress conditions

Psychological-stress scale	*M*	*SD*	*t*(1, 46)	*p*	Cohen's *d*
Stress condition	4.29	1.60	9.67	.001	2.79
Non-stress condition	1.08	0.28			

Response accuracy in the perception of emotional vs. neutral faces in the pretest (baseline) phase

For testing participants' response accuracy in experimental conditions (the null hypothesis), we conducted 2 x 2 x 2 ANOVA for repeated measures that included only the pretest (the baseline) data; Emotion (emotional vs. neutral faces) x HVF (LVF vs. RVF) as within-subject factors and Conditions (stress vs. non-stress) as a between-subject factor. Table 2 shows the one-way ANOVA indicating a statistically significant main effect of Emotion, $F(1, 86) = 11.44$, $p = .001$, $\eta_p^2 = .117$; data revealed more accurate perception of emotional faces, $M = 0.85$, $SD = 0.12$, compared with neutral faces, $M = 0.79$, $SD = 0.16$. The one-way ANOVA showed a statistically significant main effect of HVF, $F(1, 86) = 47.14$, $p < .001$, $\eta_p^2 = .354$; with a more accurate perception of faces presented to the LVF, $M = 0.86$, $SD = 0.12$, compared with faces presented to the RVF, $M = 0.78$, $SD = 0.16$. The LVF advantage over the RVF was found both for emotional and neutral faces (Fig. 2a and b).

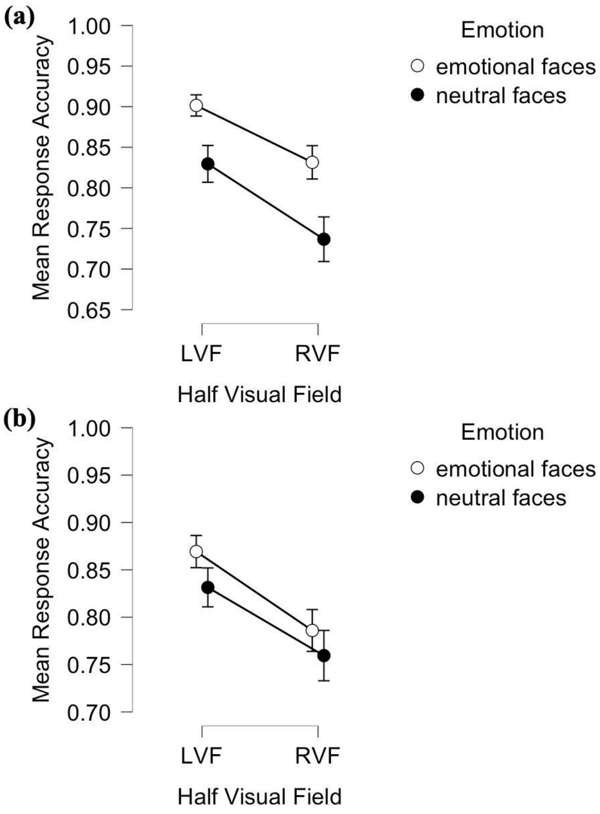


Fig. 2 Mean response accuracy for the perception of emotional and neutral faces with regard to the LVF (Left Visual Field) and the RVF (Right Visual Field) in the pretest for a) the stress condition and b) the non-stress condition. Error bars show the standard error.

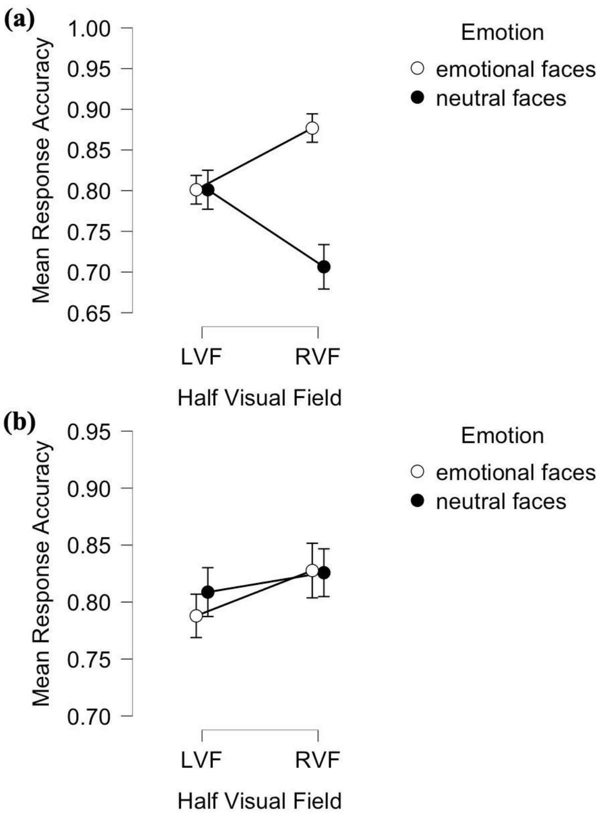


Fig. 3 Mean response accuracy for the perception of emotional and neutral faces with regard to the LVF (Left Visual Field) and the RVF (Right Visual Field) in the posttest for a) the stress condition and b) the non-stress condition. Error bars show the standard error.

The two-way ANOVAs showed that neither the main interactions between Emotion and Conditions, nor HVF and Conditions, nor HVF and Emotion, were statistically significant. The three-way ANOVA interaction between HVF, Emotion, and Conditions was non-significant. In line with our expectations, results confirmed no statistically significant difference between participants included in the stress and the non-stress condition regarding HVF and the perception of emotional and neutral faces. There was no *a priori* difference between participants, thus validating the applied experimental procedure.

Table 2. Analysis of variance of response accuracy for emotional and neutral face perception in regard to half visual field and conditions in the pretest phase

	$F(1, 86)$	p	η_p^2
Emotions	11.438	0.001	0.117
Emotions x Conditions	2.241	0.138	0.025
Half Visual Field	47.142	< .001	0.354
Half Visual Field x Conditions	0.027	0.871	0.000
Half Visual Field x Emotions	0.045	0.833	0.001
Half Visual Field x Emotions x Condition	0.401	0.528	0.005

Response accuracy in the perception of emotional vs. neutral faces in the posttest phase

For testing the hypothesis of the effect of psychological stress on the perception of emotional vs. neutral faces, we conducted 2 x 2 x 2 ANOVA for repeated measures that included only the posttest data; Emotion (emotional vs. neutral faces) x HVF (LVF vs. RVF) as within-subject factors and Conditions (stress vs. non-stress) as a between-subject factor. Table 3 shows the one-way ANOVA indicating statistically significant main effect of Emotion, $F(1, 86) = 4.08$, $p = .047$, $\eta_p^2 = .045$; data revealed a more accurate perception of emotional faces, $M = 0.82$, $SD = 0.13$, compared with neutral faces, $M = 0.79$, $SD = 0.16$. The main effect of HVF was statistically non-significant. The two-way ANOVA shows a statistically significant main interaction between Emotion and Conditions, $F(1, 86) = 6.37$, $p = .013$, $\eta_p^2 = .069$; post-hoc data revealed a more accurate perception of emotional faces compared with neutral faces in the stress condition, $t(1, 43) = 3.21$, $p < .01$, Cohen's $d = 0.343$. The two-way ANOVA indicates a statistically significant main interaction between Emotion and HVF, $F(1, 86) = 12.96$, $p < .001$, $\eta_p^2 = .131$; data revealed a more accurate perception of emotional faces in the RVF compared with emotional faces presented to the LVF, $t(1, 43) = 3.15$, $p = .011$, Cohen's $d = 0.336$; and a more accurate perception of emotional faces presented to the RVF compared with neutral faces presented to the RVF, $t(1, 43) = 3.74$, $p = .002$, Cohen's $d = 398$. The three-way ANOVA indicates a statistically significant interaction between HVF, Emotion, and Conditions, $F(1, 86) = 7.58$, $p = .007$, $\eta_p^2 = .081$ (Fig. 3a and b).

Table 3. Analysis of variance of response accuracy for emotional and neutral face perception in regard to half visual field and conditions in the posttest phase

	$F(1, 86)$	p	η_p^2
Emotions	4.08	0.047	0.045
Emotions x Conditions	6.37	0.013	0.069
Half Visual Field	0.58	0.449	0.007
Half Visual Field x Conditions	2.31	0.132	0.026
Half Visual Field x Emotions	12.96	< .001	0.131
Half Visual Field x Emotions x Conditions	7.58	0.007	0.081

Discussion

The present behavioral study examined the lateralization in the perception of emotional and neutral faces in psychological stress and non-stress conditions in healthy participants. We found higher perception accuracy for both emotional and neutral faces presented to the LVF (initially processed in the RH) compared with the RVF (initially processed in the LH) in the pretest phase (baseline) of the experiment. Consistent with the RHH (Adolphs et al., 1996; Alves et al., 2009; Borod et al., 1998; Bourne & Hole, 2006; Gainotti, 2019b), our findings confirmed that the brain is right-biased in emotion perception. In the baseline, there is a tendency of the hemispheres toward a more successful perception of faces presented to the LVF than to the RVF. We found no significant main interaction between conditions (stress vs. non-stress) and emotion (emotional vs. neutral face), nor between conditions and HVF in the pretest, thus indicating no *a priori* differences between independent samples from the stress and non-stress conditions.

We found a strong behavioral performance shift in perception accuracy of emotional and neutral faces presented randomly to both visual fields after watching movie clips (stressful and neutral) in the posttest phase. Namely, while participants in the non-stress condition demonstrated an advantage of the LVF in the perception of emotional and neutral faces, after watching a neutral movie clip participants showed relatively equalized behavioral perception performance between the LVF and RVF. Prior studies (Banich & Belger, 1990; Hughes & Rutherford, 2013) strongly demonstrated that increasing the experimental task requirements results in enhanced performance achieved by the distribution of processing between the hemispheres, indicating that the brain is highly dynamic in the perception of emotional and neutral faces and is not strictly limited by lateral functions. However, we did not vary task requirements due to constant parameters during the pretest and the posttest phase. Moreover, watching a neutral movie clip was not related to achievement in an explicit way. The psychophysiological condition caused by neutral video content resulted in relatively equalized hemispheres' performance for the perception of both emotional and neutral faces. Hence, *hemispheric functional-equivalence* represented by equalized behavioral performances may be caused by increased neurophysiological activation of both hemispheres due to watching a neutral movie clip. A previous fMRI study (Anderson et al., 2006) illustrates that watching normal video action sequences activates multiple brain regions in both hemispheres such as extrastriate, inferotemporal, posterior cingulate, parietal, and frontal areas. Thus, watching a neutral movie clip during a relatively long period may have resulted in increased inter-hemispheric (left, right) and intra-hemispheric (anterior, posterior) interaction. A recent MEG study (Kajal et al., 2020) using a face perception task with facial expressions of positive and negative valence has shown that face perception involves a functional connection among fronto-parietal brain regions; increased fronto-parietal functional connection predominantly in the RH for correctly recognized faces and influence of the LH for incorrectly recognized faces. Taken together, this suggests that emotion perception is initially right-biased but the LH plays a complementary role, whereas an external factor such as watching video content increases the performance of both hemispheres (due to the activation of a distributed brain-network).

Furthermore, we found that functional redistribution of behavioral performances between the LVF and the RVF in the perception of emotional faces also occurred after watching a stressful movie clip. Namely, while participants in the stress condition demonstrated higher perception accuracy for neutral faces in the LVF than in the RVF (such as the pattern of lateralization in the pretest phase), data revealed a diametrically opposite direction of lateralization in the perception of emotional faces: the RVF (LH) gained an advantage over the LVF (RH). An alternative interpretation is that the influence of psychological stress reduces behavioral performances of the LVF since the RH is affected by stress; however, our findings strongly confirmed that exposure to a neutral or stressful movie clip resulted in the redistribution of behavioral performance due to functional hemispheric equivalence in emotion perception. It seems that RVF performance modulation was related to LH that controls stress effects on social behavior (Lee et al., 2015). A possible psychological mechanism underlying this perception advantage of the RVF in the posttest phase, may be a visual priming effect. Visual priming has shown significant differences in affecting the LH and the RH in FBA studies on simple visual discrimination (McCormick & Seta, 2019) or more complex visual processing (Gupta, Raymond, & Vuilleumier, 2018). Exposure to brief emotional stimuli impairs the ability of visual discrimination and interferes with other RH functions (Hartikainen, Ogawa, & Knight, 2000) since in terms of evolution emotional facial expressions are more important for survival than neutral faces. Thus, long visual priming enhances processing in the RVF for emotional faces. However, a displayed emotional movie clip more likely leads to a functionally greater engagement of both hemispheres; hence, initially less prominent LH gains advantage over the RH after induced stress. Furthermore, the influence of arousal should not be underestimated. Increased arousal caused by watching psychologically disturbing scenes possibly increases the sensitivity for the perception of primarily emotional and less neutral faces**.** Increased participants' arousal may have focused attention on emotional rather than neutral faces, since emotions exert a strong influence on cognitive processing (Zinchenko et al. 2015).

In addition, we found a more accurate perception of emotional than neutral faces in both the pretest and the posttest phase. This is in line with cross-cultural (Scherer & Wallbott, 1994) and cross-sectional studies (Becker et al., 2011) demonstrating a fundamental role of emotional faces in social interaction among people. Emotional faces play a fundamental role in socialization and social interaction (Horstmann, 2003), thus being the most important channel of social communication. Emotional facial expressions are signs of non-verbal communication, whereas a neutral face does not have such power to exchange social messages.

Contrary to the results of early studies (Wittling, 1990) we found no differences in systolic and diastolic pressure prior to and following watching a movie clip with stressful and neutral content. Although Wittling (1990) applied a technique of a lateralized presentation of a movie, unlike a central presentation of a movie in the central visual field in our study, differences were obtained solely at the psychological level of measurement. This suggests higher psychological than physiological sensitivity in stress conditions i.e. physiologic changes are manifested more slowly than psychological ones.

Empirical evidence of this study confirms the line of previous work reporting on the inconsistency of FBA models in emotion perception (Demaree, Everhart, Youngstrom, & Harrison, 2005; Stanković, et al., 2015; Stanković & Nešić, 2019; Stanković, Nešić, & Milić, 2019). Although our results confirmed the RH predominance in the baseline, the use of movie clips strongly proved a shift of the right-biased brain toward hemispheric functional-equivalence. Thus, the brain is dynamic in the perception of emotional and neutral faces due to cooperation between the hemispheres. Moreover, our findings revealed re-distributed perception performance of both hemispheres for emotional and neutral faces in the non-stress condition and primarily emotional faces in the stress condition. We propose an alternative hemispheric functional-equivalence model suggesting initial RH predominance in the perception of emotional and neutral faces by default, however, with a high capacity for hemispheric functional redistribution of performances. Increased activation of the distributed neural brain-network involved in face perception and after watching a neutral or stressful content movie clip leads to functional equalization of behavioral performances between the LVF (due to the RH activation) and the RVF (due to the LH activation).

Limitations and future directions

This behavioral study did not include neurological measures (e.g., EEG/ERP and/or fMRI), thus preventing the analysis of FBA in emotion perception at a neurological level. The interpretations of the obtained results are limited to the behavioral component of lateralization in emotion perception; thus, conclusions about FBA are rather indirect. A potential limitation of this study may be related to experimental conditions since participants in the non-stress condition may have been affected by stress arising from the experimental situation (social stress). Prior studies have clearly demonstrated high-variability of anxiety as part of individual differences (Stojiljković & Stanković, 2018), whereas experimental testing of participants may modulate cognitive performance (e.g. attention) due to the influence of the social environment (Huguet, Galvaing, Monteil, & Dumas, 1999). In addition, the social environment may be associated with cognitive performance. Attention may be modulated by social stress (Chajut & Algom, 2003; Huguet, Galvaing, Monteil, & Dumas, 1999). This thesis was partially refuted by our results demonstrating significantly lower current anxiety in the posttest than in the pretest phase in non-stress condition participants, whereas anxiety was significantly higher in the posttest than in the pretest phase in stress condition participants. Theoretically, task repetition in the posttest phase may be potentially limiting due to the effect of sequential variables i.e., the influence of prior experience on task achievement; however, we used the non-stress group as a control condition. Using the face perception task in the pretest phase was crucial enabling an insight into the distribution of the lateralization of emotional and neutral faces in participants' relaxed state i.e., a clearly defined baseline. A limitation of this study is related to the absence of stress hormones (eg., cortisol) measurements, since prior study demonstrated that lateralized cortical activation moderates cortisol response during the stressful period (Hewig et al., 2008).

Future research should use eye-tracking devices to record oculomotor movements in HVF studies since the exposure of presented photographs in the experiment may have been processed not only unilaterally, but also contralaterally due to microsaccades and possible eye movements. A recent study (Kajopoulos et al. 2020) demonstrates that during a social interaction the observer's attention is mainly directed to the interlocutor's face in a top-down manner as opposed to reflexive orienting directed to social cues. More research is needed to determine the link between top-down attention and FBA in emotion perception. Further research should include at least four levels of independent variables in the experimental design: presentation of stressful/ negative video content (stress conditions), positive video content (positive emotion induced conditions), neutral video content (a non-stress group) and a group without video content (a non-stress group). This could reduce a possible confounding effect. A recent pilot study has demonstrated that hormones (i.e., oxytocin) may modulate the perception of emotional and neutral faces, specifically the perception of facial expressions of fear and surprise (Stanković, Bašić, et al., 2019); hence, future studies should explore the link with the lateralization of basic emotion perception and introduce measurements of stress hormones and emotion-related hormones. Furthermore, the influence of psychologically-induced stress on the recognition of each of the six basic emotions in a discrimination task should be explored. Since RT may be significantly prolonged in a behavioral task of the recognition of six basic emotions compared with binary tasks (emotional vs. neutral face) the use of neurological measures is highly recommended for future studies.

Conclusion

The present study has provided solid empirical evidence that the brain is initially right-biased (by default) in the emotional and neutral face perception. However, participants' interaction with a neutral movie clip resulted in the redistribution of behavioral performances between visual fields towards relative equalization (due to the relative equalization of hemispheric activation), whereas the interaction with a stressful movie clip even resulted in reversible asymmetry in the RVF (due to increased LH activation) in the perception of emotional faces**.** We have proposed a novel model of hemispheric functional-equivalence highlighting highly-integrated functional capacities of the hemispheres in emotional and neutral face perception. This model may be used as a useful theoretical framework for further interpretations of FBA in studies on emotion perception.

Compliance with ethical standards

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Ethical approval

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. The experiment was approved by the Ethics Committee of the Faculty of Medicine, University of Nis, Serbia (number 01-6481-20).

Informed consent

Informed consent was obtained from all individual participants included in the study.

Reference

Adolphs, R., Damasio, H., Tranel, D., & Damasio, A. R. (1996). Cortical systems for the recognition of emotion in facial expressions. *Journal of neuroscience*, *16*(23), 7678-7687.https://www.ncbi.nlm.nih.gov/pubmed/8922424

Alves, N. T., Aznar-Casanova, J. A., & Fukusima, S. S. (2009). Patterns of brain asymmetry in the perception of positive and negative facial expressions. *Laterality*, *14*(3), 256–272. https://doi.org/10.1080/13576500802362927

American Clinical Neurophysiology Society. (2006). Guideline 9B: guidelines on visual evoked potentials. *American Journal of Electroneurodiagnostic Technology*, *46*(3), 254–274. https://www.ncbi.nlm.nih.gov/pubmed/17042161

Anderson, D. R., Fite, K. V., Petrovich, N., & Hirsch, J. (2006). Cortical Activation While Watching Video Montage: An fMRI Study. *Media Psychology*, *8*(1), 7–24. https://doi.org/10.1207/S1532785XMEP0801_2

Arnsten, A. F. T. (2009). Stress signalling pathways that impair prefrontal cortex structure and function. *Nature Reviews. Neuroscience*, *10*(6), 410–422. https://doi.org/10.1038/nrn2648

Banich, M. T., & Belger, A. (1990). Interhemispheric interaction: how do the hemispheres divide and conquer a task? *Cortex; a Journal Devoted to the Study of the Nervous System and Behavior*, *26*(1), 77–94. https://doi.org/10.1016/s0010-9452(13)80076-7

Barel, E., & Cohen, A. (2018). Effects of acute psychosocial stress on facial emotion recognition. *Psychology, 9*(3), 403–412. https://www.scirp.org/journal/paperinformation.aspx?paperid=83476

Baron-Cohen, S., Spitz, A., & Cross, P. (1993). Do children with autism recognise surprise? A research note. *Cognition & Emotion*, *7*(6), 507–516.

https://www.tandfonline.com/doi/abs/10.1080/02699939308409202

Becker, D. V., Anderson, U. S., Mortensen, C. R., Neufeld, S. L., & Neel, R. (2011). The face in the crowd effect unconfounded: happy faces, not angry faces, are more efficiently detected in single- and multiple-target visual search tasks. *Journal of Experimental Psychology. General*, *140*(4), 637–659. https://doi.org/10.1037/a0024060

Borod, J. C., Cicero, B. A., Obler, L. K., Welkowitz, J., Erhan, H. M., Santschi, C., . . . Whalen, J. R. (1998). Right hemisphere emotional perception: Evidence across multiple channels. *Neuropsychology, 12,* 446–458. https://doi.org/10.1037/0894-4105.12.3.446

Bourne, V. J. (2006). The divided visual field paradigm: methodological considerations. *Laterality*, *11*(4), 373–393. https://doi.org/10.1080/13576500600633982

Bourne, V. J., & Hole, G. J. (2006). Lateralized repetition priming for familiar faces: Evidence for asymmetric interhemispheric cooperation. The Quarterly journal of experimental psychology, 59(6), 1117-1133. https://doi.org/10.1080/02724980543000150

Brüne, M., Nadolny, N., Güntürkün, O., & Wolf, O. T. (2013). Stress induces a functional asymmetry in an emotional attention task. *Cognition & Emotion*, *27*(3), 558–566. https://doi.org/10.1080/02699931.2012.726211

Chajut, E., & Algom, D. (2003). Selective attention improves under stress: implications for theories of social cognition. *Journal of personality and social psychology*, *85*(2), 231-248. https://doi.org/10.1037/0022-3514.85.2.231

Cook, C. J., & Crewther, B. T. (2012). Changes in salivary testosterone concentrations and subsequent voluntary squat performance following the presentation of short video clips. *Hormones and behavior*, *61*(1), 17-22. https://doi.org/10.1016/j.yhbeh.2011.09.006

Daudelin-Peltier, C., Forget, H., Blais, C., Deschênes, A., & Fiset, D. (2017). The effect of acute social stress on the recognition of facial expression of emotions. *Scientific reports*, *7*(1), 1036. https://doi.org/10.1038/s41598-017-01053-3

Davidson, R. J. (1992). Anterior cerebral asymmetry and the nature of emotion. *Brain and Cognition*, *20*(1), 125–151. https://doi.org/10.1016/0278-2626(92)90065-t

Davidson, R. J., Mednick, D., Moss, E., Saron, C., & Schaffer, C. E. (1987). Ratings of emotion in faces are influenced by the visual field to which stimuli are presented. *Brain and cognition*, *6*(4), 403-411. https://doi.org/10.1016/0278-2626(87)90136-9

Demaree, H. A., Everhart, D. E., Youngstrom, E. A., & Harrison, D. W. (2005). Brain lateralization of emotional processing: historical roots and a future incorporating “dominance”. *Behavioral and cognitive neuroscience reviews*, *4*(1), 3-20. https://doi.org/10.1177/1534582305276837

Denny-Brown, D., Meyer, J. S., & Horenstein, S. (1952). The significance of perceptual rivalry resulting from parietal lesion. *Brain: A Journal of Neurology*, *75*(4), 433–471. https://doi.org/10.1093/brain/75.4.432

Domes, G., & Zimmer, P. (2019). Acute stress enhances the sensitivity for facial emotions: a signal detection approach. *Stress*, 1-6. https://doi.org/10.1080/10253890.2019.1593366

Ekman, P. (1970). Universal facial expressions of emotions. *California Mental Health Research Digest*, *8*(4), 151–158.

Ekman, P., & Friesen, W. V. (1971). Constants across cultures in the face and emotion. *Journal of Personality and Social Psychology*, *17*(2), 124–129. https://doi.org/10.1037/h0030377

Faul, F., Erdfelder, E., Lang, A.-G., & Buchner, A. (2007). G*Power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods*, *39*(2), 175–191. https://doi.org/10.3758/bf03193146

Gainotti, G. (2019a). The Role of the Right Hemisphere in Emotional and Behavioral Disorders of Patients With Frontotemporal Lobar Degeneration: An Updated Review. *Frontiers in Aging Neuroscience*, *11*, 55. https://doi.org/10.3389/fnagi.2019.00055

Gainotti, G. (2019b). Emotions and the Right Hemisphere: Can New Data Clarify Old Models? *The Neuroscientist: A Review Journal Bringing Neurobiology, Neurology and Psychiatry*, *25*(3), 258–270. https://doi.org/10.1177/1073858418785342

Guex, R., Méndez-Bértolo, C., Moratti, S., Strange, B. A., Spinelli, L., Murray, R. J., Sander, D., Seeck, M., Vuilleumier, P., & Domínguez-Borràs, J. (2020). Temporal dynamics of amygdala response to emotion- and action-relevance. In *Scientific Reports* (Vol. 10, Issue 1). https://doi.org/10.1038/s41598-020-67862-1

Gupta, R., Raymond, J. E., & Vuilleumier, P. (2018). Priming by motivationally salient distractors produces hemispheric asymmetries in visual processing. *Psychological Research*, 1-10. https://doi.org/10.1007/s00426-018-1028-1

Hartikainen, K. M., Ogawa, K. H., & Knight, R. T. (2000). Transient interference of right hemispheric function due to automatic emotional processing. *Neuropsychologia*, *38*(12), 1576-1580. https://doi.org/ https://doi.org/10.1016/S0028-3932(00)00072-5

Hewig, J., Schlotz, W., Gerhards, F., Breitenstein, C., Lürken, A., & Naumann, E. (2008). Associations of the cortisol awakening response (CAR) with cortical activation asymmetry during the course of an exam stress period. *Psychoneuroendocrinology*, *33*(1), 83-91. https://doi.org/10.1016/j.psyneuen.2007.10.004

Horstmann, G. (2003). What do facial expressions convey: Feeling states, behavioral intentions, or actions requests?. *Emotion*, *3*(2), 150-166. https://doi.org/10.1037/1528-3542.3.2.150

Hughes, A. J., & Rutherford, B. J. (2013). Hemispheric interaction, task complexity, and emotional valence: evidence from naturalistic images. *Brain and cognition*, *81*(2), 167-175. https://doi.org/10.1016/j.bandc.2012.11.004

Huguet, P., Galvaing, M. P., Monteil, J. M., & Dumas, F. (1999). Social presence effects in the Stroop task: further evidence for an attentional view of social facilitation. *Journal of personality and social psychology*, *77*(5), 1011. https://doi.org/10.1037/0022-3514.77.5.1011

Kajal, D. S., Fioravanti, C., Elshahabi, A., Ruiz, S., Sitaram, R., & Braun, C. (2020). Involvement of top-down networks in the perception of facial emotions: a magnetoencephalographic investigation. *NeuroImage*, 117075. https://doi.org/10.1016/j.neuroimage.2020.117075

Kajopoulos, J., Cheng, G., Kise, K., Müller, H. J., & Wykowska, A. (2020). Focusing on the face or getting distracted by social signals? The effect of distracting gestures on attentional focus in natural interaction. In *Psychological Research*. https://doi.org/10.1007/s00426-020-01383-4

Killgore, W. D. S., & Yurgelun-Todd, D. A. (2007). The right-hemisphere and valence hypotheses: could they both be right (and sometimes left)? *Social Cognitive and Affective Neuroscience*, *2*(3), 240–250. https://doi.org/10.1093/scan/nsm020

Krolak-Salmon, P., Hénaff, M.-A., Vighetto, A., Bertrand, O., & Mauguière, F. (2004). Early amygdala reaction to fear spreading in occipital, temporal, and frontal cortex: a depth electrode ERP study in human. *Neuron*, *42*(4), 665–676. https://doi.org/10.1016/s0896-6273(04)00264-8

Lundqvist, D., Flykt, A., & Öhman, A. (1998). The Karolinska Directed Emotional Faces - KDEF, CD ROM from Department of Clinical Neuroscience, Psychology section, Karolinska Institutet, ISBN 91-630-7164-9

McCormick, M., & Seta, J. J. (2019). Evidence for a priming-based asymmetry in color identification. Laterality: Asymmetries of Body, Brain and Cognition, 24(1), 38-55. https:// doi.org/10.1080/1357650X.2018.1464577

Mills, C. K. (1912a). The cerebral mechanisms of emotional expression. *Transactions & Studies of the* College of Physicians of Philadelphia, 34, 381–390.

Mills, C. K. (1912b). The cortical representation of emotion, with a discussion of some points in the general nervous mechanism of expression in its relation to organic nervous mental disease. *Proceedings of the American Medico-Psychological Association*, *19*, 297–300.

Ocklenburg, S., Korte, S. M., Peterburs, J., Wolf, O. T., & Güntürkün, O. (2016). Stress and laterality–The comparative perspective. Physiology & behavior, 164, 321-329. https://www.sciencedirect.com/science/article/pii/S003193841630422X

Papousek, I., Reiser, E. M., Weber, B., Freudenthaler, H. H., & Schulter, G. (2012). Frontal brain asymmetry and affective flexibility in an emotional contagion paradigm. *Psychophysiology*, *49*(4), 489–498. https://doi.org/10.1111/j.1469-8986.2011.01324.x

Peirce, J., Gray, J. R., Simpson, S., MacAskill, M., Höchenberger, R., Sogo, H., Kastman, E., & Lindeløv, J. K. (2019). PsychoPy2: Experiments in behavior made easy. *Behavior Research Methods*, *51*(1), 195–203. https://doi.org/10.3758/s13428-018-01193-y

Peirce, J. W. (2008). Generating Stimuli for Neuroscience Using PsychoPy. *Frontiers in Neuroinformatics*, *2*, 10. https://doi.org/10.3389/neuro.11.010.2008

Poole, B. D., & Gable, P. A. (2014). Affective motivational direction drives asymmetric frontal hemisphere activation. Experimental Brain Research. Experimentelle Hirnforschung.

Experimentation Cerebrale, 232(7), 2121–2130. https://doi.org/10.1007/s00221-014-3902-4

Prete, G., Capotosto, P., Zappasodi, F., & Tommasi, L. (2018). Contrasting hemispheric asymmetries for emotional processing from event-related potentials and behavioral responses. *Neuropsychology, 32*(3), 317-328. https://doi.org/10.1037/neu0000443

Prete, G., Laeng, B., & Tommasi, L. (2014). Lateralized hybrid faces: evidence of a valence-specific bias in the processing of implicit emotions. *Laterality: Asymmetries of Body, Brain and Cognition*, *19*(4), 439-454. https://doi.org/10.1080/1357650X.2013.862255

Scherer, K. R., & Wallbott, H. G. (1994). Evidence for universality and cultural variation of differential emotion response patterning. Journal of Personality and Social Psychology, 66(2), 310–328. https://doi.org/10.1037/0022-3514.66.2.310

Shobe, E. R. (2014). Independent and collaborative contributions of the cerebral hemispheres to emotional processing. *Frontiers in Human Neuroscience*, *8*, 230. https://doi.org/10.3389/fnhum.2014.00230

Skiba, R. M., & Vuilleumier, P. (2020). Brain Networks Processing Temporal Information in Dynamic Facial Expressions. *Cerebral Cortex* . https://doi.org/10.1093/cercor/bhaa176

Spielberger, C. D. (1983). *State-Trait Anxiety Inventory for Adults (STAI-AD)* [Database record]. *PsycTESTS.* https://doi.org/10.1037/t06496-000

Stanković, M., Bašić, J., Milošević, V., & Nešić, M. (2019). Oxytocin receptor (OXTR) gene polymorphisms and recognition memory for emotional and neutral faces: A pilot study. *Learning and Motivation*, *67*, 101577. https://doi.org/10.1016/j.lmot.2019.101577

Stanković, M., Nešić, M., Obrenović, J., Stojanović, D., & Milošević, V. (2015). Recognition of facial expressions of emotions in criminal and non-criminal psychopaths: Valence-specific hypothesis. *Personality and Individual Differences*, *82*, 242-247. https://doi.org/10.1016/j.paid.2015.03

Stanković, M., & Nešić, M. (2018). Contralateral Hemisphere Activation by Unilateral Hand Contraction: ReExamining Global and Local Attention. *Perceptual and Motor Skills*, *125*(3), 438–450. https://doi.org/10.1177/0031512518769212

Stanković, M., & Nešić, M. (2019). No Evidence of Improved Emotion Perception Through

Unilateral Hand Contraction. *Perceptual and Motor Skills*, *127*(1), 126-141 https://doi.org/10.1177/0031512519888080

Stanković, M., Nešić, M., & Milić, J. (2020). Effects of unpleasant odors on emotion recognition: The right hemisphere and valence-specific hypotheses. *Psihologija*, *53*(2), 183-198. https://doi.org/10.2298/PSI190704019S

Stojiljković, J., & Stanković, M. (2018). Depressive state and social anxiety in adolescents: the role of family interactions. *The American Journal of Family Therapy*. *46*(3), 243-257. https://doi.org/10.1080/01926187.2018.1506269

Ströckens, F., Güntürkün, O., & Ocklenburg, S. (2013). Limb preferences in non-human vertebrates. *Laterality: Asymmetries of Body, Brain and Cognition*, *18*(5), 536-575. https://doi.org/10.1080/1357650X.2012.723008

Veale, J. F. (2014). Edinburgh handedness inventory–short form: a revised version based on confirmatory factor analysis. Laterality: Asymmetries of Body, Brain and Cognition, 19(2), 164-177. https://doi.org/10.1080/1357650X.2013.783045

Vuilleumier, P., & Pourtois, G. (2007). Distributed and interactive brain mechanisms during emotion face perception: evidence from functional neuroimaging. *Neuropsychologia*, *45*(1), 174–194. https://doi.org/10.1016/j.neuropsychologia.2006.06.003

Wedding, D., & Stalans, L. (1985). Hemispheric differences in the perception of positive and negative faces. *International Journal of Neuroscience*, *27*(3-4), 277-281. https://doi.org/10.3109/00207458509149773

Wittling, W. (1990). Psychophysiological correlates of human brain asymmetry: Blood pressure changes during lateralized presentation of an emotionally laden film. *Neuropsychologia*, *28*(5), 457-470.

Winston, J. S., O'Doherty, J., & Dolan, R. J. (2003). Common and distinct neural responses during direct and incidental processing of multiple facial emotions. *NeuroImage*, *20*(1), 84–97. https://doi.org/10.1016/s1053-8119(03)00303-3

Zinchenko, A., Kim, H., Danek, A., Müller, H. J., & Rangelov, D. (2015). Local feature suppression effect in face and non-face stimuli. *Psychological Research*, *79*(2), 194–205. https://doi.org/10.1007/s00426-014-0548-6.

6. General Discussion

The present doctoral dissertation sought to investigate behavioral mechanisms underlying emotion-driven attentional selection and emotional (social) reward, on the one hand, and neural mechanisms underlying attentional control performance and negative emotions (state anxiety) on the other hand. In line with a growing literature (Bourgeois et al. 2016; Vuilleumier 2015) demonstrating the influence of reward, in particular monetary reward, on attentional selection (e.g., attentional capture) through associative learning, the current dissertation examined whether a task-irrelevant feature, color (red, green), previously associated with facial expressions (happy, neutral) or social scenes (pleasant, neutral), would interfere with a visual shape-search for a singleton target. In contrast to recent studies using the value-driven attentional capture paradigm (Anderson et al., 2011; Anderson & Halpern, 2017; Cho & Cho, 2021; Qi et al., 2013; Sha & Jiang, 2016) that demonstrated an attentional capture effect by an irrelevant distractor previously associated with monetary reward, employment of emotional reward within the same 'value-driven' framework showed controversial findings (Sha & Jiang, 2016)

Moreover, recent findings (Jonauskaite, Althaus, et al., 2019; Jonauskaite et al., 2020) on color-emotion relations have demonstrated a strong emotional background in regard to color; in particular, red was often associated with emotions of love or anger, whereas green was not related to specific emotions. Typically, red is preferred in comparison with green in the spontaneous selection paradigm, strongly related to emotional context, in particular: red is preferred over green when followed by a happy face, whereas not preferred when followed by an angry face (Maier et al., 2009). Along these lines, the present dissertation focuses on attentional selection modulated by emotional reward, associative learning, and their interactions with the physical saliency of color.

In addition, the present dissertation investigated behavioral and neural mechanisms underlying attentional control performance, in particular: goal-directed visual search under experimentally induced emotion of anxiety. In regard to numerous previous research (Ghassemzadeh et al. 2019; LeDoux 1996; Moser et al. 2012; Eysenck et al. 2007), demonstrating strong influence of emotions on attentional performance, the current work extended these questions by introducing a novel dual-target attentional paradigm in order to examine whether anxiety impairs or even facilitates attentional performance. In particular, whether the goal-directed visual search for two targets is influenced by experimentally induced state anxiety due to the reduction/facilitation of top-down attentional control and its influence on bottom-up attentional capture. In parallel, the current work explored EEG signatures of goal-driven (e.g., N2pc) and stimulus-driven (e.g., Ppc, PD) attentional mechanisms under a person's state anxiety.

Finally, the present dissertation investigated hemispheric specialization for emotional and neutral face perception under the stress (i.e., anxiety) condition in healthy participants. In particular, whether experimentally induced anxiety may affect hemipsgeric specialization for emotional face perception.

In the following subsections, summaries of findings obtained in the prior six experiments will be presented together with the main conclusions.

6.1. Emotion-driven attentional capture within social reward framework

In Chapter 5.1., three behavioral experiments examining the association between emotion-driven attentional capture/interference and social reward were presented. Considering growing literature (Anderson et al., 2011; Anderson & Halpern, 2017; Cho & Cho, 2021; Qi et al., 2013; Sha & Jiang, 2016) demonstrating the influence of reward, in particular monetary reward of different magnitude (low, high), this dissertation aimed to fill a significant gap related to emotions and emotional reward. Emotionally important stimuli attract more attention than neutral stimuli (Vuilleumier & Huang, 2009), thus social reward is supposed to modulate human attentional selection. It was less known to what extent a task-irrelevant feature, color (red, green), previously associated with an emotional picture of different valence (neutral, pleasant) or arousal (low, high), may capture attention, especially since recent studies failed to demonstrate consistent and replicative findings (Anderson, 2016, 2017; Anderson & Kim, 2018; Kim & Anderson, 2020). To fill this gap three behavioral experiments were established by recruiting healthy university students and using a modified value-driven attentional paradigm including the association and the test phase (Anderson, 2011). Along these lines, across three behavioral experiments, this dissertation examined whether a task-irrelevant feature, color, may demonstrate distractor interference in the shape-search task (e.g., a diamond).

In Experiment 1, an initial association (i.e., training) phase included participant's search for a green or red circle (i.e., the target) presented among seven heterogeneous non-targets, while participants were instructed to search and report, as fast and as accurately as possible, a line orientation (horizontal, vertical) inside a red or green circle. A participant's correct response was 'rewarded' by a happy or neutral face in order to be associated with red and green color. Color-picture mapping was counterbalanced across participants. Subsequently, learned color-social-reward-association was used for attentional capture in a test where participants were instructed to search for a shape singleton (i.e., a diamond).

The obtained findings from Experiment 1 failed to replicate previous results from the initial association phase demonstrating that the relative response speed was modulated by color as such, whereas no effect was found for emotional-face feedback associated with a particular color. Thus, the red targets were responded to faster compared to the green targets, whereas neutral or positive emotional feedback showed little influence on task performance. The absence of a reliable effect in the association phase has been found in recent studies using social (instead of monetary) reward feedback (Anderson, 2016; Anderson & Kim, 2018; Kim & Anderson, 2020). In the test phase, Experiment 1 failed to establish emotion-driven modulation of attentional capture interference since happy-face associated distractors showed a similar pattern as neutral-face associated distractors. Although happy-face associated distractor trials were numerically faster, this was not significant. This appears in accord with Kim and Anderson (2017; 2020) since they report a significant difference between an absent and pleasant-associated distractor, but not between neutral and pleasant trials.

The current results from the association and the test phase indicated their weak relationship. Hence, performance from these two tasks was correlated to examine color-to-emotional-reward learning and subsequently the distractor interference. To accomplish that goal, the *color-valence preference* was calculated from individual observers as a difference in relative RTs between a target color associated with a happy and a neutral face. A positive value indicated that a happy-emotion-associated color was slower in comparison to neutral color while a negative value indicated that the happy-emotion-associated color speeded-up participants' response. Individual *color-valence preference* was further correlated with the *distractor-effect performance* such as the relative RT difference of the pleasant minus the neutral distractor-present trials from the test phase. The obtained correlation turned out to be significant, indicating a positive relationship between the color-valence preference and the distractor-effect score. Thus, the observers who responded more slowly to the happy- versus neutral-face-associated target color in the association phase tended to show greater *interference* by the happy- versus neutral-face-associated distractor color in the test phase, whereas the observers who responded faster to the happy- versus neutral-face-associated target color in the association phase tended to show greater *facilitation* by the happy- versus neutral-face-associated distractor color in the test phase. Hence, the finding demonstrated that the longer participants 'dwelled' on the happy-face-associated target color in the association phase, the more this color interfered as a distractor item in the test phase.

The present finding highlighted the role of individual differences in the value-driven attentional capture phenomena, since the potential *capture effect* may be masked or diminished by the means. A general underlying effect is that participants' responses were expressed in either the distractor interference or facilitation, reflecting indeed congruence between observer color-valence preference and a color-valence pair assigned to a particular individual in the training phase. For example, an observer who generally preferred a happy face and red color would be facilitated in the test phase in case their individual preference matched the experiment color-face assignment such as a happy-face-red-color pair, conversely, the distractor interference would be larger if individual color-valence preference did not match the experimental assignment in the test phase. This is in line with a recent study (Jonauskaite, 2019) revealing that colors are evaluated on relatively stable color-emotion mental representations. In addition, individual differences play a major role here, since some observers, such as individuals from Asian cultures, may perceive red as more pleasant compared to green.

In Experiment 2, an initial association phase included emotional pictures of different valence (pleasant, neutral) and arousal (low, high) since arousal, which was not manipulated in Experiments 1 and 3, is the second fundamental dimension of emotions (Lee et al., 2015; Mather

& Nesmith, 2008; Sutherland & Mather, 2012), next to the valence dimension. Thus, the valence-arousal dimension was manipulated through two experimental sessions such as low vs. high arousal sessions including both neutral and pleasant valence emotional pictures. Valence-arousal mapping was counterbalanced across participants throughout the two sessions, while the other experimental manipulations remained the same as in Experiment 1.

In line with the finding of Experiment 1 using facial expression feedback instead of social scenes pictures, Experiment 2 failed to establish reliable effects of the emotional-reward valence that was associated with a particular target color in the association phase, and in addition, the respective distractor color in the subsequent test phase. As a pattern already seen in the correlations from Experiment 1, the congruency between the experimental color-valence pairing and individual color-valence preferences was the dominant mechanism in Experiment 2. In particular, the presence of the valence-associated color distractor that matched individual color-valence preferences tended to facilitate performance, regardless of response speed on the green or red color. Thus, both Experiments showed *facilitation* or *interference* that was not related to the color-valence conditioning *per se* but the individual color-valence influence on task demands in the emotion-driven attentional capture paradigm. Future studies should further consider individual pre-established preferences dominating the short-term emotion-driven behavioral mechanisms.

In Experiment 3, similarly to Experiment 1, happy and neutral faces were used as a social reward. However, contrary to typical value-driven attentional capture paradigms where the color (red, green) target in the association phase was used only as an irrelevant color distractor in the subsequent shape singleton search task, in Experiment 3, the target shape singleton (i.e., a diamond) in the test phase was red (33%) or green (33%) or other colors (33%). Thus, the enhanced color signal from the association phase, since a particular color was associated with a neutral and pleasant value of social feedback-reward, should come along with a signal of the shape dimension in the test phase. Instead of the distractor interference, Experiment 3 demonstrated facilitation boosting the attentional priority of the target signal (by generating a redundancy gain driven by coactivation at the priority-map level; (e.g., Krummenacher et al., 2001, 2002; 2014) and so facilitating the allocation of attention to the target location.

Experiment 3 revealed that in an initial association phase, participants responded significantly faster on the red targets trials than the green targets, however, there was no significant modulation by emotional picture feedback, in accordance with Experiments 1 and 2, as in prior studies (Anderson, 2016; 2017; Kim & Anderson, 2020). In the test phase, colored (red, green) shape targets were significantly faster responded to in comparison to other color shape targets (e.g., yellow). In line with a general selection-history effect (Sha & Jiang, 2016) search performance was boosted even when the color was non-critical and task-irrelevant.

Of note, participants responded faster to the red targets in comparison to the green targets; however, the mean facilitation was not modulated by the emotional valence manipulation in the association phase. This indicated that a general selection-history effect was added to the color-valence preference in the majority of participants which was dominantly red, and potentially that some colors themselves may comprehensively distinct emotional associations, which was neglected in the recent literature (Jonauskaite, Althaus, et al., 2019; Jonauskaite et al., 2020; Maier et al., 2009).

Findings across three Experiments demonstrated color-valence-driven facilitation but no emotion-driven interference, thus results failed to confirm a significant emotions-feedback-dependent modulation of behavioral performance in the association phase, and consequently, no significant result was found in regard to the valence-dependent modulation of the distractor interference (Experiments 1 and 2) or target-facilitation (Experiment 3) in the test phase of the modified value-driven attentional capture paradigm.

6.2. Association between attentional control and emotions of anxiety. Implications of the dual-target attention paradigm

Chapter 5.2. presented a behavioral study that examined the association between attentional control and emotions of anxiety. The introduced study as an integral part of this dissertation investigates whether a goal-directed visual search for two targets is influenced by experimentally induced state anxiety due to the reduction/facilitation of top-down attentional control. A novel dual-target attention paradigm was implemented with a higher-level explanation of attentional control under unpleasant emotions such as anxiety or stress. In addition, the study design included irrelevant distractors (i.e., a red item) to examine whether a goal-directed visual search for two targets was influenced by a psychically salient distractor. Thus, this study, using a sample of healthy university students, investigated whether goal-directed attentional control over stimulus-driven attention is modulated by anxiety.

At group level analyses, findings showed no evidence of goal-directed attention facilitation or impairment that was affected by experimentally induced state anxiety. Both RT and accuracy indicate similar behavioral patterns among the neutral and the anxiety session. However, at a level of intra-individual differences, an increased level of state anxiety, previously induced by a short aversive movie, was negatively correlated with the goal-directed ability for the dual-target search. Emotional fluctuation in a negative direction interferes with attentional control, in particular with the visual search of the dual-target task by affecting behavioral effectiveness. A linear relationship between attentional control and state anxiety was found since there were negative correlations between state anxiety and distractor interference in regard to RT and accuracy. Thus, a task-irrelevant, but salient distractor (i.g., a red item) interfered less with the dual-target in high-anxious participants demonstrating increased vigilance and top-down attention. This study demonstrated that induced state anxiety may increase vigilance and response alertness, and in parallel reduce distractor interference, possibly using biological mechanisms of survival related to threatening stimuli (Ghassemzadeh et al., 2019; Vuilleumier, 2005).

In addition, this work has shown that the association between goal-directed visual attention and anxiety may be spatial-specific. In general, participants responded faster in the central presentation compared to the peripheral presentation, and in particular, higher anxiety participants showed less distractor interference in the central presentations than peripheral presentations. Greater anxiety reduces distractor interference by speed-up response in the central presentations, and by reducing errors rate in the peripheral presentations. Thus, state anxiety influences the effectiveness and efficiency of attention resulting in less distractibility in central (RT) and peripheral (error rates) presentations.

6.3. Neurological mechanisms underlying attentional control under induced state anxiety.

Chapter 5.3. presented a behavioral and neurophysiological study that examined the previously explored questions in regard to the association between attentional control and anxiety emotions. Considering inconsistent recent literature demonstrating impairment of attentional performance under threat (Eysenck et al., 2007; Moser et al., 2012a) or even facilitation (Kim et al., 2021), an empirical behavioral experiment was conducted to fill this gap. The emotion of anxiety may affect cognitive performance by decreasing it in a variety of ways. Previous literature has demonstrated that anxious individuals easily direct their attention to a threatening object (Moser et al. 2012), whereas the ACT showed that orienting toward threatening stimuli occurs because of a reduction in goal-driven attentional control (Eysenck & Derakshan, 2011), and simultaneously with increases of distractibility by surrounding objects (e.g., stimulus-driven attention) (Eysenck et al. 2007; Moser et al. 2012). The ACT proposes that increased anxiety in individuals would lead to decreased attentional control (Eysenck & Derakshan, 2011). Thus, anxiety would affect a human's attentional system by promoting bottom-up attention that causes increased distractor interference whereas reducing top-down attention and goal-driven attentional selection. Some theoretical accounts, such as the Attentional Control Theory (ACT), hold that reduction of attentional performance (e.g., slower RT) occurs due to a decrease in goal-driven attentional control (Eysenck & Derakshan, 2011), and in parallel higher vulnerability of the distractor interference (Eysenck et al., 2007; Moser et al., 2012a). Findings are contradictory since some studies using electric shock as a threat found attentional improvement in the Stroop task (Hu et al., 2012) but others reported performance reduction (Choi et al., 2012). The results provide strong evidence that anxiety modulated neuropsychological mechanisms underlying goal-directed attention. Event-related potential waveforms indicated that the Ppc component was affected during the early perception when observers were experimentally exposed to anxiety/arousal emotions. It has been shown that intra-individual differences play a significant role between attention and emotions since results revealed that anxiety correlated negatively with attentional performance, especially with response accuracy.

6.4. Functional brain asymmetry for emotions and anxiety

Chapter 5.4 presented a behavioral study that examined the lateralization in the perception of the neutral and emotional faces under anxiety and neutral conditions in healthy subjects. Considering previous literature (Stanković and Nešić 2019; Stanković et al. 2019; Stanković et al. 2015; Prete et al. 2022) demonstrating inconsistent results in regard to hemispheric specialization for emotional face perception, the presented study examined the perception of emotional and neutral faces under anxiety and neutral conditions. We examined whether the perception accuracy of emotional and neutral faces is higher in the left visual field (LVF) compared to the right visual field (RVF), and individual differences in the perception accuracy of emotional and neutral faces presented in the LVF and the RVF prior to and following a short stressful or neutral movie clip. A total of 88 university students (47 female) were used in the study in the behavioral experiment with the Divided Visual Field (DVF) approach. The DVF is a brief presentation of basic facial expressions (happy, surprised, fearful, sad, angry, and disgusted) and neutral faces to reevaluate the potential influence of psychological stress on emotion perception.

The present study provided strong empirical evidence that the brain is initially right-biased by default in the neutral and emotional face perception. However, under the neutral condition participants showed the redistribution of behavioral performances between visual fields towards relative equalization (due to the relative equalization of hemispheric activation), whereas exposure to the stress condition resulted in in reversed asymmetry in the RVF (due to increased LH activation) in the perception of emotional faces.

7. Conclusion

The present dissertation examined behavioral mechanisms underlying emotion-driven attentional selection and emotional (social) reward, on the one hand, and neural mechanisms underlying attentional control in relation with negative emotions (anxiety) on the other hand. Finally, the present dissertation examined hemispheric specialization for the neutral and emotional face perception in relation with negative emotions (anxiety). The present dissertation pointed out the significant role of human emotions and social in attentional selection and perception. Behavioral and neuropsychological mechanisms demonstrated solid association between emotions, attentional selection and perception.

References (General Introduction and General Discussion)

Allenmark, F., Zhang, B., Liesefeld, H. R., Shi, Z., & Müller, H. J. (2019). Probability cueing of singleton-distractor regions in visual search: the locus of spatial distractor suppression is determined by colour swapping. In *Visual Cognition* (pp. 1–19). https://doi.org/10.1080/13506285.2019.1666953

Anderson, B. A. (2013). A value-driven mechanism of attentional selection. *Journal of Vision*, *13*(3). https://doi.org/10.1167/13.3.7

Anderson, B. A. (2016a). Social reward shapes attentional biases. In *Cognitive Neuroscience* (Vol. 7, Issues 1-4, pp. 30–36). https://doi.org/10.1080/17588928.2015.1047823

Anderson, B. A. (2016b). Social reward shapes attentional biases. In *Cognitive Neuroscience* (Vol. 7, Issues 1-4, pp. 30–36). https://doi.org/10.1080/17588928.2015.1047823

Anderson, B. A. (2016c). The attention habit: how reward learning shapes attentional selection. *Annals of the New York Academy of Sciences*, *1369*(1), 24–39. https://doi.org/10.1111/nyas.12957

Anderson, B. A. (2017a). Counterintuitive effects of negative social feedback on attention. *Cognition & Emotion*, *31*(3), 590–597. https://doi.org/10.1080/02699931.2015.1122576

Anderson, B. A. (2017b). Counterintuitive effects of negative social feedback on attention. *Cognition and Emotion*, *31*(3), 590–597. https://doi.org/10.1080/02699931.2015.1122576

Anderson, B. A., Faulkner, M. L., Rilee, J. J., Yantis, S., & Marvel, C. L. (2013). Attentional bias for nondrug reward is magnified in addiction. *Experimental and Clinical Psychopharmacology*, *21*(6), 499–506. https://doi.org/10.1037/a0034575

Anderson, B. A., & Halpern, M. (2017). On the value-dependence of value-driven attentional capture. *Attention, Perception & Psychophysics*, *79*(4), 1001–1011. https://doi.org/10.3758/s13414-017-1289-6

Anderson, B. A., & Kim, H. (2018a). Relating attentional biases for stimuli associated with social reward and punishment to autistic traits. *Collabra: Psychology*, *4*(1). https://www.collabra.org/articles/119/

Anderson, B. A., & Kim, H. (2018b). Relating attentional biases for stimuli associated with social reward and punishment to autistic traits. *Collabra: Psychology*, *4*(1). https://www.collabra.org/articles/119/

Anderson, B. A., Laurent, P. A., & Yantis, S. (2011a). Value-driven attentional capture. *Proceedings of the National Academy of Sciences of the United States of America*, *108*(25), 10367–10371. https://doi.org/10.1073/pnas.1104047108

Anderson, B. A., Laurent, P. A., & Yantis, S. (2011b). Value-driven attentional capture. *Proceedings of the National Academy of Sciences of the United States of America*, *108*(25), 10367–10371. https://doi.org/10.1073/pnas.1104047108

Anderson, B. A., Laurent, P. A., & Yantis, S. (2012). Generalization of value-based attentional priority. *Visual Cognition*, *20*(6). https://doi.org/10.1080/13506285.2012.679711

Anderson, B. A., & Yantis, S. (2013). Persistence of value-driven attentional capture. *Journal of Experimental Psychology. Human Perception and Performance*, *39*(1), 6–9. https://doi.org/10.1037/a0030860

Arnsten, A. F. T. (2009a). Stress signalling pathways that impair prefrontal cortex structure and function. *Nature Reviews. Neuroscience*, *10*(6), 410–422. https://doi.org/10.1038/nrn2648

Arnsten, A. F. T. (2009b). Stress signalling pathways that impair prefrontal cortex structure and function. *Nature Reviews. Neuroscience*, *10*(6), 410–422. https://doi.org/10.1038/nrn2648

Awh, E., Belopolsky, A. V., & Theeuwes, J. (2012a). Top-down versus bottom-up attentional control: a failed theoretical dichotomy. *Trends in Cognitive Sciences*, *16*(8), 437–443. https://doi.org/10.1016/j.tics.2012.06.010

Awh, E., Belopolsky, A. V., & Theeuwes, J. (2012b). Top-down versus bottom-up attentional control: a failed theoretical dichotomy. *Trends in Cognitive Sciences*, *16*(8), 437–443. https://doi.org/10.1016/j.tics.2012.06.010

Bacon, W. F., & Egeth, H. E. (1994). Overriding stimulus-driven attentional capture. *Perception & Psychophysics*, *55*(5), 485–496. https://doi.org/10.3758/bf03205306

Beesley, T., Nguyen, K. P., Pearson, D., & Le Pelley, M. E. (2015). Uncertainty and predictiveness determine attention to cues during human associative learning. *Quarterly*

Journal of Experimental Psychology, *68*(11), 2175–2199. https://doi.org/10.1080/17470218.2015.1009919

Belopolsky, A. V., & Theeuwes, J. (2010). No capture outside the attentional window. *Vision Research*, *50*(23), 2543–2550. https://doi.org/10.1016/j.visres.2010.08.023

Bertleff, S., Fink, G. R., & Weidner, R. (2016). The role of top--down focused spatial attention in preattentive salience coding and salience-based attentional capture. *Journal of Cognitive Neuroscience*, *28*(8), 1152–1165. https://direct.mit.edu/jocn/article-abstract/28/8/1152/28536

Bourgeois, A., Chelazzi, L., & Vuilleumier, P. (2016). How motivation and reward learning modulate selective attention. *Progress in Brain Research*, *229*, 325–342. https://doi.org/10.1016/bs.pbr.2016.06.004

Bourgeois, A., Neveu, R., & Vuilleumier, P. (2016). How Does Awareness Modulate Goal-Directed and Stimulus-Driven Shifts of Attention Triggered by Value Learning? *PloS One*, *11*(8), e0160469. https://doi.org/10.1371/journal.pone.0160469

Bucker, B., Belopolsky, A. V., & Theeuwes, J. (2015). Distractors that signal reward attract the eyes. *Visual Cognition*, *23*(1-2), 1–24. https://doi.org/10.1080/13506285.2014.980483

Bucker, B., & Theeuwes, J. (2017). Pavlovian reward learning underlies value driven attentional capture. *Attention, Perception & Psychophysics*, *79*(2), 415–428. https://doi.org/10.3758/s13414-016-1241-1

Burnham, B. R. (2007). Displaywide visual features associated with a search display's appearance can mediate attentional capture. *Psychonomic Bulletin & Review*, *14*(3), 392–422. https://doi.org/10.3758/bf03194082

Canli, T. (1999). Hemispheric Asymmetry in the Experience of Emotion: A Perspective from Functional Imaging. *The Neuroscientist: A Review Journal Bringing Neurobiology, Neurology and Psychiatry*, *5*(4), 201–207. https://doi.org/10.1177/107385849900500409

Cardinal, R. N., Parkinson, J. A., Hall, J., & Everitt, B. J. (2002). Emotion and motivation: the role of the amygdala, ventral striatum, and prefrontal cortex. *Neuroscience and Biobehavioral Reviews*, *26*(3), 321–352. https://doi.org/10.1016/s0149-7634(02)00007-6

Carrasco, M. (2011). Visual attention: the past 25 years. *Vision Research*, *51*(13), 1484–

1525. https://doi.org/10.1016/j.visres.2011.04.012

Chao, C.-M., McGregor, A., & Sanderson, D. J. (2021). Uncertainty and predictiveness modulate attention in human predictive learning. *Journal of Experimental Psychology. General*, *150*(6), 1177–1202. https://doi.org/10.1037/xge0000991

Chelazzi, L., Perlato, A., Santandrea, E., & Della Libera, C. (2013). Rewards teach visual selective attention. *Vision Research*, *85*, 58–72. https://doi.org/10.1016/j.visres.2012.12.005

Choi, J. M., Padmala, S., & Pessoa, L. (2012). Impact of state anxiety on the interaction between threat monitoring and cognition. *NeuroImage*, *59*(2), 1912–1923. https://doi.org/10.1016/j.neuroimage.2011.08.102

Cho, S. A., & Cho, Y. S. (2021). Uncertainty modulates value-driven attentional capture. *Attention, Perception & Psychophysics*, *83*(1), 142–155. https://doi.org/10.3758/s13414-020-02171-3

Chun, M. M. (2000). Contextual cueing of visual attention. *Trends in Cognitive Sciences*, *4*(5), 170–178. https://www.ncbi.nlm.nih.gov/pubmed/10782102

Cohen, A., & Magen, H. (1999). Intra- and cross-dimensional visual search for single-feature targets. *Perception & Psychophysics*, *61*(2), 291–307. https://doi.org/10.3758/bf03206889

Connor, C. E., Egeth, H. E., & Yantis, S. (2004). Visual attention: bottom-up versus top-down. *Current Biology: CB*, *14*(19), R850–R852. https://doi.org/10.1016/j.cub.2004.09.041

Corbetta, M., Patel, G., & Shulman, G. L. (2008). The reorienting system of the human brain: from environment to theory of mind. *Neuron*, *58*(3), 306–324. https://doi.org/10.1016/j.neuron.2008.04.017

Corbetta, M., & Shulman, G. L. (2002a). Control of goal-directed and stimulus-driven attention in the brain. *Nature Reviews. Neuroscience*, *3*(3), 201–215. https://doi.org/10.1038/nrn755

Corbetta, M., & Shulman, G. L. (2002b). Control of goal-directed and stimulus-driven attention in the brain. *Nature Reviews. Neuroscience*, *3*(3), 201–215. https://doi.org/10.1038/nrn755

Desimone, R., & Duncan, J. (1995). Neural mechanisms of selective visual attention.

Annual Review of Neuroscience, *18*, 193–222. https://doi.org/10.1146/annurev.ne.18.030195.001205

Dodwell, G., Liesefeld, H. R., Conci, M., Müller, H. J., & Töllner, T. (2021). EEG evidence for enhanced attentional performance during moderate-intensity exercise. *Psychophysiology*, *58*(12), e13923. https://doi.org/10.1111/psyp.13923

Ekman, P., & Friesen, W. V. (1971). Constants across cultures in the face and emotion. *Journal of Personality and Social Psychology*, *17*(2), 124–129. https://doi.org/10.1037/h0030377

Eriksen, C. W., & Hoffman, J. E. (1972). Temporal and spatial characteristics of selective encoding from visual displays. *Perception & Psychophysics*, *12*(2), 201–204. https://doi.org/10.3758/BF03212870

Eysenck, M. W., & Derakshan, N. (2011). New perspectives in attentional control theory. *Personality and Individual Differences*, *50*(7), 955–960. https://doi.org/10.1016/j.paid.2010.08.019

Eysenck, M. W., Derakshan, N., Santos, R., & Calvo, M. G. (2007). Anxiety and cognitive performance: attentional control theory. *Emotion* , *7*(2), 336–353. https://doi.org/10.1037/1528-3542.7.2.336

Failing, M., & Theeuwes, J. (2018). Selection history: How reward modulates selectivity of visual attention. *Psychonomic Bulletin & Review*, *25*(2), 514–538. https://doi.org/10.3758/s13423-017-1380-y

Fecteau, J. H., & Munoz, D. P. (2006). Salience, relevance, and firing: a priority map for target selection. *Trends in Cognitive Sciences*, *10*(8), 382–390. https://doi.org/10.1016/j.tics.2006.06.011

Folk, C. L., & Remington, R. (2006). Top-down modulation of preattentive processing: Testing the recovery account of contingent capture. *Visual Cognition*, *14*(4-8), 445–465. https://doi.org/10.1080/13506280500193545

Folk, C. L., Remington, R. W., & Johnston, J. C. (1992a). Involuntary covert orienting is contingent on attentional control settings. In *Journal of Experimental Psychology: Human Perception and Performance* (Vol. 18, Issue 4, pp. 1030–1044). https://doi.org/

10.1037/0096-1523.18.4.1030

Folk, C. L., Remington, R. W., & Johnston, J. C. (1992b). Involuntary covert orienting is contingent on attentional control settings. *Journal of Experimental Psychology. Human Perception and Performance*, *18*(4), 1030–1044. https://www.ncbi.nlm.nih.gov/pubmed/1431742

Found, A., & Müller, H. J. (1996). Searching for unknown feature targets on more than one dimension: Investigating a "dimension-weighting" account. *Perception & Psychophysics*, *58*(1), 88–101. https://doi.org/10.3758/BF03205479

Frischen, A., Eastwood, J. D., & Smilek, D. (2008). Visual search for faces with emotional expressions. *Psychological Bulletin*, *134*(5), 662–676. https://doi.org/10.1037/0033-2909.134.5.662

Gainotti, G. (2019a). The Role of the Right Hemisphere in Emotional and Behavioral Disorders of Patients With Frontotemporal Lobar Degeneration: An Updated Review. *Frontiers in Aging Neuroscience*, *11*, 55. https://doi.org/10.3389/fnagi.2019.00055

Gainotti, G. (2019b). Emotions and the Right Hemisphere: Can New Data Clarify Old Models? *The Neuroscientist: A Review Journal Bringing Neurobiology, Neurology and Psychiatry*, *25*(3), 258–270. https://doi.org/10.1177/1073858418785342

Gaspelin, N., & Luck, S. J. (2018). "Top-down" Does Not Mean "Voluntary." *Journal of Cognition*, *1*(1). https://doi.org/10.5334/joc.28

Geng, J. J., & Behrmann, M. (2002). Probability cuing of target location facilitates visual search implicitly in normal participants and patients with hemispatial neglect. *Psychological Science*, *13*(6), 520–525. https://doi.org/10.1111/1467-9280.00491

Geyer, T., Müller, H. J., Olivers, C., Kim, J., Marcusson-Clavertz, D., Yoshiuchi, K., Smyth, J. M., Stanković, M., Nesic, M., West, M., & Others. (2019). Visual cognition special issue: visual search and selective attention. *Visual Cognition*, *27*(5-6), 385–386. https://www.researchgate.net/institution/Ludwig-Maximilians-University_of_Munich/department/Department_of_Psychology/publications?nav=overview&ev=dep_pub

Ghassemzadeh, H., Rothbart, M. K., & Posner, M. I. (2019). Anxiety and Brain Networks of Attentional Control. *Cognitive and Behavioral Neurology: Official Journal of the Society for*

Behavioral and Cognitive Neurology, *32*(1), 54–62. https://doi.org/10.1097/WNN.0000000000000181

Gomez, P., Ratcliff, R., & Perea, M. (2007). A model of the go/no-go task. *Journal of Experimental Psychology. General*, *136*(3), 389–413. https://doi.org/10.1037/0096-3445.136.3.389

Goschy, H., Bakos, S., Müller, H. J., & Zehetleitner, M. (2014). Probability cueing of distractor locations: both intertrial facilitation and statistical learning mediate interference reduction. *Frontiers in Psychology*, *5*, 1195. https://doi.org/10.3389/fpsyg.2014.01195

Gunther, K. L., & Dobkins, K. R. (2002). Individual differences in chromatic (red/green) contrast sensitivity are constrained by the relative number of L- versus M-cones in the eye. *Vision Research*, *42*(11), 1367–1378. https://doi.org/10.1016/s0042-6989(02)00043-3

Hall, G. (1991). Perceptual and associative learning. *Oxford Psychology Series*, *18*, 29–107. https://books.google.com/books?hl=en&lr=&id=2grsAgAAQBAJ&oi=fnd&pg=PA117&dq=associative+learning&ots=1f26dMBAgS&sig=yZdsqh7Lr6goSIs85rRx290pZig

Hammen, C. (2006). Stress generation in depression: reflections on origins, research, and future directions. *Journal of Clinical Psychology*, *62*(9), 1065–1082. https://doi.org/10.1002/jclp.20293

Harmon-Jones, E. (2004). On the relationship of frontal brain activity and anger: Examining the role of attitude toward anger. *Cognition and Emotion*, *18*(3), 337–361. https://doi.org/10.1080/02699930341000059

Harmon-Jones, E., Gable, P. A., & Peterson, C. K. (2010). The role of asymmetric frontal cortical activity in emotion-related phenomena: a review and update. *Biological Psychology*, *84*(3), 451–462. https://doi.org/10.1016/j.biopsycho.2009.08.010

Hinojosa, J. A., Mercado, F., Albert, J., Barjola, P., Peláez, I., Villalba-García, C., & Carretié, L. (2015). Neural correlates of an early attentional capture by positive distractor words. *Frontiers in Psychology*, *6*, 24. https://doi.org/10.3389/fpsyg.2015.00024

Hu, K., Bauer, A., Padmala, S., & Pessoa, L. (2012). Threat of bodily harm has opposing effects on cognition. *Emotion* , *12*(1), 28–32. https://doi.org/10.1037/a0024345

Izuma, K., Saito, D. N., & Sadato, N. (2008). Processing of social and monetary rewards in the human striatum. *Neuron*, *58*(2), 284–294. https://doi.org/10.1016/j.neuron.2008.03.020

Jiang, Y. V. (2018). Habitual versus goal-driven attention. *Cortex; a Journal Devoted to the Study of the Nervous System and Behavior*, *102*, 107–120. https://doi.org/10.1016/j.cortex.2017.06.018

Jonauskaite, D., Althaus, B., Dael, N., Dan-Glauser, E., & Mohr, C. (2019). What color do you feel? Color choices are driven by mood. *Color Research and Application*, *44*(2), 272–284. https://doi.org/10.1002/col.22327

Jonauskaite, D., Parraga, C. A., Quiblier, M., & Mohr, C. (2020). Feeling Blue or Seeing Red? Similar Patterns of Emotion Associations With Colour Patches and Colour Terms. *I-Perception*, *11*(1), 2041669520902484. https://doi.org/10.1177/2041669520902484

Julesz, B. (1984). A brief outline of the texton theory of human vision. *Trends in Neurosciences*, *7*(2), 41–45. https://doi.org/10.1016/S0166-2236(84)80275-1

Kahnt, T., Park, S. Q., Haynes, J.-D., & Tobler, P. N. (2014). Disentangling neural representations of value and salience in the human brain. *Proceedings of the National Academy of Sciences of the United States of America*, *111*(13), 5000–5005. https://doi.org/10.1073/pnas.1320189111

Katsuki, F., & Constantinidis, C. (2014). Bottom-up and top-down attention: different processes and overlapping neural systems. *The Neuroscientist: A Review Journal Bringing Neurobiology, Neurology and Psychiatry*, *20*(5), 509–521. https://doi.org/10.1177/1073858413514136

Kim, A. J., & Anderson, B. A. (2020a). Neural correlates of attentional capture by stimuli previously associated with social reward. *Cognitive Neuroscience*, *11*(1-2), 5–15. https://doi.org/10.1080/17588928.2019.1585338

Kim, A. J., & Anderson, B. A. (2020b). Neural correlates of attentional capture by stimuli previously associated with social reward. *Cognitive Neuroscience*, *11*(1-2), 5–15. https://doi.org/10.1080/17588928.2019.1585338

Kim, A. J., Lee, D. S., & Anderson, B. A. (2021). The influence of threat on the efficiency of goal-directed attentional control. *Psychological Research*, *85*(3), 980–986. https://doi.org/

10.1007/s00426-020-01321-4

Krummenacher, J., Müller, H. J., & Heller, D. (2002). Visual search for dimensionally redundant pop-out targets: parallel-coactive processing of dimensions is location specific. *Journal of Experimental Psychology. Human Perception and Performance*, *28*(6), 1303–1322. https://doi.org/10.1037/0096-1523.28.6.1303

Leber, A. B., & Egeth, H. E. (2006a). It's under control: top-down search strategies can override attentional capture. *Psychonomic Bulletin & Review*, *13*(1), 132–138. https://doi.org/10.3758/bf03193824

Leber, A. B., & Egeth, H. E. (2006b). Attention on autopilot: Past experience and attentional set. *Visual Cognition*, *14*(4-8), 565–583. https://doi.org/10.1080/13506280500193438

LeDoux, J. E. (1996). The Emotional Brain Simon Schuster. *New York*, *384*.

LeDoux, J. E., & Pine, D. S. (2016). Using Neuroscience to Help Understand Fear and Anxiety: A Two-System Framework. *The American Journal of Psychiatry*, *173*(11), 1083–1093. https://doi.org/10.1176/appi.ajp.2016.16030353

Le Pelley, M. E., Beesley, T., & Griffiths, O. (2011). Overt attention and predictiveness in human contingency learning. *Journal of Experimental Psychology. Animal Behavior Processes*, *37*(2), 220–229. https://doi.org/10.1037/a0021384

Le Pelley, M. E., Mitchell, C. J., Beesley, T., George, D. N., & Wills, A. J. (2016). Attention and associative learning in humans: An integrative review. *Psychological Bulletin*, *142*(10), 1111–1140. https://doi.org/10.1037/bul0000064

Le Pelley, M. E., Pearson, D., Griffiths, O., & Beesley, T. (2015). When goals conflict with values: counterproductive attentional and oculomotor capture by reward-related stimuli. *Journal of Experimental Psychology. General*, *144*(1), 158–171. https://doi.org/10.1037/xge0000037

Libera, C. D., Della Libera, C., & Chelazzi, L. (2006). Visual Selective Attention and the Effects of Monetary Rewards. In *Psychological Science* (Vol. 17, Issue 3, pp. 222–227). https://doi.org/10.1111/j.1467-9280.2006.01689.x

Liesefeld, H. R., Liesefeld, A. M., Pollmann, S., & Müller, H. J. (2018). *Current Topics in Behavioral Neurosciences: Processes of Visuo-spatial Attention and Working Memory*.

Liesefeld, H. R., & Müller, H. J. (2019). Distractor handling via dimension weighting. *Current Opinion in Psychology*, *29*, 160–167. https://doi.org/10.1016/j.copsyc.2019.03.003

Liesefeld, H. R., & Müller, H. J. (2020). Modulations of saliency signals at two hierarchical levels of priority computation revealed by spatial statistical distractor learning. *Journal of Experimental Psychology. General*. https://doi.org/10.1037/xge0000970

Luck, S. J. (2014). *An Introduction to the Event-Related Potential Technique, second edition*. MIT Press. https://play.google.com/store/books/details?id=y4-uAwAAQBAJ

Maier, M. A., Barchfeld, P., Elliot, A. J., & Pekrun, R. (2009). Context specificity of implicit preferences: the case of human preference for red. *Emotion* , *9*(5), 734–738. https://doi.org/10.1037/a0016818

Mine, C., & Saiki, J. (2018). Pavlovian reward learning elicits attentional capture by reward-associated stimuli. *Attention, Perception & Psychophysics*, *80*(5), 1083–1095. https://doi.org/10.3758/s13414-018-1502-2

Miyazawa, S., & Iwasaki, S. (2010). Do happy faces capture attention? The happiness superiority effect in attentional blink. *Emotion* , *10*(5), 712–716. https://doi.org/10.1037/a0019348

Moser, J. S., Becker, M. W., & Moran, T. P. (2012). Enhanced attentional capture in trait anxiety. *Emotion* , *12*(2), 213–216. https://doi.org/10.1037/a0026156

Mulckhuyse, M. (2018). The influence of emotional stimuli on the oculomotor system: A review of the literature. *Cognitive, Affective & Behavioral Neuroscience*, *18*(3), 411–425. https://doi.org/10.3758/s13415-018-0590-8

Müller, H. J., Geyer, T., Zehetleitner, M., & Krummenacher, J. (2009). Attentional capture by salient color singleton distractors is modulated by top-down dimensional set. *Journal of Experimental Psychology. Human Perception and Performance*, *35*(1), 1–16. https://doi.org/10.1037/0096-1523.35.1.1

Müller, H. J., Heller, D., & Ziegler, J. (1995). Visual search for singleton feature targets within and across feature dimensions. *Perception & Psychophysics*, *57*(1), 1–17. https://doi.org/10.3758/bf03211845

Müller, H. J., & Krummenacher, J. (2006). Locus of dimension weighting: Preattentive or postselective? *Visual Cognition*, *14*(4-8), 490–513. https://doi.org/10.1080/13506280500194154

Müller, H. J., Reimann, B., & Krummenacher, J. (2003). Visual search for singleton feature targets across dimensions: Stimulus- and expectancy-driven effects in dimensional weighting. *Journal of Experimental Psychology. Human Perception and Performance*, *29*(5), 1021–1035. https://doi.org/10.1037/0096-1523.29.5.1021

Müller, H. J., Töllner, T., Zehetleitner, M., Geyer, T., Rangelov, D., & Krummenacher, J. (2010). Dimension-based attention modulates feed-forward visual processing [Review of *Dimension-based attention modulates feed-forward visual processing*]. *Acta Psychologica*, *135*(2), 117–122; discussion 133–139. https://doi.org/10.1016/j.actpsy.2010.05.004

Müller, H. J., von Mühlenen, A., & Geyer, T. (2007). Top-down inhibition of search distractors in parallel visual search. *Perception & Psychophysics*, *69*(8), 1373–1388. https://www.ncbi.nlm.nih.gov/pubmed/18078228

Neumann, E., & DeSchepper, B. G. (1991). Costs and benefits of target activation and distractor inhibition in selective attention. *Journal of Experimental Psychology. Learning, Memory, and Cognition*, *17*(6), 1136–1145. https://doi.org/10.1037/0278-7393.17.6.1136

Nissens, T., Failing, M., & Theeuwes, J. (2017). People look at the object they fear: oculomotor capture by stimuli that signal threat. *Cognition & Emotion*, *31*(8), 1707–1714. https://doi.org/10.1080/02699931.2016.1248905

Öhman, A., Flykt, A., & Esteves, F. (2001). Emotion drives attention: Detecting the snake in the grass. *Journal of Experimental Psychology. General*, *130*(3), 466–478. https://doi.org/10.1037/0096-3445.130.3.466

Pinkham, A. E., Griffin, M., Baron, R., Sasson, N. J., & Gur, R. C. (2010). The face in the crowd effect: anger superiority when using real faces and multiple identities. *Emotion* , *10*(1), 141–146. https://doi.org/10.1037/a0017387

Pollmann, S., Weidner, R., Müller, H. J., & von Cramon, D. Y. (2000). A fronto-posterior network involved in visual dimension changes. *Journal of Cognitive Neuroscience*, *12*(3), 480–494. https://doi.org/10.1162/089892900562156

Posner, M. I. (1980a). Orienting of Attention. In *Quarterly Journal of Experimental*

Psychology (Vol. 32, Issue 1, pp. 3–25). https://doi.org/10.1080/00335558008248231

Posner, M. I. (1980b). Orienting of attention. *The Quarterly Journal of Experimental Psychology*, *32*(1), 3–25. https://doi.org/10.1080/00335558008248231

Posner, M. I., & Petersen, S. E. (1990). The attention system of the human brain. *Annual Review of Neuroscience*, *13*, 25–42. https://doi.org/10.1146/annurev.ne.13.030190.000325

Prete, G., Croce, P., Zappasodi, F., Tommasi, L., & Capotosto, P. (2022). Exploring brain activity for positive and negative emotions by means of EEG microstates. *Scientific Reports*, *12*(1), 3404. https://doi.org/10.1038/s41598-022-07403-0

Prete, G., Laeng, B., & Tommasi, L. (2014). Lateralized hybrid faces: evidence of a valence-specific bias in the processing of implicit emotions. *Laterality*, *19*(4), 439–454. https://doi.org/10.1080/1357650X.2013.862255

Qi, S., Zeng, Q., Ding, C., & Li, H. (2013). Neural correlates of reward-driven attentional capture in visual search. *Brain Research*, *1532*, 32–43. https://doi.org/10.1016/j.brainres.2013.07.044

Reinholdt-Dunne, M. L., Mogg, K., & Bradley, B. P. (2009). Effects of anxiety and attention control on processing pictorial and linguistic emotional information. *Behaviour Research and Therapy*, *47*(5), 410–417. https://doi.org/10.1016/j.brat.2009.01.012

Roper, Z. J. J., Vecera, S. P., & Vaidya, J. G. (2014). Value-Driven Attentional Capture in Adolescence. *Psychological Science*, *25*(11), 1987–1993. https://doi.org/10.1177/0956797614545654

Rosenholtz, R., Huang, J., & Ehinger, K. A. (2012). Rethinking the role of top-down attention in vision: Effects attributable to a lossy representation in peripheral vision. *Frontiers in Psychology*, *3*(FEB). https://doi.org/10.3389/fpsyg.2012.00013

Sauter, M., Hanning, N. M., Liesefeld, H. R., & Müller, H. J. (2021). Post-capture processes contribute to statistical learning of distractor locations in visual search. *Cortex; a Journal Devoted to the Study of the Nervous System and Behavior*, *135*, 108–126. https://doi.org/10.1016/j.cortex.2020.11.016

Sauter, M., Liesefeld, H. R., & Müller, H. J. (2019). Learning to suppress salient distractors in the target dimension: Region-based inhibition is persistent and transfers to distractors in a nontarget dimension. *Journal of Experimental Psychology. Learning, Memory, and Cognition*, *45*(11), 2080–2097. https://doi.org/10.1037/xlm0000691

Sauter, M., Liesefeld, H. R., Zehetleitner, M., & Müller, H. J. (2018). Region-based shielding of visual search from salient distractors: Target detection is impaired with same- but not different-dimension distractors. In *Attention, Perception, & Psychophysics* (Vol. 80, Issue 3, pp. 622–642). https://doi.org/10.3758/s13414-017-1477-4

Sawaki, R., & Luck, S. J. (2013). Active suppression after involuntary capture of attention. *Psychonomic Bulletin & Review*, *20*(2), 296–301. https://doi.org/10.3758/s13423-012-0353-4

Schmidt, L. J., Belopolsky, A. V., & Theeuwes, J. (2015). Attentional capture by signals of threat. *Cognition & Emotion*, *29*(4), 687–694. https://doi.org/10.1080/02699931.2014.924484

Schubö, A., & Müller, H. J. (2009). Selecting and ignoring salient objects within and across dimensions in visual search. *Brain Research*, *1283*, 84–101. https://doi.org/10.1016/j.brainres.2009.05.077

Schubö, A., Wykowska, A., & Müller, H. J. (2007). Detecting pop-out targets in contexts of varying homogeneity: investigating homogeneity coding with event-related brain potentials (ERPs). *Brain Research*, *1138*, 136–147. https://doi.org/10.1016/j.brainres.2006.12.059

Sha, L. Z., & Jiang, Y. V. (2016a). Components of reward-driven attentional capture. In *Attention, Perception, & Psychophysics* (Vol. 78, Issue 2, pp. 403–414). https://doi.org/10.3758/s13414-015-1038-7

Sha, L. Z., & Jiang, Y. V. (2016b). Components of reward-driven attentional capture. *Attention, Perception & Psychophysics*, *78*(2), 403–414. https://doi.org/10.3758/s13414-015-1038-7

Shaw, M. L., & Shaw, P. (1977). Optimal allocation of cognitive resources to spatial locations. *Journal of Experimental Psychology. Human Perception and Performance*, *3*(2), 201–211. https://www.ncbi.nlm.nih.gov/pubmed/864393

Skinner, B. F. Science and human behavior. New York: The Macmillan Company, 1953. 461 P. $4.00. (1954). *Science Education*, *38*(5), 436–436. https://doi.org/10.1002/

sce.37303805120

Stanković, M. (2020). A conceptual critique of brain lateralization models in emotional face perception: Toward a hemispheric functional-equivalence (HFE) model. *International Journal of Psychophysiology: Official Journal of the International Organization of Psychophysiology*. https://www.sciencedirect.com/science/article/pii/S0167876020302579

Stanković, M., Bašić, J., Milošević, V., & Nešić, M. (2019). Oxytocin receptor (OXTR) gene polymorphisms and recognition memory for emotional and neutral faces: A pilot study. *Learning and Motivation*, *67*, 101577. https://doi.org/10.1016/j.lmot.2019.101577

Stanković, M., & Nešić, M. (2019). No Evidence of Improved Emotion Perception Through Unilateral Hand Contraction. *Perceptual and Motor Skills*, 31512519888080. https://doi.org/10.1177/0031512519888080

Stanković, M., & Nešić, M. (2020). Functional brain asymmetry for emotions: psychological stress-induced reversed hemispheric asymmetry in emotional face perception. *Experimental Brain Research. Experimentelle Hirnforschung. Experimentation Cerebrale*, *238*(11), 2641–2651. https://doi.org/10.1007/s00221-020-05920-w

Stanković, M., Nešić, M., Čičević, S., & Shi, Z. (2021). Association of smartphone use with depression, anxiety, stress, sleep quality, and internet addiction. Empirical evidence from a smartphone application. *Personality and Individual Differences*, *168*, 110342. https://doi.org/10.1016/j.paid.2020.110342

Stanković, M., Nešić, M., & Milić, J. (2019). Effects of unpleasant odors on emotion recognition: the right hemisphere and valence-specific hypotheses. *Psihologija*, *00*, 19–19.

Stanković, M., Nešić, M., Obrenović, J., Stojanović, D., & Milošević, V. (2015). Recognition of facial expressions of emotions in criminal and non-criminal psychopaths: Valence-specific hypothesis. *Personality and Individual Differences*, *82*, 242–247. https://doi.org/10.1016/j.paid.2015.03.002

Stigchel, S. V. der, Van der Stigchel, S., Belopolsky, A. V., Peters, J. C., Wijnen, J. G., Meeter, M., & Theeuwes, J. (2009). The limits of top-down control of visual attention. In *Acta Psychologica* (Vol. 132, Issue 3, pp. 201–212). https://doi.org/10.1016/j.actpsy.2009.07.001

Stojiljković, J., & Stanković, M. (2018). Depressive state and social anxiety in adolescents: the role of family interactions. *The American Journal of Family Therapy*. https://www.tandfonline.com/doi/abs/10.1080/01926187.2018.1506269

Sussman, T. J., Heller, W., Miller, G. A., & Mohanty, A. (2013). Emotional distractors can enhance attention. *Psychological Science*, *24*(11), 2322–2328. https://doi.org/10.1177/0956797613492774

Theeuwes,. (2019). Goal-driven, stimulus-driven, and history-driven selection. *Current Opinion in Psychology*, *29*, 97–101. https://doi.org/10.1016/j.copsyc.2018.12.024

Theeuwes, J. (1991). Cross-dimensional perceptual selectivity. *Perception & Psychophysics*, *50*(2), 184–193. https://doi.org/10.3758/bf03212219

Theeuwes, J. (2010). Top–down and bottom–up control of visual selection. *Acta Psychologica*, *135*(2), 77–99. https://doi.org/10.1016/j.actpsy.2010.02.006

Theeuwes, J. (2018). Visual Selection: Usually Fast and Automatic; Seldom Slow and Volitional. *Journal of Cognition*, *1*(1), 29. https://doi.org/10.5334/joc.13

Theeuwes, J., & Failing, M. (2020). *Attentional Selection: Top-Down, Bottom-Up and History-Based Biases*. Cambridge University Press. https://play.google.com/store/books/details?id=Y732DwAAQBAJ

Theeuwes, J., Reimann, B., & Mortier, K. (2006). Visual search for featural singletons: No top-down modulation, only bottom-up priming. *Visual Cognition*, *14*(4-8), 466–489. https://doi.org/10.1080/13506280500195110

Thompson, K. G., & Bichot, N. P. (2005). A visual salience map in the primate frontal eye field. *Progress in Brain Research*, *147*, 251–262. https://doi.org/10.1016/S0079-6123(04)47019-8

Thorndike, E. L. (1911). *Animal Intelligence Macmillan: New York.*

Töllner, T., Müller, H. J., & Zehetleitner, M. (2012). Top-down dimensional weight set determines the capture of visual attention: Evidence from the PCN component. *Cerebral Cortex* , *22*(7), 1554–1563. https://doi.org/10.1093/cercor/bhr231

Treisman, A., & Paterson, R. (1984). Emergent features, attention, and object perception. *Journal of Experimental Psychology. Human Perception and Performance*, *10*(1), 12–31.

https://doi.org/10.1037//0096-1523.10.1.12

Treisman, A., & Souther, J. (1985). Search asymmetry: a diagnostic for preattentive processing of separable features. *Journal of Experimental Psychology. General*, *114*(3), 285–310. https://doi.org/10.1037//0096-3445.114.3.285

Van der Stigchel, S., Mulckhuyse, M., & Theeuwes, J. (2009). Eye cannot see it: the interference of subliminal distractors on saccade metrics. *Vision Research*, *49*(16), 2104–2109. https://doi.org/10.1016/j.visres.2009.05.018

Vecera, S. P., Cosman, J. D., Vatterott, D. B., & Roper, Z. J. J. (2014). The control of visual attention: Toward a unified account. In *Psychology of learning and motivation* (Vol. 60, pp. 303–347). Elsevier. https://www.sciencedirect.com/science/article/pii/B9780128000908000081

Vuilleumier, P. (2005a). How brains beware: neural mechanisms of emotional attention. In *Trends in Cognitive Sciences* (Vol. 9, Issue 12, pp. 585–594). https://doi.org/10.1016/j.tics.2005.10.011

Vuilleumier, P. (2005b). How brains beware: neural mechanisms of emotional attention. *Trends in Cognitive Sciences*, *9*(12), 585–594. https://doi.org/10.1016/j.tics.2005.10.011

Vuilleumier, P. (2015). Affective and motivational control of vision. *Current Opinion in Neurology*, *28*(1), 29–35. https://doi.org/10.1097/WCO.0000000000000159

Vuilleumier, P., & Huang, Y.-M. (2009). Emotional Attention: Uncovering the Mechanisms of Affective Biases in Perception. *Current Directions in Psychological Science*, *18*(3), 148–152. https://doi.org/10.1111/j.1467-8721.2009.01626.x

Watson, P., Pearson, D., Most, S. B., Theeuwes, J., Wiers, R. W., & Le Pelley, M. E. (2019). Attentional capture by Pavlovian reward-signalling distractors in visual search persists when rewards are removed. *PloS One*, *14*(12), e0226284. https://doi.org/10.1371/journal.pone.0226284

Wolfe, J. M. (1994). Guided Search 2.0 A revised model of visual search. *Psychonomic Bulletin & Review*, *1*(2), 202–238. https://doi.org/10.3758/BF03200774

Wolfe, J. M. (2021). Guided Search 6.0: An updated model of visual search. *Psychonomic Bulletin & Review*, *28*(4), 1060–1092. https://doi.org/10.3758/s13423-020-01859-9

Wolfe, J. M., Cave, K. R., & Franzel, S. L. (1989). Guided search: an alternative to the feature integration model for visual search. *Journal of Experimental Psychology. Human Perception and Performance*, *15*(3), 419–433. https://doi.org/10.1037//0096-1523.15.3.419

Wolfe, J. M., & Gray, W. (2007). Guided search 4.0. *Integrated Models of Cognitive Systems*, 99–119. https://books.google.com/books?hl=en&lr=&id=eB9nDAAAQBAJ&oi=fnd&pg=PA99&dq=Wolfe+J+M+Gray+W+(2007)+Guided+search+4+0+Integrated+models+of+cognitive+systems+99-119&ots=zURY5zgmKA&sig=Q7-b2luWx1JYfcuW3zw11YKhQ0o

Wong, I., Mahar, D., Titchener, K., & Freeman, J. (2013). The impact of anxiety on processing efficiency: Implications for the Attentional Control Theory. *The Open Behavioral Science Journal*, *7*(6), 7–15. https://eprints.qut.edu.au/56005/

Yantis, S., & Jonides, J. (1990). Abrupt visual onsets and selective attention: voluntary versus automatic allocation. *Journal of Experimental Psychology. Human Perception and Performance*, *16*(1), 121–134. https://doi.org/10.1037//0096-1523.16.1.121

Zehetleitner, M., Goschy, H., & Müller, H. J. (2012). Top-down control of attention: it's gradual, practice-dependent, and hierarchically organized. *Journal of Experimental Psychology. Human Perception and Performance*, *38*(4), 941–957. https://doi.org/10.1037/a0027629

Zehetleitner, M., Krummenacher, J., Geyer, T., Hegenloh, M., & Müller, H. J. (2011). Dimension intertrial and cueing effects in localization: support for pre-attentively weighted one-route models of saliency. *Attention, Perception & Psychophysics*, *73*(2), 349–363. https://doi.org/10.3758/s13414-010-0035-0

Zehetleitner, M., Krummenacher, J., & Müller, H. J. (2009). The detection of feature singletons defined in two dimensions is based on salience summation, rather than on serial exhaustive or interactive race architectures. *Attention, Perception & Psychophysics*, *71*(8), 1739–1759. https://doi.org/10.3758/APP.71.8.1739

Zehetleitner, M., Proulx, M. J., & Müller, H. J. (2009). Additional-singleton interference in efficient visual search: a common salience route for detection and compound tasks. *Attention, Perception & Psychophysics*, *71*(8), 1760–1770. https://doi.org/10.3758/

APP.71.8.1760

Zhang, B., Allenmark, F., Liesefeld, H. R., Shi, Z., & Müller, H. J. (2019). Probability cueing of singleton-distractor locations in visual search: Priority-map- versus dimension-based inhibition? *Journal of Experimental Psychology. Human Perception and Performance*, *45*(9), 1146–1163. https://doi.org/10.1037/xhp0000652

Zhang, B., Weidner, R., Allenmark, F., Bertleff, S., Fink, G. R., Shi, Z., & Müller, H. J. (2021). Statistical Learning of Frequent Distractor Locations in Visual Search Involves Regional Signal Suppression in Early Visual Cortex. *Cerebral Cortex* . https://doi.org/10.1093/cercor/bhab377

Zinchenko, A., Kanske, P., Obermeier, C., Schröger, E., & Kotz, S. A. (2015). Emotion and goal-directed behavior: ERP evidence on cognitive and emotional conflict. *Social Cognitive and Affective Neuroscience*, *10*(11), 1577–1587. https://doi.org/10.1093/scan/nsv050

Zinchenko, A., Obermeier, C., Kanske, P., Schröger, E., & Kotz, S. A. (2017). Positive emotion impedes emotional but not cognitive conflict processing. *Cognitive, Affective & Behavioral Neuroscience*, *17*(3), 665–677. https://doi.org/10.3758/s13415-017-0504-1

Deutsche Zusammenfassung

Im Alltag wird die Aufmerksamkeit der Menschen durch zahlreiche relevante und irrelevante Reize herausgefordert. Das Überleben und das Wohlergehen der Menschen hängen davon ab, relevante Faktoren zu priorisieren und irrelevante Umwelteinflüsse zu ignorieren. Menschen müssen ihre Aufmerksamkeit relativ schnell neu ausrichten und ihr aktuelles Verhaltensmuster ändern, wenn sie mit neuen, potenziell lohnenden oder bedrohlichen Reizen konfrontiert werden (Corbetta et al., 2008). Dies deutet darauf hin, dass die Aufmerksamkeit als zentrale, organisierte Funktion bei Wahrnehmung, Kognition und Handlung dynamische sensorische Informationen filtert und Reaktionen zur Erreichung von Verhaltenszielen vermittelt. Die Aufmerksamkeit wählt Reize für die kognitive Verarbeitung aus und der diesem Prozess zugrunde liegende Mechanismus ist entweder freiwillig durch visuelle Suchziele oder unfreiwillig durch die physische Attraktivität der Reize angetrieben (Anderson, 2013). Es gibt eine fortwährende Debatte darüber, wie Menschen ihre Aufmerksamkeit in visuellen Modalitäten einsetzen. Die Befürworter der stimulusgesteuerten Aufmerksamkeit versuchen Beweise dafür zu liefern, dass ein abrupter, physisch salienter Reiz Aufmerksamkeit erregt, wenn er in das „Zoomobjektiv" der Aufmerksamkeit fällt, unabhängig von den aktuellen Zielen des Beobachters oder sogar entgegen der Top-down-Kontrolle (Theeuwes 1991; 2010; Van der Stigchel et al. 2009; Theeuwes und Failing 2020), wohingegen die Befürworter der zielorientierten Aufmerksamkeit argumentierten, dass eine reine Bottom-up-Aufmerksamkeit nicht existiert, da die Aufmerksamkeitsselektion immer ein Ergebnis der Top-down-Absichten ist (Folk et al. 1992). Die freiwillige oder unfreiwillige Art der Aufmerksamkeitsverarbeitung arbeitet mit Strategien, die auf früheren Erfahrungen basieren und von der Selektionsgeschichte (Theeuwes, 2019) beeinflusst werden. Die Aufmerksamkeitsauswahl wird darüber hinaus durch das emotional assoziative Lernen beeinflusst. Neuere Studien zeigen jedoch die Perspektive auf, dass der Belohnung eine entscheidende Roll bei der Aufmerksamkeitsauswahl zukommt.

In den letzten 15 Jahren wurde sehr lebhaft darüber diskutiert, inwieweit ein Reiz, der zuvor mit Belohnung assoziiert (Konditionierung) wurde, immer noch Aufmerksamkeit erregt. Dies ist nicht verwunderlich, da die Bedeutung der Glückseligkeit und die Abwesenheit von Schmerz für die Lebensführung bereits im antiken Griechenland diskutiert wurden (z. B. Epikur, altgriechisch: Ἐπίκουρος). Das Auftreten eines belohnungsbezogenen Stimulus setzt diese Funktion auch dann noch fort, wenn keine Belohnung mehr signalisiert wird. Eine bahnbrechende Studie zum Einfluss von Belohnungslernassoziationen auf die selektive visuelle Aufmerksamkeit war die Arbeit von Libera (Libera et al., 2006). Libera et al. haben anhand einer Prime-Probe-Aufgabe gezeigt, dass eine monetäre Belohnung als Feedback die Effizienz in einer visuellen selektiven Aufmerksamkeitsaufgabe moduliert, und damit demonstriert, dass Belohnung als Belohnungsregime beim operanten Lernen zur Verhaltensformung (Skinner, 1954), aber auch für anspruchsvollere Formen des Lernens bei der visuellen Aufmerksamkeitsselektion verwendet werden kann. Das derzeit am häufigsten verwendete Paradigma zur Untersuchung des Phänomens der Aufmerksamkeitsauswahl ist das Paradigma der wertorientierten Aufmerksamkeitserfassung (Anderson et al., 2011).

Um sich adaptiv zu verhalten, wird die menschliche Aufmerksamkeit freiwillig (zielorientiert) oder unfreiwillig (reizorientiert) gelenkt, wobei die Strategien der bisherigen Erfahrungen (historiengesteuert) genutzt werden (Theeuwes, 2019). Vorangegangene Forschungen betonen jedoch, dass die Aufmerksamkeit durch den motivationalen und emotionalen Wert von Reizen gesteuert werden kann (Bourgeois et al., 2016), wohingegen der Einfluss des Belohnungslernens auf Aufmerksamkeitsprozesse schnell zu einem Bereich intensiver Forschung geworden ist (Anderson, 2016b). Bei einer Suchaufgabe richtet sich die Aufmerksamkeit stärker auf emotionale als auf neutrale Gesichter (Frischen et al., 2008), während ERP-Studien (Zinchenko et al., 2015, 2017) einen starken Einfluss von Emotionen auf die kognitive und emotionale Konfliktverarbeitung belegen und die Bedeutung von Emotionen bei der Entscheidungsfindung betonen. Es stellt sich daher die grundlegende Frage, ob es einen Unterschied zwischen dem Einfluss von motivationalen und emotionalen Werten von Reizen auf die Aufmerksamkeitsauswahl und -erfassung gibt. Bei bisherigen Forschungsarbeiten wurde hauptsächlich eine monetäre Belohnung als Motivationsreiz im Paradigma der wertorientierten Aufmerksamkeitssteuerung verwendet (Anderson et al., 2011; Le Pelley et al., 2015; Nissens et al., 2017; Watson et al., 2019). Neben positiver Verstärkung kann auch Bestrafung eingesetzt werden, um die Aufmerksamkeit in ähnlicher Weise zu fesseln. Dies deutet darauf hin, dass die motivationale Bedeutung des Ergebnisses (ein hohes Maß an Belohnung/Bestrafung führt dabei zu größerer Erregung als ein geringes Maß an Belohnung/Bestrafung) und nicht die Valenz des Ergebnisses einen entscheidenden Einfluss auf die Aufmerksamkeitserfassung ausübt (Le Pelley et al., 2016). Eine fMRT-Studie (Kahnt et al., 2014) hat bei der Vorhersage von Aufgabenergebnissen gezeigt, dass die neuronalen Kodierungsmuster bei der Vorhersage von Ergebniswerten bei belohnenden und aversiven Reizen ähnlich sind, was möglicherweise auf ein einzigartiges valenzbezogenes Netzwerk hinweist.

In einer neueren Studie von Kim und Anderson (2020) wurden emotionale Gesichter als emotionale (soziale) Belohnung verwendet, um den Aufmerksamkeitserfassungseffekt durch Belohnungs-Lern-Assoziationen zu untersuchen. Anstelle der Verwendung des üblichen monetären Feedbacks für korrekte Antworten in einer visuellen Suchaufgabe wurde in der Assoziationsphase ein Foto mit positiver oder neutraler Valenz (d.h. glückliches Gesicht vs.

neutrales Gesicht) mit einem farblich definierten Ziel (rot vs. grün) assoziiert. In der Nicht-Belohnungs-Phase suchten die Teilnehmer nach einem einförmigen Ziel (d.h. einem Kreis unter Rauten oder einer Raute unter Kreisen), wobei sie die Farbe der präsentierten Objekte ignorierten.

In den oben genannten Studien deutet dies darauf hin, dass ein irrelevanter Ablenker, der zuvor mit motivationalen und emotionalen Stimuli in Verbindung gebracht wurde, die Aufmerksamkeit gleichermaßen auf sich zieht. Aber ist das wirklich der Fall? In einer Studie von Kim und Anderson (2020) wurde kein signifikanter Effekt zwischen hoher und niedriger Belohnung in der Assoziationsphase gefunden, während in der Phase ohne Belohnung ein Unterschied zwischen einem abwesenden Ablenker und einem niedrig- und hochwertigen Ablenker, aber nicht zwischen einem niedrig- und einem hochwertigen Ablenker festgestellt wurde. Dies stellt die auf emotionalen Werten basierende Aufmerksamkeitserfassung in Frage.

Es gibt deutliche Hinweise darauf, dass die selektive Aufmerksamkeit durch eine Top-down-Aufmerksamkeitskontrolle, eine Bottom-up-Aufmerksamkeitserfassung und eine historisch bedingte Auswahl bestimmt wird. In jüngster Zeit hat eine wachsende Zahl von Studien gezeigt, dass belohnungsorientierte Reize unwillkürlich und automatisch die Aufmerksamkeit auf sich ziehen können, selbst wenn diese Reize nicht aufgabenrelevant sind. Es bleibt jedoch unklar, inwieweit die Aufmerksamkeitserfassung erfolgt, wenn ein irrelevanter Ablenker zuvor mit motivationalen (z. B. monetären) Belohnungen im Vergleich zu emotionalen (z. B. glücklichen Gesichtern) assoziiert wird. Es wurden solide Beweise dafür geliefert, dass zusätzlich zu bestehenden Formen der Aufmerksamkeitsauswahl die erlernte Vorhersagekraft (Erwartung) die visuelle Aufmerksamkeit grundlegend modulieren und die Wahrnehmung formen kann.

Es bleiben also viele offene Fragen zu klären. Daher haben wir uns in dieser Arbeit mit mehreren grundlegenden Fragen befasst: Inwieweit kann ein irrelevanter Ablenkungsreiz, der zuvor mit einer Belohnung in Verbindung gebracht wurde, immer noch Aufmerksamkeit erregen? Hängt die Aufmerksamkeitserfassung von einem irrelevanten Ablenkungsreiz, der zuvor mit Belohnung assoziiert wurde, davon ab, ob der Belohnungswert motivierend oder emotional ist? Ist die Aufmerksamkeitserfassung durch einen Ablenkungsreiz, der zuvor mit

Belohnung verbunden war, vom angewandten assoziativen Lernen abhängig (d. h. Pawlowsche Konditionierung, instrumentelles Lernen)? Hängt die Aufmerksamkeitserfassung von individuellen Unterschieden (z. B. psychologischen Merkmalen) zwischen Menschen ab?

In der Einführung (1.2.) dieser Arbeit werden Phänomene der Aufmerksamkeitsselektion im Allgemeinen, insbesondere Top-down-, Bottom-up- und historisch bedingte Selektion skizziert. Kapitel (1.3.) beschreibt die zielgerichtete Aufmerksamkeitsauswahl als eine kritische Komponente der Aufmerksamkeit detaillierter, da wir in unserem Alltag ständig durch visuellen Input aktualisiert werden, indem wir diesen als Quelle der Aufmerksamkeitsnavigation nutzen, um unsere Aufmerksamkeit zu steuern. Es wird davon ausgegangen, dass die Aufmerksamkeit auf ein bestimmtes Objekt durch willentliche Kontrolle gelenkt wird, da sie die aktuellen Selektionsziele des Beobachters repräsentiert. Im Kapitel (1.4.) wird die reizgesteuerte Aufmerksamkeitsselektion beschrieben und auf theoretische Erklärungen hingewiesen, die die nicht-willentliche Komponente reiner Bottom-up-Mechanismen aufzeigen. Darüber hinaus wird in Kapitel (1.5.) das Phänomen der Aufmerksamkeitserfassung beschrieben, welches in Studien zur Erforschung der Bottom-up-Aufmerksamkeitsselektion häufig zu beobachten ist. Die Exposition eines physisch auffälligen (z. B. roten) Gegenstandes zieht automatisch die Aufmerksamkeit des Beobachters auf sich, was insbesondere bei neuartigen auffälligen Reizen (z. B. bei abruptem Einsetzen) oft nicht zu vermeiden ist. Weiterhin wird im nächsten Kapitel (1.6.) die Geschichtsselektion als Interaktion zwischen Top-down- und Bottom-up-Aufmerksamkeitsselektionsmechanismen erklärt, da viele Entscheidungen des Beobachters durch frühere Erfahrungen gesteuert werden. Bisherige Erfahrungen bestimmen das weitere Aufmerksamkeitsverhalten in einer Weise, dass implizite oder explizite Erfahrungen die aktuelle Aktion der Aufmerksamkeitsauswahl prägen. In Kapitel (2) wird die Rolle der Belohnung bei der Aufmerksamkeitsselektion erläutert, da die historische Selektion so erfolgen kann, dass neutrale Reize, die zuvor mit einer Belohnung (z. B. monetär oder emotional) verbunden waren, die Aufmerksamkeit auf sich ziehen können. Die belohnungsbasierte Lerngeschichte und die Selektionsgeschichte im Paradigma der wertgesteuerten Aufmerksamkeitserfassung werden im Kapitel 2.1 und 2.2 beschrieben. Zusätzlich wird das Paradigma der wertorientierten Aufmerksamkeitserfassung im Detail erläutert. Kapitel 2.3. erörtert einige theoretische

Darstellungen, welche die Pawlowsche Konditionierung und das instrumentelle Lernen als Haupttypen des assoziativen Lernens von Bedeutung bei der wertorientierten Aufmerksamkeitsauswahl betrachten, die als wichtige Bestandteile der Auswahlgeschichte angesehen wird. Die Kapitel 3.1. und 3.2. stellen die zielgerichtete, reiz- und historiengesteuerte Selektion durch neurologische Mechanismen vor und fassen insbesondere neuere EEG-Aufmerksamkeitsstudien zusammen. Die Hauptziele der Dissertation werden in Kapitel 4 dargestellt. Der entscheidende Abschnitt 5 umfasst drei Einzelstudien als Hauptbestandteil der kumulativen Dissertation. Schließlich hebt Kapitel 6 die allgemeine Diskussion über drei Studien hervor, darunter ein entscheidendes Experiment (vier Verhaltensexperimente und ein EEG). Anregungen für weitere Forschungsarbeiten finden sich am Ende des Diskussionsteils. Eine Zusammenfassung der Ergebnisse erfolgt im abschließenden Kapitel 7.

In der vorliegenden Dissertation wurden zum einen Verhaltensmechanismen untersucht, die der emotionsgesteuerten Aufmerksamkeitsselektion und der emotionalen (sozialen) Belohnung zugrunde liegen, und zum anderen neuronale Mechanismen, die der Aufmerksamkeitskontrollleistung und negativen Emotionen (Angstzustand) zugrunde liegen.

Unter Beachtung der aktueller Forschungen (Bourgeois et al. 2016; Vuilleumier 2015), die den Einfluss von insbesondere monetären Belohnungen auf die Aufmerksamkeitsselektion (z.B. Aufmerksamkeitserfassung) durch assoziatives Lernen aufzeigt, wurde in der vorliegenden Arbeit untersucht, ob ein aufgabenirrelevantes Merkmal, wie zum Beispiel Farbe (rot, grün), das zuvor mit Gesichtsausdrücken (glücklich, neutral) oder sozialen Szenen (angenehm, neutral) assoziiert wurde, die visuelle Formsuche nach einem einzelnen Ziel beeinträchtigen würde.

Im Gegensatz zu neueren Studien, die das Paradigma der wertorientierten Aufmerksamkeitserfassung verwenden (Anderson et al., 2011; Anderson & Halpern, 2017; Cho & Cho, 2021; Qi et al., 2013; Sha & Jiang, 2016) und die einen Effekt der Aufmerksamkeitserfassung durch einen irrelevanten und zuvor mit einer monetären Belohnung assoziierten Ablenker nachweisen konnten, zeigte die Verwendung einer emotionalen Belohnung im gleichen "wertorientierten" Rahmen kontroverse Ergebnisse (Sha & Jiang, 2016).

Darüber hinaus haben neuere Erkenntnisse (Jonauskaite, Althaus, et al., 2019; Jonauskaite et al., 2020) über die Beziehung zwischen Farbe und Emotion einen starken emotionalen Hintergrund in Bezug auf die Farbe gezeigt; insbesondere Rot wurde häufig mit Emotionen wie Liebe oder Wut assoziiert, während Grün nicht mit spezifischen Emotionen in Verbindung gebracht wurde. Typischerweise wird Rot im Vergleich zu Grün im spontanen Selektionsparadigma bevorzugt, was stark mit dem emotionalen Kontext zusammenhängt: Rot wird gegenüber Grün bevorzugt, wenn ein fröhliches Gesicht folgt, wohingegen das Gegenteil der Fall ist, wenn es sich ein wütendes Gesicht anschließt (Maier et al., 2009). In diesem Sinne konzentriert sich die vorliegende Dissertation auf die Aufmerksamkeitsauswahl, die durch emotionale Belohnung, assoziatives Lernen und deren Wechselwirkungen mit der physischen Bedeutung von Farbe moduliert wird.

In der vorliegenden Dissertation wurden weiterhin die verhaltensbezogenen und neuronalen Mechanismen untersucht, die der Leistung der Aufmerksamkeitskontrolle zugrunde liegen, insbesondere die zielgerichtete visuelle Suche unter experimentell induzierten Angstgefühlen. In Anbetracht zahlreicher früherer Forschungsarbeiten (Ghassemzadeh et al. 2019; LeDoux 1996; Moser et al. 2012; Eysenck et al. 2007), die einen starken Einfluss von Emotionen auf die Aufmerksamkeitsleistung belegen, wurden diese Fragen in der vorliegenden Arbeit durch die Einführung eines neuartigen dualen Zielaufmerksamkeitsparadigmas erweitert, um zu untersuchen, ob Angst die Aufmerksamkeitsleistung beeinträchtigt oder sogar fördert. Insbesondere wird untersucht, ob die zielgerichtete visuelle Suche nach zwei Zielen durch experimentell induzierte Angstzustände aufgrund der Verringerung / Erleichterung Top-down-Aufmerksamkeitskontrolle und deren Einfluss auf die Bottom-up-Aufmerksamkeitserfassung beeinflusst wird. Parallel dazu wurden in der aktuellen Arbeit neuropsychologische Modalitäten zielgerichteter (z. B. N2pc) und reizgesteuerter (z. B. PD) Aufmerksamkeitsmechanismen bei Angstzuständen einer Person untersucht.

In den folgenden Kapiteln werden die in den fünf vorangegangenen Versuchen gewonnenen Erkenntnisse zusammengefasst und die wichtigsten Schlussfolgerungen dargelegt. Allgemeine Einschränkungen weisen auf mögliche Schwachstellen der Ergebnisse hin, während zukünftige Richtungen Empfehlungen für weitere wissenschaftliche Arbeiten auf Grundlage der erzielten Ergebnisse und Folgeinterpretationen aufzeigen.

In Kapitel 5.1. werden drei Verhaltensexperimente vorgestellt, in denen der Zusammenhang zwischen emotionsgesteuerter Aufmerksamkeitserfassung/-interferenz und sozialer Belohnung untersucht wurde. In Anbetracht der zunehmenden Literatur (Anderson et al., 2011; Anderson & Halpern, 2017; Cho & Cho, 2021; Qi et al., 2013; Sha & Jiang, 2016), die den Einfluss von Belohnungen, insbesondere monetärer Belohnungen unterschiedlicher Höhe (niedrig, hoch), nachweist, zielt diese Dissertation darauf ab, eine erhebliche Lücke im Zusammenhang mit Emotionen und emotionaler Belohnung zu schließen. Emotional wichtige Stimuli ziehen mehr Aufmerksamkeit auf sich als neutrale Reize (Vuilleumier & Huang, 2009), daher wird angenommen, dass soziale Belohnung die menschliche Aufmerksamkeitsselektion moduliert. Weniger bekannt war, inwieweit ein aufgabenirrelevantes Merkmal, die Farbe (rot, grün), die zuvor mit einem emotionalen Bild unterschiedlicher Valenz (neutral, angenehm) oder Erregung (niedrig, hoch) assoziiert wurde, die Aufmerksamkeit auf sich ziehen kann, zumal neuere Studien keine konsistenten und replizierbaren Ergebnisse zeigen konnten (Anderson, 2016, 2017; Anderson & Kim, 2018; Kim & Anderson, 2020). Um diese Lücke zu schließen, wurden drei Verhaltensexperimente durchgeführt, bei denen gesunde Universitätsstudenten rekrutiert wurden und ein modifiziertes wertorientiertes Aufmerksamkeitsparadigma mit Assoziations- und Testphase zur Anwendung kam (Anderson, 2011).Die Ergebnisse der drei Experimente zeigten eine farbvalenzgesteuerte Erleichterung, aber keine emotionsgesteuerte Interferenz, so dass die Ergebnisse keine signifikante emotionsabhängige Modulation der Verhaltensleistung in der Assoziationsphase bestätigen konnten. Folglich wurde kein signifikantes Ergebnis in Bezug auf die valenzabhängige Modulation der Distraktorinterferenz (Experimente 1 und 2) oder der Zielerleichterung (Experiment 3) in der Testphase des modifizierten wertgesteuerten Aufmerksamkeitserfassungsparadigmas gefunden.

In Kapitel 5.2. wird eine Verhaltensstudie vorgestellt, in welcher der Zusammenhang zwischen Aufmerksamkeitskontrolle und Angstgefühlen untersucht wurde. Als integraler Bestandteil dieser Dissertation wird in der vorgestellten Studie untersucht, ob eine zielgerichtete visuelle Suche nach zwei Zielen durch experimentell induzierte Angstzustände aufgrund der Reduktion/Erleichterung der Top-down-Aufmerksamkeitskontrolle beeinflusst wird. Ein neuartiges duales Zielaufmerksamkeitsparadigma wurde implementiert, um die

Aufmerksamkeitskontrolle bei unangenehmen Emotionen wie Angst oder Stress auf einer höheren Ebene zu erklären. Zusätzlich wurden irrelevante Distraktoren (z.B. ein roter Gegenstand) in das Studiendesign aufgenommen, um zu untersuchen, ob eine zielgerichtete visuelle Suche nach zwei Zielen durch einen psychisch auffälligen Ablenker beeinflusst wird. In dieser Studie wurde daher anhand einer Stichprobe gesunder Universitätsstudenten untersucht, ob die zielgerichtete Aufmerksamkeitskontrolle über die reizgesteuerte Aufmerksamkeit durch Angst moduliert wird.

Die Analysen auf Gruppenebene ergaben keine Hinweise auf eine Erleichterung oder Beeinträchtigung der zielgerichteten Aufmerksamkeit, die durch experimentell induzierte Angstzustände beeinflusst wurde. Sowohl RT als auch die Genauigkeit weisen auf ähnliche Verhaltensmuster in der neutralen und der Angstsitzung hin. Auf einer Ebene intraindividueller Unterschiede korrelierte jedoch ein erhöhtes Maß an Angst, das zuvor durch einen kurzen aversiven Film induziert wurde, negativ mit der zielgerichteten Fähigkeit zur Doppelzielsuche. Emotionale Schwankungen in negativer Richtung beeinträchtigen die Aufmerksamkeitskontrolle, insbesondere bei der visuellen Suche der Doppelzielaufgabe, indem sie die Verhaltenseffektivität beeinträchtigen. Es wurde ein nichtlinearer Zusammenhang zwischen Aufmerksamkeitskontrolle und Angstzustand festgestellt, da es negative Korrelationen zwischen Angstzustand und Ablenkungsinterferenz in Bezug auf RT und die Genauigkeit gab. Ein aufgabenirrelevanter, aber auffälliger Ablenker (z. B. ein roter Gegenstand) störte somit weniger das Doppelziel bei hochängstlichen Teilnehmern, die eine erhöhte Wachsamkeit und Top-down-Aufmerksamkeit zeigten. Diese Studie zeigt, dass induzierte Angstzustände die Wachsamkeit und Reaktionsbereitschaft erhöhen und gleichzeitig die Interferenz mit Ablenkern verringern können, möglicherweise durch biologische Überlebensmechanismen im Zusammenhang mit bedrohlichen Reizen (Ghassemzadeh et al., 2019; Vuilleumier, 2005).

Darüber hinaus hat diese Arbeit gezeigt, dass der Zusammenhang zwischen zielgerichteter visueller Aufmerksamkeit und Angst möglicherweise raumspezifisch ist. Im Allgemeinen reagierten die Teilnehmer bei der zentralen Präsentation schneller als bei der peripheren Präsentation, und insbesondere Teilnehmer mit höherer Ängstlichkeit zeigten bei der zentralen Präsentation weniger Störungen durch Ablenkungen als bei der peripheren

Präsentation. Größere Ängstlichkeit reduziert die Interferenz durch Ablenker, indem sie die Reaktion in den zentralen Präsentationen beschleunigt und die Fehlerquote in den peripheren Präsentationen verringert. Somit beeinflusst der Angstzustand die Effektivität und Effizienz der Aufmerksamkeit, was zu einer geringeren Ablenkbarkeit bei zentralen (RT) und peripheren (Fehlerraten) Präsentationen führt.

In Kapitel 5.3. wird eine verhaltensbiologische und neurophysiologische Studie vorgestellt, in der die zuvor untersuchten Fragen im Hinblick auf den Zusammenhang zwischen Aufmerksamkeitskontrolle und Angstgefühlen untersucht wurden. Angesichts der widersprüchlichen neueren Literatur, die eine Beeinträchtigung der Aufmerksamkeitsleistung bei Bedrohung (Eysenck et al., 2007; Moser et al., 2012a) oder sogar eine Erleichterung (Kim et al., 2021) aufzeigt, wurde ein empirisches Verhaltensexperiment durchgeführt, um diese Lücke zu schließen. Die Emotion Angst kann die kognitive Leistungsfähigkeit auf verschiedene Weise beeinträchtigen. Frühere Forschungsarbeiten haben gezeigt, dass ängstliche Personen ihre Aufmerksamkeit leicht auf ein bedrohliches Objekt richten (Moser et al. 2012), wohingegen die ACT zeigte, dass die Ausrichtung auf bedrohliche Stimuli aufgrund einer Verringerung der zielgerichteten Aufmerksamkeitskontrolle (Eysenck & Derakshan, 2011) erfolgt und gleichzeitig mit einer Zunahme der Ablenkbarkeit durch umgebende Objekte (z.B. stimulusgesteuerte Aufmerksamkeit) verbunden ist (Eysenck et al. 2007; Moser et al. 2012). Die ACT geht davon aus, dass erhöhte Angst bei Individuen zu einer verminderten Aufmerksamkeitskontrolle führt (Eysenck & Derakshan, 2011). Demnach würde sich Angst auf das Aufmerksamkeitssystem eines Menschen auswirken, indem sie die Bottom-up-Aufmerksamkeit fördert, die zu einer verstärkten Interferenz mit Ablenkern führt, während die Top-down-Aufmerksamkeit und die zielgerichtete Aufmerksamkeitsauswahl reduziert werden. Einige theoretische Ansätze, wie z. B. die Attentional Control Theory (ACT), gehen davon aus, dass eine Verringerung der Aufmerksamkeitsleistung (z. B. eine langsamere RT) auf eine Abnahme der zielgerichteten Aufmerksamkeitskontrolle zurückzuführen ist (Eysenck & Derakshan, 2011) und parallel dazu eine höhere Anfälligkeit für die Störung durch den Distraktor besteht (Eysenck et al., 2007; Moser et al., 2012a). Die Ergebnisse sind widersprüchlich, da einige Studien, bei denen Stromschläge als Bedrohung eingesetzt wurden, eine Verbesserung der Aufmerksamkeit bei der

Stroop-Aufgabe festgestellten (Hu et al., 2012), andere Studien jedoch von einer Leistungsminderung berichteten (Choi et al., 2012). Die Ergebnisse liefern deutliche Hinweise darauf, dass Angst die neuropsychologischen Mechanismen moduliert, welche der zielgerichteten Aufmerksamkeit zugrunde liegen. Die Wellenformen ereigniskorrelierter Potenziale zeigten, dass die Ppc-Komponente während der frühen Wahrnehmung beeinflusst wurde, wenn die Beobachter experimentell Angst/Angstgefühlen ausgesetzt waren. Es hat sich herausgestellt, dass intraindividuelle Unterschiede eine wichtige Rolle zwischen Aufmerksamkeit und Emotionen spielen, da die Ergebnisse zeigten, dass Angst negativ mit der Aufmerksamkeitsleistung korreliert, insbesondere mit der Reaktionsgenauigkeit.

Curriculum Vitae

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BAYHOST scholarship – Bavarian Academic Center for Central, Eastern and Southeastern Europe

◦ Projects and Programs of the Bavarian Academic Center for Central, Eastern and Southeastern Europe. 01/10/2019 – 01/10/2022

DAAD Research Grant – German Academic Exchange Service (DAAD)

◦ Research Grants for Doctoral Candidates and Young Academics and Scientists (DAAD). 01/08/2014 – 01/08/2015

CEEPUS Grant – CEEPUS (Central European Exchange Programme for University Studies)

◦ CEEPUS Summer School, Department of Cognitive Science and Psychology, New Bulgarian University, Sofia, Bulgaria. 01/06/2017 – 30/06/2017; 01/06/2019 – 30/06/2019

Editorial Board Member

1. Consulting Editor in Musicae Scientiae
2. Review Editor in Emotional Science in Frontiers in Psychology.

Ad hoc reviewer for the following International Journals:

1. Musicæ Scientiæ
2. Mathematical Biosciences and Engineering
3. Psychology
4. British Journal of Psychology
5. Anxiety, Stress & Coping
6. Cognitive Processing
7. Perceptual and Motor Skills
8. Frontiers in Neurology
9. Frontiers in Psychiatry
10. Psychoneuroendocrinology
11. Quarterly Journal of Experimental Psychology
12. Scientific reports
13. Psychology Research and Behavior
14. Clinical Child Psychology and Psychiatry

15. Personality and Individual Differences
16. Biological psychology

List of Publications

1. Stanković, M., Nešić, M., Čičević, S., & Shi, Z. (2021). Association of smartphone use with depression, anxiety, stress, sleep quality, and internet addiction. Empirical evidence from a smartphone application. *Personality and Individual Differences*, *168*, 110342. https://doi.org/10.1016/j.paid.2020.110342
2. Stanković, M. (2020). A conceptual critique of brain lateralization models in emotional face perception: Toward a hemispheric functional-equivalence (HFE) model. *International Journal of Psychophysiology: Official Journal of the International Organization of Psychophysiology*. https://www.sciencedirect.com/science/article/pii/S0167876020302579
3. Stanković, M., & Nešić, M. (2020). Functional brain asymmetry for emotions: psychological stress-induced reversed hemispheric asymmetry in emotional face perception. *Experimental Brain Research. Experimentelle Hirnforschung. Experimentation Cerebrale*, *238*(11), 2641–2651. https://doi.org/10.1007/s00221-020-05920-w
4. Stanković, M., & Nešić, M. (2019). No Evidence of Improved Emotion Perception Through Unilateral Hand Contraction. *Perceptual and Motor Skills*, 31512519888080. https://doi.org/10.1177/0031512519888080
5. Stanković, M., Nešić, M., & Milić, J. (2019). Effects of unpleasant odors on emotion recognition: the right hemisphere and valence-specific hypotheses. *Psihologija*, *00*, 19–19.
6. Stanković, M., Bašić, J., Milošević, V., & Nešić, M. (2019). Oxytocin receptor (OXTR) gene polymorphisms and recognition memory for emotional and neutral faces: A pilot study. *Learning and Motivation*, *67*, 101577. https://doi.org/10.1016/j.lmot.2019.101577
7. Stanković, M., Simonović, N., Bulatović, J., & Stojiljković, J. (2019). The prediction of criminal recidivism in male juvenile delinquents. *Psihologija*. https://www.ceeol.com/

search/article-detail?id=793535

8. Stanković, M., & Nešić, M. (2018). Contralateral Hemisphere Activation by Unilateral Hand Contraction: ReExamining Global and Local Attention. *Perceptual and Motor Skills*, *125*(3), 438–450. https://doi.org/10.1177/0031512518769212
9. Bašić, J., Milošević, V., Stanković, M., Stoimenov, T. J., Cvetković, T., Despotović, M., & Pavlović, D. (2019). The influence of rs53576 and rs2254298 oxytocin receptor gene polymorphisms on plasma oxytocin levels and measures of empathy. *Archives of Biological Sciences*, *71*(1), 159–165. http://www.serbiosoc.org.rs/arch/index.php/abs/article/view/3724
10. Stojiljković, J., & Stanković, M. (2018). Depressive state and social anxiety in adolescents: the role of family interactions. *The American Journal of Family Therapy*. https://www.tandfonline.com/doi/abs/10.1080/01926187.2018.1506269
11. Stanković, M., Nešić, M., Obrenović, J., Stojanović, D., & Milošević, V. (2015). Recognition of facial expressions of emotions in criminal and non-criminal psychopaths: Valence-specific hypothesis. *Personality and Individual Differences*, *82*, 242–247. https://doi.org/10.1016/j.paid.2015.03.002