Neuroscience and Biobehavioral Reviews 80 (2017) 688–702

Contents lists available at ScienceDirect

Neuroscience and Biobehavioral Reviews

journal homepage: www.elsevier.com/locate/neubiorev

Review article

The link between optimism bias and attention bias: A neurocognitive perspective

Laura Kress*, Tatjana Aue

University of Bern, Switzerland

ARTICLE INFO

Keywords:
Optimism bias
Expectancy bias
Attention bias
Memory bias
Positivity
Reward

ABSTRACT

Both optimism bias and reward-related attention bias have crucial implications for well-being and mental health. Yet, the extent to which the two biases interact remains unclear because, to date, they have mostly been discussed in isolation. Examining interactions between the two biases can lead to new directions in neurocognitive research by revealing their underlying cognitive and neurophysiological mechanisms. In the present article, we suggest that optimism bias and reward-related attention bias mutually enforce each other and recruit a common underlying neural network. Key components of this network include specific activations in the anterior and posterior cingulate cortex with connections to the amygdala. We further postulate that biased memory processes influence the interplay of optimism and reward-related attention bias. Studying such causal relations between cognitive biases reveals important information not only about normal functioning and adaptive neural pathways in maintaining mental health, but also about the development and maintenance of psychological diseases, thereby contributing to the effectiveness of treatment.

1. Introduction

Being able to adequately predict future events is crucial in everyday life, especially when planning behavior and making decisions (Damasio, 1994). Humans, however, tend to overestimate the likelihood of future positive events and underestimate the likelihood of future negative events (Sharot et al., 2011; Weinstein, 1980). This phenomenon, named optimism bias, describes a positivity bias in expectancies about the future and has cognitive (forming beliefs about the future, imagining and judging future events, estimating probabilities), motivational (maintaining favorable self-perception, denying threat), and affective origins (mood, hope; Armor and Taylor, 1998). Moreover, it entails a behavioral component (initiating goal-directed behavior, persistent pursuit of goals).

Optimism bias has been studied extensively in recent years because of its implications in everyday life (e.g., goal persistence, positive affect; Armor and Taylor, 1998; Shepperd et al., 2015) and in the clinical domain (e.g., better physical health, lowered depression rates; Garrett et al., 2014; Hevey et al., 2014; Korn et al., 2014). Despite the theoretical and practical significance of optimism bias, its underlying neural and physiological functioning have not yet been completely identified, and its interplay with other cognitive biases, for instance, in attention or memory, remains to be determined.

Of note, taking other cognitive biases into account instead of studying optimism bias in isolation can fill several important gaps in the literature. Such an approach could (a) shed further light on the cognitive mechanisms underlying optimism bias, (b) allow investigation of why optimism bias exists and how it is maintained over time, and (c) help with the understanding of the extent to which the highly beneficial role of optimism bias is rooted in other cognitive biases. Moreover, studying optimism bias (known to play a role in mental health; Garrett et al., 2014; Korn et al., 2014) in relation to other cognitive biases could (d) uncover divergences and commonalities in health and psychopathology (first by comparing interplay among reward-related biases between the two populations; subsequently by also comparing reward-related and negative biases) and contribute to a better understanding of psychopathologies by (e) including potential mediating and moderating factors in models of psychiatric diseases, thereby fostering the understanding of complex disease-specific chains of causality, and (f) revealing how interacting cognitive biases constitute risk factors for psychopathologies and identifying the mechanisms impeding their treatment (Kraemer et al., 2001). Furthermore, taking into account how different cognitive biases that are relevant in psychological disorders interact can (g) enhance prevention of psychopathology, (h) improve the effectiveness of state-of-the-art treatment (Aue and Okon-Singer, 2015; Everaert et al., 2012; Hirsch et al., 2006), and (i) lead to more fine-grained diagnosis of patients. In summary, studying optimism bias in relation to other cognitive biases could not only broaden our

* Corresponding author at: University of Bern, Institute of Psychology, Division of Experimental Psychology and Neuropsychology, Fabrikstr. 8, 3012 Bern, Switzerland.
E-mail address: laura.kress@psy.unibe.ch (L. Kress).

http://dx.doi.org/10.1016/j.neubiorev.2017.07.016
Received 19 October 2016; Received in revised form 31 May 2017; Accepted 31 July 2017
Available online 02 August 2017

knowledge about the bias itself (a–c) but could also advance theoretical models in psychopathology (d–f) and provide help for clinical practice (h–i).

In order to take a first step toward filling these gaps in the literature, the present article aims to (a) set up a framework of neurocognitive processes that might influence or be influenced by biased optimistic expectancies and (b) stimulate future research in the field by outlining specific hypotheses within the framework that are yet to be examined. We concentrate on attentional processes with a specific focus on *reward-related* processes (for the sake of brevity, we use the term "attention bias" instead of "reward-related attention bias" in the remainder of this article). Several ways in which optimism bias and attention bias may interact and the extent to which they rely on shared neural mechanisms are outlined.

We specifically focus on the interplay between optimism bias and (reward-related) attention bias for several reasons: First, it is likely that optimism and attention biases interact to reach a common goal: A motivation to reach a rewarding goal has been suggested to underlie both biases and is associated with shared neural activations (optimism bias: Bateson, 2016; Buehler et al., 1997; Richter et al., 2012; attention bias: Mohanty et al., 2008; Pessoa and Engelmann, 2010; Small et al., 2005). Here, motivation represents the driving force for behavior that is directed to a specific goal (i.e., a desired outcome), whereas reward functions as an incentive that makes this goal desirable. Second, in the empirical literature and theories on psychopathology (Aue and Okon-Singer, 2015), attentional processes have been repeatedly suggested to influence (optimistic) expectancies, which further underscores our claim that both biases should be examined by using an integrative approach. For instance, certain brain activations have been proposed to contribute to optimism bias by biasing attention to positive stimuli (Aue et al., 2012; Sharot, 2011; Sharot et al., 2007). Third, the first evidence that processes present in optimism bias and attention bias are indeed causally associated has been provided (Kress et al., submitted; Peters et al., 2015). Specifically, induced state optimism has been causally related to biased attention away from negative stimuli (Peters et al., 2015), and induced optimistic expectancies have been shown to guide attention toward rewarding and away from punishing stimuli (Kress et al., submitted).

Although the main aim of the current paper is to stimulate research on the interplay of optimism and attention bias, we also discuss the potential role of biased memories in influencing the link between optimism and attention bias. Notably, because attention and memory are highly interactive processes (Chun and Turk-Browne, 2007) and biased memories have been associated with optimistic expectancies (Roy et al., 2005), consideration of memory bias provides additional important information about critical cognitive bias interplay. Therefore, we want not only to emphasize the role of other cognitive biases that may influence the link between optimism and attention bias, but also to motivate researchers to take additional biases into account in future investigations and theoretical models.

It is further important to note that our ideas build on past work from our laboratory on expectancy biases in fear and anxiety and their link to attention biases (Aue and Okon-Singer, 2015). Although the previous and current articles focus on biased expectancies as related to attention processes, the current article adds several new and important aspects:

a. Optimism bias represents a specific form of future expectancies that stands out from other forms in terms of robustness (as shown by selective updating of pessimistic but not optimistic expectancies when people are confronted with disconfirming feedback; see Sharot et al., 2012b, 2011).

b. Because optimism bias is suggested to play an important role in the maintenance of depression (Garret et al., 2014; Korn et al., 2014), in regard to implications for the clinical context, we concentrate on implications for depression in the current article, in contrast to anxiety in the previous article.

c. The current article focuses on reward-related biases in information processing that likely derive from a motivation that is different from negativity biases, which are most often centered around various forms of punishment (including frustrating non-reward), the latter being the focus of the previous article.

d. The current article proposes possible mechanisms of neural communication that link optimism bias and attention bias and therefore could advance future research paths not only in cognitive research but also in neuroscientific research.

After outlining the rationale for the current framework and its specific focus on optimism and attention bias, we next briefly introduce the two phenomena of interest. We emphasize their relevance and underlying neural networks, which constitute the basis on which we have built our framework. Of note, we keep these sections short, as both optimism bias and attention bias have been reviewed earlier (optimism bias: Sharot, 2011; reward-related attention bias: Pool et al., 2016a). In the present article, therefore, our primary focus is on the relation of the two cognitive biases and the neural foundations of the proposed relation. To further refine our model and inspire future research and theorizing in the area, we additionally propose that memory processes influence the interplay of the two biases of main interest.

2. Optimism bias

When trying to define optimism bias, one encounters a major problem: On the one hand, different terms (e.g., wishful thinking, unrealistic optimism, comparative optimism, and overoptimism) have been used to refer to the same psychological phenomenon (or at least highly similar phenomena), while on the other hand, the same terms have been used for slightly different phenomena in past research. Despite being aware that there are fine-grained differences between the different concepts, we pool them together by using the broad term *optimism bias* (as currently there is not enough literature on any of the subconcepts of optimism bias to focus our framework on just one of them). Representing the main character of all concepts mentioned, optimism bias is thus defined as an overestimation of positive future events and an underestimation of negative future events (this definition is used by all studies on optimism bias cited in this article). Moreover, in the present article, optimism bias is exclusively defined as a bias in expectancies directed toward the future (not the present or past), a definition that has been widely accepted in the literature (e.g., Armor and Taylor, 1998; Campbell et al., 2007; Chambers et al., 2003; Jefferson et al., 2016; Sharot, 2011; Shepperd et al., 2013; Weinstein, 1980; for a more detailed discussion on the definition of optimism bias, see Bortolotti and Antrobus, 2015).

Moreover, it is important to note that optimism bias is closely linked to anticipation of reward (Sharot, 2011). In fact, in humans, optimistic expectancies are usually directed toward a rewarding goal (Bateson, 2016), and anticipating reward is the crucial motivating force in optimism bias shown by non-human animals (e.g., Matheson et al., 2008). One major component of reward is "wanting". It describes individuals being motivated to strive for reward through both unconscious incentive salience processes and conscious desires for incentives or cognitive goals (Berridge and Kringelbach, 2008; Pool et al., 2016b). Because it represents the phase of reward expectation, wanting is an important factor in shaping optimism bias. In contrast to wanting (i.e., reward expectation), "liking" (i.e., reward consummation) represents the pleasure component of reward, and "learning" (i.e., reward satiety) refers to associations and representations about rewards (Berridge and Kringelbach, 2011). Both liking and learning might additionally contribute to optimism bias by determining the hedonic value of the expected reward and influencing subsequent predictions about future rewards. The three phases of Berridge and Kringelbach's model can, therefore, be essential to the formation of optimism bias and its maintenance over time.

2.1. Relevance of optimism bias

In everyday life, optimism bias ensures that people engage in a task, a crucial and beneficial aspect when a task is difficult and its outcome self-relevant (Armor and Taylor, 1998; Shepperd et al., 2015). Hence, being optimistic about one´s future can help in obtaining rewards, which in turn justifies that optimism bias exists. In fact, optimism bias might even have derived from evolutionary advantages. More precisely, when a situation is uncertain and risky, optimism has been suggested to help people make better decisions and avoid mistakes, thereby contributing to survival (Bortolotti and Antrobus, 2015). In line with this idea, overly optimistic expectancies are not human specific, but have been reported in animals as well (Brydges et al., 2011; Douglas et al., 2012; Harding et al., 2004; Matheson et al., 2008; Richter et al., 2012).

In humans, optimism bias functions on a continuum, with normal stamping having great benefits and extreme stamping having dramatic negative consequences. For instance, optimism bias is thought to foster physical and mental health (Garrett et al., 2014; Hevey et al., 2014; Korn et al., 2014). Whereas healthy people display optimism bias and update their expectancies of future events selectively into an optimistic (i.e., desirable) direction when feedback suggests modifying them, patients with depression display no bias at all, or even pessimism bias, and update their expectancies in both the optimistic (i.e., desirable) and the pessimistic (i.e., undesirable) direction (note that causality of the association between depression and lowered optimism bias remains to be investigated; Garrett et al., 2014; Korn et al., 2014; Strunk et al., 2006). However, extreme optimism bias can also have dramatic negative consequences and costs emerging from it. Individuals characterized by optimism bias underestimate health risks (Weinstein et al., 2005, 2004) and refrain from showing preventive health behavior (Davidson and Prkachin, 1997; Pligt, 1998), engage in risky activities because they are overly optimistic about future payoffs (e.g., Calderon, 1993; Linnet et al., 2012), and possibly consume substances because they overestimate the positive effects of a drug and underestimate its negative effects (e.g., Dillard et al., 2009; Fromme and D'Amico, 2000; Goldberg and Fischhoff, 2000). In conclusion, therefore, a systematic investigation of normal and pathological types of optimism bias is of great interest for individuals and society. Important insights can be gained by looking into the neurocognitive mechanisms underlying optimism bias.

2.2. Neural correlates of optimism bias

Recent functional magnetic resonance imaging (fMRI) studies investigated the neural mechanisms of optimism bias and found altered activity in the following key areas: (a) the rostral anterior cingulate cortex (rACC), possibly extending into the ventromedial prefrontal cortex (vmPFC); (b) the amygdala; and (c) the inferior frontal gyrus (IFG) (Blair et al., 2013; Sharot et al., 2007; see Fig. 1 for visualization of peak voxel activations reported by studies referred to in this section and see Table 1 for included studies; note that these structures are not specific to optimism bias, but are relevant to many psychological characteristics such as emotion processing in general; Phan et al., 2002; Sabatinelli et al., 2011). Whereas increased activity in the rACC has been related to optimism bias for positive events (increased probability of positive events occurring to oneself compared with others), decreased activity in the dorsomedial prefrontal cortex and the insula has been associated with optimism bias for negative events (decreased probability of negative events occurring to oneself compared with others; Blair et al., 2013).

Along these lines, activity in the rACC and the amygdala has been shown to be highly correlated when participants are forming positive (compared with negative) expectancies about the future (Sharot et al., 2007). The amygdala is central for emotional processing (Ochsner et al., 2012; Phelps, 2006) and assumed to index personal salience (Cunningham and Brosch, 2012; Liberzon et al., 2003). Among other things, the amygdala is critically involved in many different aspects of

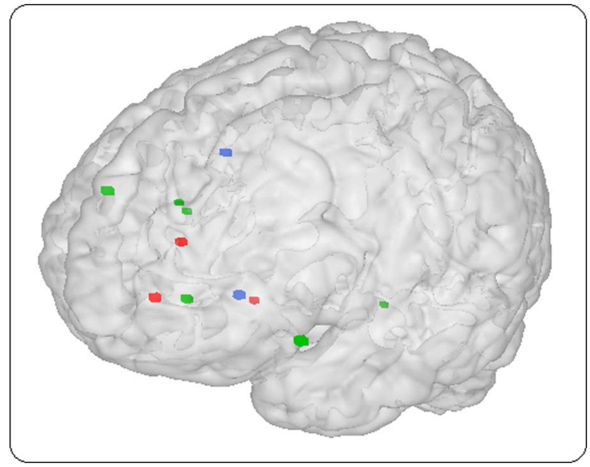

Fig. 1. Peak voxel activations reported in studies on optimism bias. See Table 1 for a list of included studies. *Red* dots represent stronger activations in optimism bias, *blue* dots represent stronger deactivations in optimism bias, and *green* dots represent stronger activations in biased optimistic updating. Only data reported by studies on healthy participants are displayed in the figure. Peak voxel coordinates are depicted as dots (size: 3 mm) on a Montreal Neurological Institute (MNI) brain, as provided in the Mango 4.0 Desktop Application for Windows (Research Imaging Institute, The University of Texas Health Science Center at San Antonio; http://ric.uthscsa.edu/mango/). If peak activations were originally reported in Talairach coordinates, either they were converted to MNI coordinates by using the Yale BioImage Suite Application (http://sprout022.sprout.yale.edu/mni2tal/mni2tal.html), or original MNI coordinates were requested from the study authors. Video 1 displays an animated version of this figure with the brain rotating 360°.

emotions (e.g., development of fear, emotional appraisal and recognition, perception and memory of affective stimuli, reward learning and appetitive behavior; LeDoux, 2003; Wassum and Izquierdo, 2015) and may also be involved in forming emotional expectancies. Sharot et al. (2007) suggest that the rACC regulates emotional and motivational signals generated by (and stored in) the amygdala.

Although the rACC and the amygdala are considered fundamental, optimism bias may rely on characteristic activations and deactivations in additional areas. As described in Section 2.1, healthy people show an updating asymmetry in an optimistic direction (only updating future expectancies in a desirable but not an undesirable direction when presented with disconfirming evidence; Sharot et al., 2011). Brain activity in the left IFG, left and right medial frontal cortex, right cerebellum, and vmPFC was positively correlated with desirable updating of expectancies (Kuzmanovic et al., 2016; Sharot et al., 2011). Additionally, activity in the vmPFC and right IFG correlated negatively with undesirable updating of expectancies, thus further supporting the idea that undesirable information is not integrated when the right IFG is activated (Kuzmanovic et al., 2016; Sharot et al., 2011). In addition, optimism bias can be magnified by administering L-DOPA, thereby increasing dopamine function and impairing updating of undesirable information (Sharot et al., 2012a). Consistent with this picture, the right IFG, an area known to have projections from dopaminergic neurons (Fallon and Moore, 1978), has been shown to be involved when patients with depression update their beliefs toward an undesirable direction (Garret et al., 2014).

3. Reward-related attention bias

A reward-related bias is observed not only in expectancies (as described in Section 2 on optimism bias), but also in attention. In line with the outlined relation between optimism bias and reward, recent studies imply that reward-associated (i.e., desirable) stimuli capture visual attention to a greater extent than neutral and sometimes negative stimuli do. This phenomenon has been shown by altered reaction times and biased eye movements when reward-related stimuli capture visual

Table 1
List of studies on optimism bias included in Fig. 1. The table shows the respective brain areas found and the coordinates of peak voxel activation in MNI and Talairach space. Coordinates that were originally reported in the studies are written in italics.

Study	Hemisphere	Brain Area	MNI coordinates			Talairach coordinates			(De) activation	Study content
			X	Y	Z	X	Y	Z		
Blair et al. (2013)	R	rACC	*5*	*32*	*12*				A	Optimism bias
	L	dmPFC	*−6*	*22*	*43*				D	
	L	Insula	*−27*	*26*	*3*				D	
Sharot et al. (2007)	R	Amygdala	21	−7	−21	*20*	*−9*	*−14*	A	Optimism bias
	L	rACC	−11	47	−1	*−11*	*42*	*−1*	A	
Sharot et al. (2011)	L	IFG	−58	22	0	*−58*	*21*	*−1*	A	More desirable updating
	B	mPFC	−10	62	34	*−10*	*62*	*28*	A	
	R	Cerebellum	34	−80	−38	*33*	*−79*	*−28*	A	
	R	IFG	46	12	10	*46*	*12*	*9*	A	Less undesirable updating
	R	IFG	60	10	10	*60*	*10*	*9*	A	
Kuzmanovic et al. (2016)	L	vmPFC	*−6*	*34*	*−6*				A	Favorable self-related updating

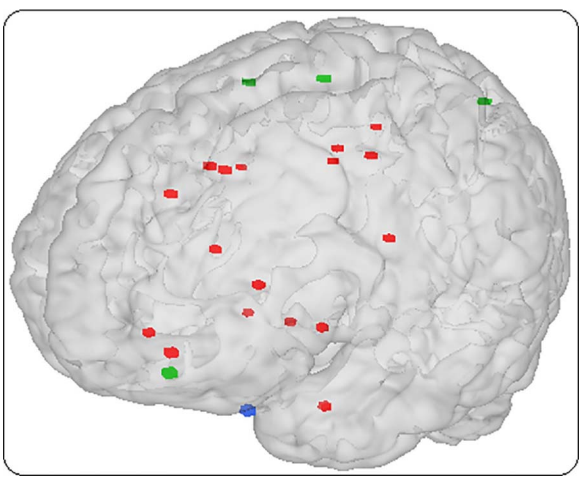

Fig. 2. Peak voxel activations reported in studies on attention bias. See Table 2 for a list of included studies. *Red* dots represent stronger activations in expectancy-related attention capture, *blue* dots represent stronger deactivations in expectancy-related attention capture, and *green* dots represent stronger activations in threat-related attention bias. Only data reported by studies on visual attention are displayed in the figure. Peak voxel coordinates are depicted as dots (size: 3 mm) on an MNI brain, as provided in the Mango 4.0 Desktop Application for Windows (Research Imaging Institute, The University of Texas Health Science Center at San Antonio; http://ric.uthscsa.edu/mango/). Peak activations that were originally reported in Talairach coordinates have been converted to MNI coordinates by using the Yale BioImage Suite Application (http://sprout022.sprout.yale.edu/mni2tal/mni2tal.html). Video 2 displays an animated version of this figure with the brain rotating 360°.

attention during a task (Anderson and Yantis, 2012; Theeuwes and Belopolsky, 2012). Attention capture is most often considered to be an automatic phenomenon, independent of strategic top-down control (Theeuwes and Belopolsky, 2012): Even when participants have a strong top-down goal to look for a specific target, a currently task-irrelevant but salient distractor can capture attention (Balcetis et al., 2012; Godijn and Theeuwes, 2002; Miendlarzewska et al., 2016).

3.1. Relevance of reward-related attention bias

An attention bias to reward-related information enables people to efficiently detect events in an environment in which several stimuli compete for access to limited attentional resources (Pool et al., 2016a). Rewarding stimuli are suggested to have a positive hedonic value and therefore elicit wanting and approach behavior (Berridge and Kringelbach, 2008; Schultz, 2004). If people preferably attend to rewarding stimuli in their environment in everyday life, they are more likely to perceive chances to maximize future gains, which in turn contributes to survival fitness (Schultz, 2004). Having said this, it is correct to assume that attention bias to rewarding stimuli might have derived from an evolutionary benefit. In support of this idea, such biased attention does not seem to be human specific but is also displayed by animals (Paul et al., 2005; similar to optimism bias; see Section 2.1).

In humans, biased attention toward reward-related stimuli plays an important role in the clinical domain. Mirroring research on optimism bias, attention bias toward rewarding stimuli is not shown by depressed or by dysphoric people, nor is it shown by formerly depressed people, in comparison to healthy controls (Duque and Vázquez, 2015; Gotlib et al., 2004; Joorman and Gotlib, 2007; Koster et al., 2005; Murphey et al., 1999). On the other hand, some clinical symptoms are characterized by the existence of positive biases, and these biases do not need to be restricted to the specific diagnosis. For example, patients with addictions are characterized by an attention bias not only for substance-related reward stimuli, but also for non-substance-related reward stimuli (Anderson et al., 2013). Moreover, neural indices of biased attention toward (socially rewarding) happy face pictures have been associated with a risk for psychiatric and behavioral symptoms such as rule breaking and social problems in anxious youth (Bunford et al., 2016). It is thus important to examine the neural underpinnings of normal and dysfunctional attention bias to better understand their respective underlying mechanisms.

3.2. Neural correlates of reward-related attention bias

Recent fMRI studies on the neural mechanisms underlying attention bias to reward-related stimuli have found altered activity in the following key areas: (a) the ACC, (b) the posterior cingulate cortex (PCC), (c) the posterior parietal cortex (PPC), (d) the amygdala, and (e) the orbitofrontal cortex (OFC) (Armony and Dolan, 2002; Hickey et al., 2010; Mohanty et al., 2008; Pool et al., 2016a; Small et al., 2005; see Fig. 2 for visualization of peak voxel activations reported by studies referred to in this section and see Table 2 for a list of included studies). As is the case for optimism bias, the ACC, an area strongly interconnected with dopaminergic structures (Marín et al., 1998), turns out to be a critical structure underlying reward-related visual attention. For instance, the ACC response to reward feedback predicted the magnitude of reward-related attention bias in a visual search paradigm (Hickey et al., 2010). Reward-related mesolimbic dopamine might bias attention toward reward-associated stimuli rather than less beneficial stimuli. This was the case even when people knew that attending to reward-associated features would be counterproductive and result in

Table 2
List of studies on attention bias included in Fig. 2. The table shows the respective brain areas found and the coordinates of peak voxel activation in MNI and Talairach space. Coordinates that were originally reported in the studies are written in italics.

Study	Hemisphere	Brain Area	MNI coordinates			Talairach coordinates			(De) activation	Study content
			X	Y	Z	X	Y	Z		
Armony and Dolan (2002)	L	ACC	−13	−7	67	*−12*	*−2*	*60*	A	Negative attention bias
	R	ACC	4	8	64	*4*	*12*	*58*	A	
	L	Parietal cortex	−33	−54	63	*−32*	*−50*	*58*	A	
	L	OFC	−33	50	−8	*−32*	*46*	*−6*	A	
Small et al. (2005)	R	Inferior parietal lobule	*63*	*−27*	*27*				A	Motivated attention disengagement
	R	PCC	*21*	*−39*	*36*				A	Motivated visual spatial expectancy
	R	ACC	*9*	*30*	*30*				A	
	L	Parahippocampal gyrus	*−24*	*−9*	*−33*				A	
	R	Parahippocampal gyrus	*33*	*−15*	*−21*				A	
	L	OFC	*−18*	*42*	*−9*				A	
Mohanty et al. (2008)	L	PCC	*−9*	*−42*	*15*				A	Expectancy-related attention
	R	PPC	*21*	*−57*	*48*				A	
	R	mOFC	*21*	*30*	*−18*				A	
	L	lOFC	*−45*	*33*	*−18*				D	
Engelmann et al. (2009)	R	PCC	6	−29	43	*6*	*−26*	*40*	A	Expectancy-related attention
	L	PCC	−9	−31	43	*−8*	*−28*	*40*	A	
	R	ACC	4	20	39	*4*	*21*	*36*	A	
	L	ACC	−3	19	39	*−2*	*20*	*36*	A	
	R	Caudate	14	11	10	*13*	*9*	*11*	A	
	L	Caudate	−8	8	4	*−8*	*5*	*7*	A	
	R	Substantia nigra	9	−17	−17	*8*	*−18*	*−10*	A	
	L	Substantia nigra	−9	−17	−13	*−8*	*−18*	*−7*	A	

suboptimal outcomes (Hickey et al., 2010; the process could again be triggered by wanting and is possibly mediated by optimistic expectancies formed in the ACC; see Section 4.4 for further details).

Attention can be influenced by object saliency in a “bottom-up” manner, meaning that salient stimuli attract people's attention automatically as an output of the sensitized dopaminergic system (i.e., in particular concerning initial orienting of attention; Field and Cox, 2008; Franken, 2003). Thus, the primary structures associated with processing of salient stimuli are the amygdala and insula. Whereas the amygdala has been observed to play a key role in the detection and attribution of salience (Liberzon et al., 2003), the insula is suggested to act as a hub structure within a bigger salience network (e.g., comprising the ACC). The purpose is to detect salient events, activate other brain structures needed to access attention and memory resources, and generate appropriate behavioral responses to salient stimuli (Menon and Uddin, 2010).

Moreover, attention can be controlled in a “top-down” manner (e.g., by monetary incentives signaling reward; Small et al., 2005). In this context, two processes of top-down attentional control were examined in a target detection task: visual spatial expectancy (the degree to which a predictive spatial cue benefits performance) and disengagement (the degree to which a misleading spatial cue diminishes performance). Whereas visual spatial expectancy was associated with activity in limbic regions and the PCC, disengagement was associated with activity in the inferior parietal lobule. These processes of the attention network were enhanced through monetary incentives. Findings show that expecting incentives (i.e., optimistic expectancies) can boost neural processing within the attention network in a top-down manner, which can be important in fulfilling the current behavioral goal (Small et al., 2005; Hahn and Gronlund, 2007). In summary, reward-related information seems to be integrated with spatial attention in the parietal and cingulate cortices.

In line with this assumption, stronger functional coupling between the PPC and PCC was present in attention bias toward reward-related targets (i.e., food images when participants were hungry) in a covert spatial attention paradigm (Mohanty et al., 2008). In this study, activity in the OFC, the intraparietal sulcus, and the PCC was correlated with how fast attention shifted toward reward-related targets after participants had seen spatial cues indicating the location at which they should expect the target. Supporting this finding, Engelmann et al. (2009) reported that reward-related incentives modulated attention, which accompanied increased activation in fronto-parietal sites, including the ACC and PCC, as well as nodes of the reward system such as the caudate and substantia nigra.

In conclusion, the PPC and PCC integrate motivational information with visual attention, a process that is essential in everyday life (Mohanty et al., 2008). Moreover, several structures, such as the amygdala, the ACC, and the PCC, have been demonstrated to play a key role in both optimism and attention bias. Along these lines, the studies by Mohanty et al. (2008) and Small et al. (2005) provide good examples of expectancy-attention interactions (e.g., visual spatial expectancy determining the top-down control of attention) and therefore give a good starting point for our interactive cognitive bias framework. We now introduce the theoretical and empirical work that further corroborates our suggestion that reward-related biases in expectancies and attention should be examined by using an integrative approach.

4. Possible interactions between optimism bias and attention bias

After reviewing the literature on optimism and attention bias in isolation, we now begin with the core focus of our article, namely, the link between optimism bias and attention bias. In what follows, we show that ideas derived from theoretical considerations converge with existing empirical data on the interplay between optimism and attention processes. These converging ideas, in concert with widely overlapping neural activations at the basis of optimism and attention bias (see Sections 2, 3, and 4.3), give strong hints that the two phenomena interact, which is the central statement of our framework. To reveal the motivation for our framework, we first draw on theoretical models in favor of a link between optimism and attention bias (Section 4.1). Thereafter, by first describing empirical support for such an association (Section 4.2) and shared neural networks (Section 4.3), we thoroughly outline our framework, which is organized around three core principles: First, optimism bias and attention bias do not work in isolation, but enforce each other in both directions. Second, both optimism bias and attention bias rely on activations in overlapping brain areas (such as the ACC and PCC). Third, both phenomena are characterized by similar underlying motivational processes (i.e., striving for reward possibly initiated by limbic structures), a fact likely related to the observation of shared neural activations of the two biases. In conclusion, we propose three mechanisms of neural communication between optimism bias and attention bias by taking into account the overlapping neural substrates that have been reviewed (Section 4.4).

4.1. Theoretical models on the link between cognitive biases

As currently little empirical work has been done on the relation between optimism bias and reward-related attention bias, we substantially base our framework on theoretical models that are in favor of links between biases displayed in different domains of information processing. First, we explain how established models of psychopathology (Beck et al., 1979; Joorman et al., 2007; Williams et al., 1997), including the combined cognitive biases hypothesis (Hirsch et al., 2006), propose the general need to study cognitive biases in an integrative way. These theoretical approaches, hence, are fully in line with the rationale for our own framework. Second, we elaborate how predictive coding theory (Summerfield et al., 2006a; Zelano et al., 2011) and our interpretation of Broadbent's filter model of attention (1958) can provide further support for a connection between the two specific phenomena of interest in the present framework, namely, biased (optimistic) expectancies and attention. Third, we demonstrate the numerous important implications that an integrative view on cognitive biases will have for future research and clinical practice.

Influential models of psychopathology, such as Beck's cognitive theory of depression (1979), suggest that negativity biases are crucial for the development and maintenance of psychological disorders. Beck's cognitive triad refers to negative views about the self, the world (including aspects of attention), and the future (including expectancies) shown by patients with depression. According to Beck, these negative cognitions contribute to various symptoms of depression, such as apathy, paralysis of the will, and suicidal wishes. More recent models of depression additionally introduce the interactive nature of these cognitive biases. For instance, an interplay of biased attention, memory, and interpretation has been proposed to act at the basis for depression (Joorman et al., 2007; Williams et al., 1997). Together, these models of psychopathology have led to the evolution of the combined cognitive biases hypothesis in clinical research. It holds that negative cognitive biases (e.g., in attention, interpretation, and self-imagery) rarely exist in isolation (Everaert et al., 2012; Hirsch et al., 2006), but rather interact and mutually enforce each other. Recently, this perspective has been extended to additionally include negative expectancy biases (Aue and Okon-Singer, 2015).

Even though these models of psychopathology (Beck et al., 1979; Joorman et al., 2007; Williams et al., 1997) are widely accepted and implemented in psychotherapy, research on the influence of cognitive biases on psychopathological symptoms has mainly examined the different biases separately, thereby neglecting important information about their interactive effects (Everaert et al., 2016). Going beyond such restricted considerations, the combined cognitive bias hypothesis constitutes an important starting point for future integrative investigations on cognitive biases. Among other things, it guides research in the field by proposing possible mechanisms in psychopathology, including specific directions of interaction between diverse biases.

Studying interactive and mutually enforcing cognitive biases in psychopathology can have pivotal implications for clinical research and practice. In clinical research, it can, for instance, reveal how specific interactions among cognitive biases contribute to complex chains of causality that lead to psychopathologies or create conditions that impede successful treatment (e.g., because one bias mediates or moderates the association between another bias and certain psychopathological symptoms). Moreover, in clinical practice, it can lead to more fine-grained diagnoses of patients (e.g., by taking into account how the strength and time course of interacting cognitive biases influence the severity of symptoms) and can improve the effectiveness of contemporary treatment options by simultaneously targeting multiple cognitive mechanisms involved in the development and maintenance of psychological diseases (e.g., during focused cognitive bias modification training; Aue and Okon-Singer, 2015; Everaert et al., 2012; Hirsch et al., 2006). In sum, leading models of psychopathology, in particular the combined cognitive biases hypothesis described above, present strong arguments for the interaction of negative biases displayed in psychological disorders (Everaert et al., 2014, 2013, 2012; Hirsch et al., 2006).

With the current framework, we extend this compelling perspective by suggesting that the same holds true for positive reward-related biases. Attention bias, which makes people preferably attend to reward-related information, can well accompany optimism bias, which makes people overly optimistic about future rewards. More precisely, we postulate that optimism bias increases when people preferably attend to rewarding information in their environment and that reward-related attention bias increases when people have overly optimistic expectancies about their future (for a more detailed outline of these causal links, see Section 4.4). Furthermore, application of the combined cognitive biases hypothesis to reward-related biases implies that additional cognitive biases (e.g., in memory) interact with the proposed link between optimism and attention bias (see Section 5 for further details). Effects of reward-related biases are proposed to mutually reinforce each other, thereby establishing and conserving a positive outlook and mental health in the long run. Therefore, interactions of reward-related biases are especially interesting for life quality (e.g., how mutually enforcing biases maintain well-being during the ups and downs of everyday life) but also for the prevention of psychopathology (e.g., how psychoeducation about causal influences among reward-related biases can prevent negative mutual enforcement and increase positive mutual enforcement before a disease is developed).

Compared with the combined cognitive biases hypothesis and models of psychopathology proposing that different cognitive biases are generally linked, predictive coding theory specifically emphasizes the interplay of expectancy and attention processes. Furthermore, its postulates are not restricted to negative cognitions. Predictive coding theory states that when expecting certain outcomes (of any valence) in the future, humans use prior experience to create a mental template or "search image" and then compare incoming sensory information to this template (e.g., Summerfield et al., 2006a; Zelano et al., 2011). This interplay helps to efficiently process a wealth of sensory information and facilitates the choice of subsequent behavior. It has been suggested that the predictive template created in the brain is updated according to incoming information, implying that the process constantly repeats over time (Rao and Ballard, 1999).

Whether predictive coding theory can transfer to optimism bias and attention bias has yet to be examined empirically and therefore constitutes an interesting aspect that has just recently started to be investigated. It is imaginable that individuals characterized by overly optimistic expectancies create a mental image that directs their attention to confirming reward-related sensory input. In fact, empirical evidence supports such a mechanism (Kress et al., submitted; see Section 4.2 for details). Although such confirming sensory input stabilizes optimism bias over time, disconfirming sensory input that reaches attentional awareness can lead to an update of the mental template (Rao and Ballard, 1999), thereby counteracting optimism bias. Empirical evidence about such processes that are implied by predictive coding theory will guide neurocognitive research in the field of cognitive bias interactions because it directly proposes a direction of influence (influence of expectancies on attention). Studying such causal influences of optimistic expectancies on attention allows, for instance, the investigation of how optimism bias is maintained over time (e.g., because optimistic expectancies guide attention toward confirming rewarding evidence, which, in turn, further strengthens optimism bias; see Kress et al., submitted, for supportive empirical findings).

In contrast to predictive coding theory that implies expectancy influences on attention, Broadbent's filter model of attention (1958) claims that selective attention acts as a sensory filter that prevents the information-processing system from being overloaded. Prioritized selective attention to rewarding (often self-relevant) information then leads to preferable processing of such desirable information (Pessoa, 2005; Pessoa et al., 2002). This again should strengthen optimism bias because future expectancies are generally based on available information (Metcalfe, 1998). Empirical evidence for such influences of attention on optimism bias have outstanding implications. For instance, such evidence can reveal that optimism bias and its benefits, such as the initiation of goal-directed behavior, are rooted in underlying attentional mechanisms and that these benefits therefore cannot necessarily be solely attributed to optimism bias itself.

Broadbent's filter model basically implies the opposite direction of influence (influence of attention on expectancies) to that of predictive coding theory (influence of expectancies on attention). Both theories reveal the importance of examining causal relationships (i.e., directions of influence) between different biases and therefore guide future research in the field away from correlational and toward experimental studies. Only these studies can reveal the mechanisms underlying healthy and pathological functioning, such as specific circumscribed expectancy-attention interactions contributing to well-being or symptoms of psychopathology.

In summary, the three theoretical approaches presented in this section provide strong supportive evidence for a link between optimism and attention bias. Whereas models of psychopathology, particularly the combined cognitive biases hypothesis, suggest that different cognitive biases are generally linked and should be examined by using an integrative approach, predictive coding theory is in line with the idea of causal influences of optimism bias on attention bias, and Broadbent's filter model implies causal influences of attention bias on optimism bias. From an integration of these approaches, we postulate bidirectional influences between both biases (see Section 4.4). After having outlined these theoretical models in favor of our framework, we now continue by briefly reviewing the first empirical findings that further substantiate our claim of a close association between optimism and attention bias.

4.2. *Empirical evidence of optimism-attention associations*

The first core principle of our framework states that optimism bias and attention bias do not work in isolation but enforce each other in both directions. In support of this principle, first empirical findings by Peters et al. (2015) revealed an effect of experimentally induced state optimism (i.e., temporarily increased optimistic expectancies induced through external manipulation; Peters et al., 2015) on attention to faces displaying different emotional expressions. Even though, in general, their optimism manipulation did not influence gaze behavior, the authors observed an effect of state optimism in a post hoc analysis: Those participants who displayed increased state optimism because of the manipulation looked at angry (i.e., socially punishing) faces for a significantly shorter time. Moreover, they looked at joyful (i.e., socially rewarding) faces for a nearly significant longer time. To our knowledge, this is the first study that has examined how visual attention is causally influenced by induced state optimism that likely shares important features with optimism bias (although both phenomena are characterized by optimistic expectancies about the future, these expectancies are not necessarily unrealistic or biased in state optimism), thus supporting our claim regarding the existence of optimism-attention bias interactions.

In line with this study, the first evidence from our own laboratory suggests that induced optimistic and pessimistic expectancies alter attention to rewarding and punishing stimuli, with optimistic expectancies having a stronger effect on attention deployment than pessimistic expectancies (Peters et al., 2015, induced state optimism at the beginning of the experiment; in contrast, we induced optimistic and pessimistic expectancies by verbal cues on a trial-to-trial basis in our study; Kress et al., submitted). Although optimistic expectancies strongly biased attention toward rewarding compared with punishing stimuli in our experiment, pessimistic expectancies had either no effect or a weaker effect on attention deployment to punishing versus rewarding stimuli. An important consideration is that this observation is generally in accordance with our framework's postulate of causal relations between optimism and attention bias. Moreover, this finding in our laboratory delineates important differences between biased reward- and punishment-related processing (e.g., optimism vs. pessimism) and strongly supports the idea that optimism has an outstanding impact on other types of cognitive processing (i.e., optimism exerts stronger influences on cognitive biases than pessimism). Such differences between reward- and punishment-related processing imply that influences among cognitive biases can be valence specific. Further details about how such valence-specific biased cognitive processing contributes to health and psychopathology can have crucial implications for everyday life and clinical practice.

Generally in line with the idea of causal influences of optimistic expectancies on attention (Kress et al., submitted), expectancy cues have been shown to guide visual attention to reward-related stimuli and to modify attention via top-down control outside the area of optimism bias research. In a covered attention shift paradigm, participants reacted faster to spatially cued reward-related targets that were motivationally relevant compared with those that were motivationally irrelevant (i.e., food pictures when participants were hungry vs. full; Mohanty et al., 2008). Other studies showed that attention to socially rewarding stimuli (happy as opposed to angry faces) could be enhanced through top-down modulation (i.e., by specific instructions or cues; Hahn and Gronlund, 2007; Williams et al., 2005). These studies thus give further hints that influences of expectancies on attention deployment exist in the reward-related domain. Even if these findings do not directly refer to optimism bias, they are supportive of our claim of expectancy-attention interactions because they touch upon expectancies about future outcomes. Furthermore, they correspond well with Peters et al. (2015) results concerning the influence of state optimism on attention to happy and angry faces.

One can find further inspiration from the literature on expectancy-attention interactions in the negative domain (Aue et al., 2013b; Aue and Okon-Singer, 2015; Mohanty et al., 2009). For negative affective phenomena, a strong correlation between attention deployment and expectancies has already been revealed (Aue et al., 2013b). Moreover, experimentally manipulated expectancies, induced by prior cues in a visual search task, causally influenced attention to neutral stimuli, but – interestingly – not consistently to negative stimuli (Aue et al., 2016, 2013a; Burra and Kerzel, 2013; Mohanty et al., 2009). Similarities and divergences between positive and negative cognitive bias interactions still need to be revealed, an aspect that should substantially advance theorizing and prevention in clinical psychology, as well as the adaptation of individual treatments.

In summary, behavioral studies reported in this section provide supportive evidence that optimism bias and attention bias are related and that optimism causally influences attention deployment (similar interactions have been proposed in animal research; Mendl et al., 2009). Behavioral studies revealed an association between expectancies and attention not only by using negative affective (Aue et al., 2013b; Mohanty et al., 2009) and neutral stimuli (Aue et al., 2016, 2013a; Burra and Kerzel, 2013), but also by using appetitive and reward-related stimuli in experiments that did not directly address optimism bias (Hahn and Gronlund, 2007; Mohanty et al., 2008; Williams et al., 2005). Most important, state optimism and induced optimistic expectancies – two manipulations representing important aspects of optimism bias – have recently been shown to causally influence subsequent attention deployment (Kress et al., submitted; Peters et al., 2015). Such evidence, which is in line with the idea of a link between optimism and attention bias, has yet to be corroborated by additional empirical data in the behavioral domain. Also of note is that, although we were able to outline supportive empirical evidence for causal influences of optimistic expectancies on attention, no empirical evidence is yet available on causal influences of attention on optimism bias. Thus, future studies should straightforwardly and systematically target this direction of influence.

The continuous adaption and combination of currently dominant experimental paradigms in each area will enable researchers to uncover the central interplay between cognitive biases. Demonstrating causal associations between biases has crucial implications for future cognitive research about both optimism and attention bias. Such a research strategy has, for instance, the potential to reveal fundamental operating principles at the basis of both biases, thereby contributing to our understanding of positively biased cognitions and current theorizing. Moreover, it should reveal important commonalities and divergences in the cognitive mechanisms underlying health and psychopathology. An important aspect of cognitive functioning in health and disease is that much can be learned from knowledge about the neural foundations of associations between cognitive biases. In the next sections, we therefore integrate findings from neuroimaging studies on optimism bias and attention bias (Section 4.3) and propose different ways in which the corresponding neural mechanisms interact (Section 4.4).

4.3. Shared neural networks in optimism bias and attention bias

The second core principle of our framework affirms that both optimism bias and reward-related attention bias rely on activations in overlapping and interacting brain areas. Key areas identified in research on optimism bias (Section 2.2) and attention bias (Section 3.2) do indeed overlap considerably. In line with this principle, recent fMRI studies on optimism bias also propose shared mechanisms and conform to the idea that biases in expectancies are shaped by biases in attention or vice versa (Sharot, 2011; Sharot et al., 2007). For instance, the ACC has been implicated in optimism bias (Blair et al., 2013; Sharot et al., 2011, 2007) and was suggested to guide attention toward rewarding information while people imagine future events (see Hickey et al., 2010, for its implication in reward-related enhancement of selective attention). Moreover, activity in this region has been found to vary as a function of amygdala activity in optimism bias (Sharot et al., 2007), suggesting that the salience of an anticipated outcome shapes the extent of the optimism bias displayed (Bastardi et al., 2011; Weinstein, 1980). Further supporting the idea of a link between optimism and attention bias, object saliency and associated amygdala activity have also been related to attentional capture (Field and Cox, 2002; Franken, 2003).

Besides amygdala and ACC activity, connectivity between occipital areas associated with visual attention and the human reward system (striatum), as well as with the PCC, has been observed to be at the basis of optimism bias (Aue et al., 2012). Again, there are convincing commonalities with findings on attention bias. For example, the PCC has been reported to be critically involved in selective attention (Corbetta and Shulman, 2002). Such an observation is consistent with the idea that the more the PCC is recruited when a specific piece of information is encoded, the more this information's valence will influence the overall impression formed (Schiller et al., 2009). Indeed, the PCC has been proposed to be a hub structure connecting motivation-related processing with top-down control of attention (Mohanty et al., 2008; Small et al., 2005). Thus, we suggest that the striatum and the amygdala, in concert with the PCC, initiate shifts in visual attention that then contribute to how future expectancies are formed (see Section 4.4, first mechanism, for details).

Notably, in accordance with the findings outlined earlier and with our claims, Rolls (2013) proposes that attention and expectancies recruit a common neural network: Mediated by the ACC and the OFC, both "cognition" (including expectancies; original term used by Rolls, 2013) and attention exert top-down influences on the processing of bottom-up sensory inputs. These top-down influences can facilitate activation of selective neuronal assemblies and inhibit other neuronal assemblies in the early information processing stream. Consequently, certain stimulus representations will be enhanced and others suppressed (Desimone and Duncan, 1995). In this way, subsequent processing will be biased. Along these lines, selective attention can be assumed to influence activity in early visual processing areas, possibly mediated by the functional connectivity between fronto-parietal brain regions associated with attentional control and the human reward system (e.g., dorsal striatum; Padmala and Pessoa, 2011; Pessoa and Engelmann, 2010). What remains to be investigated is whether or not this is part of the mechanism by which attentional processes bias expectancies or vice versa.

Direct evidence for the neural mechanisms that we propose to underlie generally beneficial optimism-attention interactions will not just support behavioral findings in the field: Apart from revealing patterns of healthy neural processing, such findings also have the potential to pinpoint vulnerability factors for psychopathology by specifying activations that are responsible for a disruption of the generally healthy neural patterns. Moreover, documentation of neural interactions during the normal interplay of optimism and attention bias will have important implications for pharmacological treatment of psychological disorders in which none of the biases are displayed. For instance, drugs that influence the dopamine system can be used to alter important processes in the brain, thereby enhancing reward-related biases and their interplay (in line with this idea, L-Dopa has already been shown to enhance optimism bias; Sharot et al., 2012a).

Before these ultimate goals are reached, however, causal influences between optimism and attention bias and their neural correlates have yet to be purposefully examined. Because direct neuroscientific evidence about the association between optimistic expectancies and attention in the reward-related domain is to date missing, research on optimism-attention bias interactions might be inspired by research in the negative bias domain. In the negative domain, the association between visual attention and expectancies has indeed been shown to be mediated by activity in key regions such as the OFC, the ACC, and the precuneus (Aue et al., 2013b). Moreover, in a visual search task, in which attention to angry facial expressions was influenced by prior knowledge about the location and type of the target stimulus, spatially informative cues (predicting the location of a subsequent target) activated the fusiform gyrus and parts of the frontoparietal spatial attention network (such as the intraparietal sulcus and the frontal eye field), and emotionally informative cues (predicting angry faces) additionally activated limbic areas, including the amygdala (Mohanty et al., 2009). Notably, the authors propose that expectancy-related emotional information is essential to generate a top-down salience map that guides visual attention. Together, these findings suggest that the spatial attention network, in concert with limbic areas, constitutes the neural substrates at the basis of expectancy-driven emotional spatial attention.

As outlined in greater detail in the next section (Section 4.4, second mechanism), we suggest that optimism bias can modulate attention toward rewarding stimuli in a highly similar way. Positive rewarding and negative threatening stimuli have been shown to recruit partly overlapping neural networks (including the amygdala and the OFC; Li et al., 2008; Murray, 2007; Pool et al., 2016a). Consequently, expectancies about significant positive future events likely recruit at least partly intersecting brain mechanisms and likewise generate a salience map that guides attention toward rewarding stimuli.

In conclusion, the neuroscientific literature on optimism and attention bias provides supportive evidence that both biases are closely related. Brain areas underlying optimism bias and reward-related attention bias overlap considerably. An interplay between the amygdala and the human-reward system with cingulate areas such as the ACC and PCC is proposed in both optimism (Aue et al., 2012; Sharot et al., 2007) and attention bias (Field and Cox, 2002; Franken, 2003; Hickey et al., 2010) and these areas can therefore represent critical underlying structures for bidirectional interactions between both biases. Yet, concrete empirical evidence on the neural mechanisms of *causal* links between optimism and attention bias is still needed. Such evidence will greatly advance knowledge about the neurocognitive mechanisms underlying optimism bias and therefore allows further investigation into why the bias exists and how it is maintained. Moreover, it will advance theories on cognitive bias interactions, such as the combined cognitive biases hypothesis, and will generate new hypotheses about the specific causal relations between optimism and attention bias by revealing the involved brain areas and their functional and structural connectivity (see Aue et al., 2009). Finally, research in the area has the potential to contribute to the identification of significant neural vulnerability factors in psychopathology and to impact on current treatment strategies.

4.4. Possible mechanisms of neural communication linking optimism bias and attention bias

Given that the ideas derived from fundamentally different sources (theoretical models outlined in Section 4.1, empirical studies outlined in Section 4.2, and neuroscientific evidence outlined in Section 4.3) converge, it is more than timely to address the potential interplay between optimism and reward-related attention bias. In what follows, therefore, we outline three mechanisms of possible interaction between these biases. All three mechanisms are based on the idea that anticipated reward (i.e., positive outcomes) functions as an incentive that drives motivation. This hypothesis corresponds to the third core principle of our framework, namely, that both optimism bias and attention bias are characterized by similar underlying motivational processes (i.e., striving for reward, as initiated by limbic structures; see Bateson, 2016; Small et al., 2005). Moreover, this similar underlying motivation is proposed to be reflected in the shared neural activations of the two biases. Through this motivation to strive for reward, specific expectancy and attention systems are (re)directed to maximize reward consumption (for an overview of brain areas involved, see Fig. 3).

Of note, all three proposed mechanisms imply that a minimum of attention is always needed to identify stimuli: In order to ignore or attend to individual pieces of information, it is necessary to know in advance whether they contain positive or negative value. However, we propose that the depth of processing of any given piece of evidence can be substantially modified by varying the *amount* of attention it receives, which influences optimism bias, on the one hand, and is influenced by optimism bias on the other. For instance, attention processes that exert a causal influence on optimism bias can be imagined in various situations. To illustrate, in Las Vegas, winning money can be perceived as a rewarding positive outcome that (re)directs our ongoing attention toward other people who just won money through gambling, consequently making us more optimistic about being the next one to win. Such a view is consistent with the first mechanism within our framework. At this point, it is important to note that the first mechanism (causal influences of attention bias on optimism bias) and the second mechanism (causal influences of optimism bias on attention bias) are not necessarily mutually exclusive; rather, based on the findings displayed in Sections 4.1–4.3, we suggest the existence of bidirectional influences between optimism (expectancies) and attention bias.

First mechanism: causal influence of attention bias on optimism bias. In accordance with Broadbent's filter model of attention (1958), we postulate that selectively attending to reward-related information (and away from negative information) leads to optimism bias, in that selective visual attention determines which part of the environmental information is preferably processed. Wanting (striatum, amygdala) drives ongoing visual attention to rewarding stimuli. This is in line with Berridge and Robinson's (1998) incentive salience theory, in which mesolimbic and neostriatal dopamine functions to increase wanting of specific rewards and thereby shapes the attention-capturing quality and neural representation of reward-related stimuli. We propose that the critical structures to shift attention are the PPC and the PCC, and selective attention then impacts on how early visual input is processed (e.g., reflected in the primary visual cortex; Desimone and Duncan, 1995; Padmala and Pessoa, 2011; the suggested flow of information is depicted in Fig. 3a). By allocating selective attention, desirable evidence is processed preferably (striatum, amygdala), thus creating or strengthening optimism regarding goal achievement (ACC, OFC, and vmPFC).

Coming back to our Las Vegas example, wanting to win a lot of money through gambling directs our ongoing visual attention preferably to smiling faces of people in the environment who just won a game, while mostly ignoring those who lost and look sad, thus making us more optimistic about winning money ourselves, for it seems to happen to so many other people. In contrast to this example of healthy processing, patients with depression do not show biased attention to

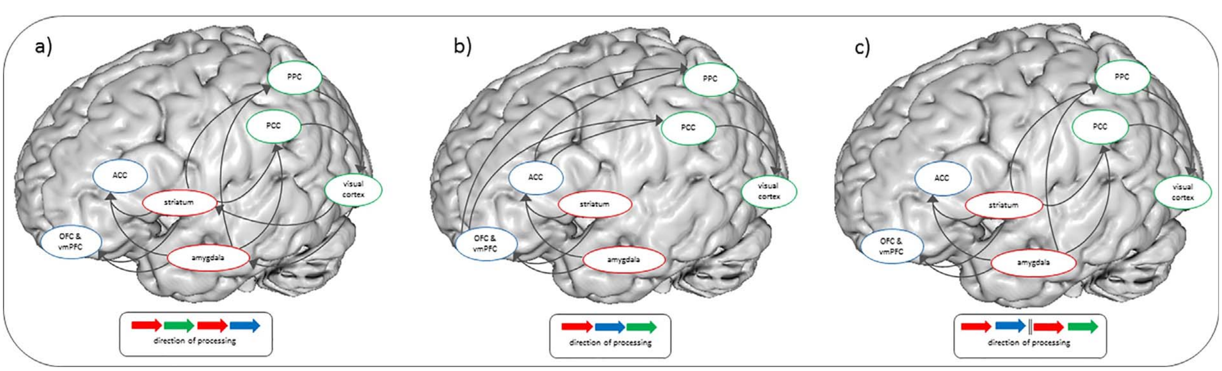

Fig. 3. Brain regions that have been most consistently involved in the processing of optimistic expectancies and positive attention bias. The proposed mechanisms of neural communication linking optimism bias and positive attention bias (see Section 4.4) are illustrated in separate parts of the figure. Note that the depicted arrows show functional, not anatomical, connections. None of the mechanisms have been examined experimentally and are thus hypotheses of what underlying neural communication could look like. Different mechanisms and brain areas may be involved. The brain templates have been created with the sample MNI image, as provided in the Mango 4.0 Desktop Application for Windows (Research Imaging Institute, The University of Texas Health Science Center at San Antonio; http://ric.uthscsa.edu/mango/). Colored arrows display the suggested direction of processing. **a)** First mechanism: *Causal influence of attention bias on optimism bias.* Wanting (striatum, amygdala) is suggested to drive ongoing visual attention to rewarding stimuli. The critical structures to shift attention are the PPC and the PCC, and selective attention then affects how early visual input is processed (reflected in the primary visual cortex). By allocating selective attention, desirable evidence is processed preferably (striatum, amygdala), thus creating or strengthening optimism regarding goal achievement (ACC, OFC, and vmPFC). **b)** Second mechanism: *Causal influence of optimism bias on attention bias*. Wanting (striatum, amygdala) can directly shape optimism bias in order to further increase goal-directed appetitive motivation and task engagement; via top-down mechanisms (ACC, OFC, and vmPFC), optimism bias is then proposed to redirect currently ongoing visual attention (PCC, PPC, and visual cortex) toward supportive environmental evidence (while largely ignoring negative evidence) in order to facilitate pursuing the goal to obtain the reward. **c)** Third mechanism: *No causal influence between optimism bias and attention bias.* Wanting (striatum, amygdala) independently initiates supportive attentive (PPC, PCC, and visual cortex) and expectancy-related processes (ACC, OFC, and vmPFC) with no interaction between the two.

rewarding stimuli (but rather to negative stimuli; Gotlib et al., 2004) and are simultaneously not characterized by an optimism bias (Garrett et al., 2014; Korn et al., 2014; Strunk et al., 2006). In fact, we suggest that biased attention to negative rather than positive stimuli among patients with depression leads to more negative expectancies about the future (in line with mechanisms involved in fear and anxiety described by Aue and Okon-Singer, 2015), thereby maintaining a generally negative view. On a neural level, it is imaginable that connections between the amygdala and striatum associated with wanting, on the one hand, and the PPC and PCC areas important for shifting attention, on the other, are missing or dysfunctional and therefore prevent the formation of an attention bias toward rewarding stimuli in patients with depression. Alternatively (or additionally), one can speculate that an interaction between reward-related biases in attention (PPC, PCC) and expectancies (ACC, OFC, vmPFC) is not established because of dysfunctional activity of the amygdala and the striatum. Such a deviation would also hinder the above proposed "normal" flow of information.

Second mechanism: Causal influence of optimism bias on attention bias. From the considerations outlined in the previous sections, we further suggest that wanting (striatum, amygdala) can directly shape optimism bias in order to further increase goal-directed appetitive motivation and task engagement. In line with postulates derived from predictive coding theory, we hypothesize that optimism bias, via top-down mechanisms (ACC, OFC, and vmPFC), redirects currently ongoing visual attention (PCC, PPC, and visual cortex) toward supportive environmental evidence (while largely ignoring negative evidence) in order to facilitate the pursuit of a goal to obtain a reward (see Fig. 3b). Re-entrant neural processes in that sense have already been shown in the field of perception (Amaral and Price, 1984; Keil et al., 2009) and could apply to the redirection of attention in a highly similar fashion.

In our example, wanting to win money through gambling makes us highly optimistic about winning that money in the next game and having the best hand of cards, which then redirects ongoing attention toward supportive evidence, such as our friend smiling to encourage us. In contrast to this process suggested to be shown by healthy individuals, patients with depression or other psychopathologies do not display optimism bias in the first place (Garrett et al., 2014; Korn et al., 2014), but have negative expectancies about the future (Strunk et al., 2006). These expectancies can then lead to biased attention toward negative as opposed to positive stimuli (Gotlib et al., 2004), thereby generally maintaining negative cognitions. On a neural level, at least two dysfunctional scenarios are imaginable as being responsible for an absence of healthy optimism-attention interactions in psychopathology. On the one hand, malfunctioning connectivity of the amygdala and the striatum with the ACC, OFC, and vmPFC could prevent wanting from shaping optimism bias in the first place. On the other hand, it is conceivable that optimism bias does not exert top-down influences on attention because connections of the ACC, OFC, and vmPFC with the PCC, PPC, and visual cortex are dysfunctional.

Third mechanism: No causal influence between optimism bias and attention bias. Although we consider it improbable, at the moment we cannot rule out that wanting (striatum, amygdala) independently initiates supportive attentive (PPC, PCC, and visual cortex) and expectancy-related processes (ACC, OFC, and vmPFC) with no interaction between the two (Fig. 3c). In our example, this would mean that wanting to win money in Las Vegas would (re)direct attention toward other people winning money and shape expectancies toward optimism about winning independently. However, research on the link between attention and expectancies in threatening and in reward-related situations suggests that both processes are highly correlated in salient situations, with attention causally influencing expectancies or vice versa (e.g., Aue et al., 2013b; Aue and Okon-Singer, 2015; Hahn and Gronlund, 2007; Mohanty et al., 2009; Peters et al., 2015; Williams et al., 2005). Therefore, we generally predict that the attention and expectancy systems are coordinated and mutually reinforce each other. In addition, although there is clear evidence that wanting affects both optimism and attention (Bastardi et al., 2011; Hickey et al., 2010; Weinstein, 1980), there is no reason to suspect that the impact of attention (optimistic expectancies) on optimistic expectancies (attention) is mediated by changes in wanting.

In sum, all three proposed mechanisms are imaginable. An important consideration, as mentioned earlier, is that the first and the second mechanism are not necessarily mutually exclusive. In fact, we anticipate that the first two mechanisms combine. The concrete direction of influence between the biases can be context dependent. In both cases, neural key activations would be expected in areas such as the striatum, amygdala, ACC and PCC, and primary visual cortex. However, from our review of the literature (Sections 2.2 and 3.2), we hypothesize that causal influences of optimistic expectancies additionally recruit more frontal areas, whereas causal attention influences rely on supplementary parietal areas.

Investigating functional and structural connectivity between these areas will yield important insights into the nature of the neural networks that underlie normal and pathological relations between reward-related biases in expectancies and attention. Neuroscientific evidence on such causal relations between attention and optimism bias has further important implications for the treatment of psychopathology and can help intervene in mutually enforcing negative bias patterns displayed by patients with psychological diseases (Aue and Okon-Singer, 2015; Everaert et al., 2016; Hirsch et al., 2006). Information about the direction of influence between attention bias and optimism bias can, for instance, give hints on which biases should be targeted as a priority in psychotherapy (namely, those biases that can automatically alter other clinically relevant biases) and on their specific role in the causation of pathological symptoms. Moreover, knowledge about the specific neural structures involved in optimism-attention bias interplay and their functional connectivity can be decisive for the development of novel psychopharmacological treatments (see Fossati, 2008).

In conclusion, with the present framework, we propose that biased optimistic expectancies causally influence attention deployment, and attention bias causally influences optimism. Through this mutually reenforcing interplay, reward-related biases are preserved in the long term and a positive view of the environment and the future is maintained. This framework can be used to understand previous and future neurocognitive work on optimism and attention bias because it will (a) help to integrate research on single reward-related biases into a bigger picture of interacting cognitive biases resulting from the overarching motivation to pursue reward (i.e., motivation to reach a reward that drives both biases in expectancies and attention); (b) make it easier to interpret pivotal findings in research that focus on only one phenomenon (e.g., updating asymmetry in optimism bias), which often partly represents effects additionally arising from another, simultaneously present, bias (e.g., attention bias; see Kress et al., submitted); (c) shed light on the mechanisms related to the development and maintenance of each bias (e.g., underlying attention processes contributing to biased optimistic expectancies and vice versa); (d) help to uncover divergences and commonalities in health and psychopathology (e.g., by testing how evidence on interacting negative cognitive biases displayed in psychopathology can be replicated in reward-related biases and whether health and psychopathology result from different or similar interactions between cognitive biases); and (e) inspire new, personally adapted, therapeutic interventions (e.g., by taking into account which specific biases are shown by an individual and how their interplay affects particular symptoms of disease).

5. Potential roles of memory in the interplay of optimism bias and attention bias

So far, we have argued that optimism and attention bias are linked. However, according to the combined cognitive biases hypothesis (introduced in Section 4.1), additional information processing biases (i.e., in memory or interpretation) can come into play. In particular, there is evidence that expectancy and memory processes are highly related to each other (Aue and Okon-Singer, 2015) and that many optimistic expectancies we have as humans are based on our prior experiences (Metcalfe, 1998). At the same time, memory and attention processes are highly interactive processes, as evidenced by a large body of behavioral and neuroscientific research (Chun and Turk-Browne, 2007). It is for this reason that we now point out how memory processes have been observed to interact with optimism bias on the one hand and attention bias on the other. We then suggest how memory processes can influence the interplay of optimism and attention bias, one possibility being that memory functions as a mediator in the optimism bias–attention bias associations we put forth earlier. Evidence about such threefold interactions can reveal even more refined mechanisms underlying the benefits of reward-related biases and explain how a positive outlook is ultimately maintained in healthy individuals.

Concerning the relation between optimism and memory bias, it has been suggested that optimism bias is the result of memory-based processing heuristics. If – as proposed – people use all information at hand (e.g., evoked from memory) to build expectancies, optimism bias simply arises because the information at hand is not always correct and complete (Metcalfe, 1998). As a consequence, unreasonably positive memories can lead to biased expectancies in the form of optimism bias. Accordingly, in a meta-analysis on time estimations of future events, Roy et al. (2005) indeed found strong support for a positive association between biased memories and expectancies. Some famous examples of overoptimistic time expectancies have been observed in the time estimations for the construction of various important buildings, such as the Sydney Opera House or the Channel Tunnel between England and France. Specifically, the authors state that people base their predictions of future task duration on their memories of how long past events have taken, but these memories systematically underestimate the true duration. Although these links between memory and optimistic expectancies primarily concern temporal aspects, one also wants to consider the valence aspect. For instance, people who better remember positive events in their life than others do are likely prone to see their future more optimistically. Empirical evidence for such a mechanism will have wide-reaching implications for the treatment of psychopathology, as it implies the need to correct the absence of positive memory biases (e.g., through cognitive restructuring; Liang et al., 2011; Rinck and Becker, 2005; Watkins et al., 1996) to make patients see their future more optimistically.

In a similar vein, it has been suggested that attention processes are strongly related to memory processes (Chun and Turk-Browne, 2007). Numerous investigations have demonstrated that the current focus of attention determines which information is encoded in memory (e.g., Everaert et al., 2014; Fougnie, 2008) and that attention during memory retrieval predicts subsequent memory bias of positive information (Everaert and Koster, 2015). Therefore, preferably attending to positive stimuli in one's environment is likely closely related to the predominance of positive information in memory (see Tran et al., 2011, for similar reflections on the relation between interpretation bias and memory bias).

In addition to these influences of attention on memory, the opposite direction of influence has also been proposed, namely, that past experience reflected in multiple memory systems guides attention (Chun and Turk-Browne, 2007). Evidence for this memory-guided attention allocation has been shown for implicit long-term memory experience (Johnson et al., 2007; Summerfield et al., 2006b). In conclusion, memory and attention interact in both directions: First, memory has a limited capacity and therefore depends on selective attention processes that determine which pieces of information will be encoded. Second, memory about past experiences guides attention in order to secure optimal selection (Chun and Turk-Browne, 2007). Of note, the existence of bidirectional influences between memory and attention has important implications not just for the clinical context, because these influences contribute to the development and maintenance of psychological diseases (Everaert et al., 2014). Such interactions may be equally momentous for healthy processing by ensuring positive mood and well-being.

Even though there is evidence for both optimism-memory and attention-memory interactions, to our knowledge no studies have yet empirically examined the threefold relationship between optimism bias, attention bias, and memory bias. However, one can speculate that a threefold link exists (for similar reflections in the negative domain, see Aue and Okon-Singer, 2015). On the one hand, a positivity bias in memory has been suggested to initiate shifts in attention (e.g., Hutchinson and Turk-Browne, 2012) toward positive stimuli in the environment, which can then lead to biased optimistic expectancies about future events. On the other hand, it is also imaginable that biased memories directly shape optimistic expectancies about the future (Metcalfe, 1998; Roy et al., 2005), which then result in biased attention toward the internal and external environment (Kress et al., submitted; Peters et al., 2015). In applying this to affective disorders, one can assume that if depressed patients do not show a positivity bias in memory (Watkins et al., 1996), they also form less optimistic expectancies about their future. The latter is characteristic for patients with depression (Garrett et al., 2014; Korn et al., 2014) and has been suggested to bias attention less toward rewarding stimuli and more toward negative stimuli in the environment (Beck, 1976; Bradley et al., 1997; Koster et al., 2005; Leyman et al., 2007).

In line with mutual influences among the three biases, it is also conceivable that memory processes mediate the link between expectancies and attention. For instance, the current focus of attention determines which information is encoded in memory (Craik and Rose, 2012; Fougnie, 2008). Biased attention toward reward-related stimuli can, therefore, lead to a positivity bias in memory. Subsequently, expectancies about the future are too optimistic, as future expectancies derive at least partly from biased past experience (Metcalfe, 1998; Roy et al., 2005). Furthermore, memory bias can also mediate how expectancies influence attention. In this scenario, biased expectancies activate corresponding working memory content in the form of an a priori map or a mental template. This template then drives attention toward rewarding stimuli in a top-down manner (Kress et al., submitted; for related ideas in the negative domain and corresponding studies, see Aue et al., 2016, 2013a). Empirical evidence for such mediating mechanisms of memory content regarding the link between attention and optimism can explain further details about multifaceted cognitive bias interactions and contribute to a more nuanced view on how exactly these interactions are related to emotion regulation and mental health.

Further information regarding the determining mechanisms in these bias interactions can be gained from studying the neural correlates of the different biases. Critical brain structures underlying emotional memories usually consist of the amygdala (Morris et al., 1998), the insula (Hamann, 2001), and the septo-hippocampal system (McNaughton and Corr, 2004), as well as prefrontal cortex regions such as the vmPFC (Dolcos et al., 2012; Phelps et al., 2004). The amygdala, the ACC – an area often coactivated with the insula (Menon and Uddin, 2010) – and the prefrontal cortex areas have also been involved in optimism bias (Sharot et al., 2011, 2007) and attention bias (Mohanty et al., 2008; Naghavi and Nyberg, 2005). This points to similar neural networks at the basis of the different cognitive biases and therefore further supports the idea of intimately intertwined processes. Consequently, studying the neurophysiological nature of a link between all three biases is of high interest.

One promising approach for uncovering the neurophysiological nature of multiple bias interactions has been provided by Soto et al. (2008). They suggest that neurons in the prefrontal and more posterior brain regions are active when certain stimuli are held in working memory. Such neural activation has been proposed to drive attention in a top-down manner. According to these authors, "the sustained enhancement of cells tuned to particular features might provide the neural correlate of expectancies that influence subsequent selection, leading to enhanced responding when the item in memory is represented in a search display" (p. 346). This is one possible neural mechanism that explains the threefold link between biased expectancies, memory, and attention. However, Soto et al. (2008) do not explicitly refer to optimism bias, which is why further research is still needed. Together, the theoretical considerations outlined in this section strongly call for an integrated view of overlapping processes related to memory, attention, and expectancies. Revealing the underlying neural mechanisms of optimism-attention-memory interplay can stimulate hypotheses for future neurocognitive research (e.g., regarding functional and structural connectivity among specific brain areas) and has the potential to improve current psychopharmacological treatment options (Fossati, 2008).

6. Concluding remarks and future directions

Optimism bias represents a – usually – highly beneficial cognitive phenomenon that not only is associated with mental and physical health (Hevey et al., 2014; Garrett et al., 2014; Korn et al., 2014) but that also has a high impact on our society. However, in order to identify the mechanisms underlying optimism bias, it is important for other cognitive biases and their neural correlates to be taken into account. Studying different cognitive biases in an integrated approach helps us understand causalities and connections that are still unclear and thereby contributes to a more advanced view of each bias, improves theoretical models, and provides help for clinical practice. One promising approach is to investigate the link between optimism and attention bias. The outlined framework of bidirectional interplay between optimism and attention bias can be used to (a) understand prior and future research, (b) guide future work in the field by emphasizing methodological advice for and specific hypotheses to be tested in future empirical research, and (c) outline a number of open questions that might lead to further refinement of the current framework.

Regarding improved understanding of prior and future research, our theoretical framework implies that isolated studies that examine cognitive biases, especially optimism bias and attention bias, should be evaluated with caution. Attention processes can be present but not detected in studies on optimism and vice versa. For instance, taking attention bias into account can extend, alter, or explain past findings on optimism bias (e.g., updating asymmetry in optimism bias being shown because of biased attention processes; see Kress et al., submitted). Moreover, the current framework calls for caution in interpreting neuroscientific findings on optimism and attention bias in isolation. We have shown that neural correlates of optimism and attention bias widely overlap and can therefore be attributed to either of the two biases or their interplay. This aspect is thus evidently of great importance for the interpretation of existing data in terms of specific study questions.

In order to distinguish biased expectancy and attention processes and to ensure that reliable conclusions can be drawn from studies on interacting cognitive biases, the current framework calls for fundamental methodological changes to guide future research in the field. To date, correlational methods are often used to examine associations between optimism and attention bias. However, additional consideration of causality is imperative in order to identify the cognitive processes underlying optimism bias and should thus be emphasized. Causal relations can be examined by manipulating one of the biases and measuring its effect on the other, just as was done in the study of Peters et al. (2015). Such causal influences should be investigated in both possible directions (i.e., optimism bias on attention bias and attention bias on optimism bias). The first evidence from our laboratory suggests that manipulated optimistic and pessimistic expectancies alter attention to rewarding and punishing stimuli. More important, optimistic expectancies repeatedly had a stronger effect on attention deployment than pessimistic expectancies did, thereby emphasizing the powerful effects of optimism on other types of information processing (Kress et al., submitted). Whether causal influences of attention on optimism bias, as suggested by our framework, exist in a similar manner is yet to be investigated in empirical studies.

By additionally proposing a network of brain areas serving as the underlying neural correlate of cognitive bias interplay, our framework helps generate specific hypotheses to be tested in future empirical research. The suggested network includes the amygdala, which generates emotions, on the one hand, and the fronto-parietal and cingulate cortices, which are involved in emotion regulation and attentional control, on the other. Different mechanisms regarding the relationship between optimism and attention bias are conceivable, but there are most likely bidirectional influences. For instance, wanting can lead visual attention to rewarding stimuli driven by the PPC and PCC and can strengthen optimism regarding goal achievement. We also postulate that wanting can directly shape optimism bias, which then exerts top-down influences (ACC, OFC, and vmPFC) on visual attention and activity in the visual cortex.

Both of these mechanisms of neural communication are driven by goal-directed behavior toward reward (Bateson, 2016; Small et al., 2005), a central underlying motivational factor for optimism and attention bias that we emphasize in our framework. It is for this reason that we have specifically focused on reward-related attention processes. In this regard, the dominant role of neurotransmitters, especially dopamine, in reward processing (Berridge and Robinson, 1998) has to be investigated because this has been shown to have important implications in both optimism and attention bias (Field and Cox, 2008; Franken, 2003; Sharot et al., 2012a) and could reveal crucial information about the neural mechanisms underlying their interplay (e.g., concerning the question of whether administration of L-DOPA enhances not only optimism bias, but also its interplay with attention bias; Sharot et al., 2012a). Moreover, even though we propose a pivotal role for reward as a motivational factor in our framework, future theoretical and empirical investigation should determine whether optimism-attention interplay extends to non-reward-related forms of positive attention bias, such as biased attention to stimuli, which have a positive value but no direct relevance for the observer (e.g., pictures displaying sport scenes; Pool et al., 2016a; see Armstrong and Olatunji, 2012; Peckham et al., 2010, for meta-analyses on this broader view of positive attention bias).

The proposed framework can still be extended in different directions. Therefore, we discuss a number of open questions to be answered by future theoretical and empirical work in the remainder of this section. According to a recent taxonomy by Chun et al. (2011), attention processes can be classified as internal or external (internal attention refers to internal cognitive representations, whereas external attention refers to the external, perceptual world). Within these two areas, one can further distinguish between selection, modulation, and vigilance. Because of limited processing capacity, people need to select which information they attend to from numerous competing stimuli. After a piece of information is selected from these competing options, attention modulation refers to how this selected piece is processed (influencing subsequent behavior and memory). Whereas modulation refers to the current, immediate effects on attention processing, vigilance refers to the ability to sustain attention over time (Chun et al., 2011). Future research on the interplay of optimism and attention bias should take these different processes into account to shed further light on the question of whether particular attention processes are differently influenced by, or can differently influence, optimism bias. It will be an important benefit to the literature if prospective empirical research in the field of interacting cognitive biases distinguishes between the different aspects of attention represented in selection, modulation, and vigilance.

In a similar vein, the proposed framework may need to be adapted to specific forms of optimism bias (e.g., unrealistic optimism, wishful thinking; see Section 2) that, in the present article – because of limited numbers of studies in any area – were pooled together under the broad term *optimism bias.* Findings on the interplay between optimism bias and attention and memory processes could differ if one differentiates between subconcepts of optimism bias instead of working with a possibly multifaceted concept, as we did in the current framework.

Likewise, it will be interesting to further study whether a possible link between attention, expectancy, and memory biases applies equally to optimism and pessimism. It is assumed that, because of its adaptive and beneficial use in human life, optimism bias is a unique cognitive bias (support for this is provided by Kress et al., submitted). Thus, the processes underlying pessimism can indeed be different. However, one problem in examining pessimism is that it is often defined as the opposite of optimism. It can sometimes even be assessed on the same scales as optimism, which then automatically leads to the detection of comparable mechanisms (Mehrabian and Ljunggren, 1997; Scheier et al., 1994). Similarly, to distinguish between optimism and pessimism, future research needs to determine whether valence-specific biases in attention and memory have a differential impact on other cognitive biases (e.g., whether reward-related and punishment-related biases in attention and memory differently influence or are influenced by expectancies).

In addition, as we have emphasized, the role of memory processes in possibly influencing attention and optimism bias, or their association, needs to be examined in greater detail. This is because forming biased expectancies about the future has been suggested to be based on biased memories, which also appear to be related to biased attention (see Section 5 for additionally proposed causal influences between the three biases). Moreover, interpretation bias is another phenomenon that is possibly linked to the cognitive biases mentioned earlier, which calls for the need to extend our framework to include even more cognitive biases. For example, it has been shown that imagery of positive events could lead to a positive interpretation bias (Holmes et al., 2009; Pictet et al., 2011; Torkan et al., 2014) and that interpretation bias modification training affects memory (Tran et al., 2011). However, interpretation biases toward positive information in general and their neural correlates have been examined to a much lesser extent than have memory biases; hence, this is the reason that we focused on optimism, attention, and memory.

Furthermore, when investigating the threefold relationship between optimism, attention, and memory bias, one also has to be aware that on the one hand, different changes in one bias might lead to the same outcome in another bias (equifinality), and on the other, the same change in one bias in different contexts might lead to different outcomes in another bias (multifinality). These concepts of equifinality and multifinality are commonly used in developmental research (Cichetti and Rogosch, 1996) and can well apply to research on multidirectional influences between cognitive biases. For instance, it is conceivable that various forms of reward-related biases in attention (e.g., during selection, modulation, and vigilance; Chun et al., 2011) and memory (e.g., during encoding and retrieval; Everaert et al., 2014; Everaert and Koster, 2015; Fougnie, 2008) can result in optimism bias. At the same time, the same single form of reward-related bias in attention and memory displayed at different moments in time or in different contexts does not necessarily result in a comparable optimism bias. Whether the concept of equifinality and multifinality really applies to cognitive bias interplay and which specific (neural) circumstances might lead to equifinal and multifinal outcomes in the relation between attention, memory, and optimism bias could be the topic of intriguing questions in future neurocognitive research and theoretical considerations.

Finally, differentially salient situations and stimuli have been suggested to correspond with differences in cognitive processing (Corbetta and Shulman, 2002; Menon and Uddin, 2010). Investigations should therefore be made into how a possible link between attention and optimism differs when highly salient stimuli are used compared with low salient stimuli. This is particularly interesting for an application in the clinical context. Stimuli that are relevant for biased expectancies and attention in clinical settings (e.g., cigarettes or drugs) are often highly salient for the person concerned, whereas stimuli frequently used in attention tasks in nonclinical settings (e.g., colored letters or graphical objects) are of comparatively low personal saliency even if they are associated with small monetary incentives. However, how stimulus saliency affects the link between attention and optimism is also relevant in everyday life. For instance, companies should use highly salient stimuli when advertising their products to increase people's attention, hence making potential customers more optimistic about the benefits of their products.

In summary, positivity biases in the past, present, and future – i.e. memories, attention, and expectancies – share specific characteristics. They are important for goal-directed behavior and related to well-being and health. It is therefore reasonable to suggest that these biases are intimately intertwined and interact or mutually influence each other. Notably, because the simultaneous consideration of different biases has very much advanced research, insights, and therapeutic interventions in the negative domain (e.g., regarding anxiety disorders), a combined cognitive biases approach cannot be ignored by researchers when examining optimism bias. Determining exactly how reward-related cognitive biases interact will have a large impact on theoretical considerations as well as on practical applications. For instance, solving the question of whether the relation between these biases has a specific direction or acts bidirectionally will reveal important mechanisms for the prevention of psychopathology. Moreover, a more profound understanding of the interactive nature of cognitive biases and their neural determinants not only will help explain how psychological disorders such as depression, addiction, and mania are developed and maintained, but will also reveal possible mechanisms to be targeted in psychotherapy.

Acknowledgement

This research was supported by the Swiss National Science Foundation grant PP00P1_150492 awarded to T. Aue.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.neubiorev.2017.07.016.

References

Amaral, D.G., Price, J.L., 1984. Amygdalo-cortical projections in the monkey (macaca fascicularis). J. Comp. Neurol. 230, 465–496.
Anderson, B.A., Yantis, S., 2012. Value-driven attentional and oculomotor capture during goal-directed, unconstrained viewing. Attent. Percept. Psychophys. 74 (8), 1644–1653.
Anderson, B.A., Faulkner, M.L., Rilee, J.J., Yantis, S., Marvel, C.L., 2013. Attentional bias for nondrug reward is magnified in addiction. Exp. Clin. Psychopharmacol. 21 (6), 499–506.
Armony, J.L., Dolan, R.J., 2002. Modulation of spatial attention by fear-conditioned stimuli: an event-related fMRI study. Neuropsychologica 40, 817–826.
Armor, Taylor, 1998. Situated optimism: specific outcome expectancies and self-regulation. Adv. Exp. Soc. Psychol. 30, 309–379.
Armstrong, T., Olatunji, B.O., 2012. Eye tracking of attention in the affective disorders: a meta-analytic review and synthesis. Clin. Psychol. Rev. 32 (8), 704–723.
Aue, T., Okon-Singer, H., 2015. Expectancy biases in fear and anxiety and their link to biases in attention. Clin. Psychol. Rev. 42, 83–95.
Aue, T., Lavelle, L.A., Cacioppo, J.T., 2009. Great expectations: what can fMRI research tell us about psychological phenomena? Int. J. Psychophysiol. 73, 10–16.
Aue, T., Nusbaum, H.C., Cacioppo, J.T., 2012. Neural correlates of wishful thinking. Soc. Cogn. Affect. Neurosci. 7 (8), 991–1000.
Aue, T., Guex, R., Chauvigné, L.A.S., Okon-Singer, H., 2013a. Varying expectancies and attention bias in phobic and non-phobic individuals. Front. Hum. Neurosci. 7, 418.
Aue, T., Hoeppli, M.-E., Piguet, C., Sterpenich, V., Vuilleumier, P., 2013b. Visual avoidance in phobia: particularities in neural activity, autonomic responding, and cognitive risk evaluations. Front. Hum. Neurosci. 7, 194.
Aue, T., Chauvigné, L.A.S., Bristle, M., Okon-Singer, H., Guex, R., 2016. Expectancy influences on attention to threat are only weak and transient: behavioral and physiological evidence. Biol. Psychol. 121, 173–186.
Balcetis, E., Dunning, D., Granot, Y., 2012. Subjective value determines initial dominance in binocular rivalry. J. Exp. Soc. Psychol. 48 (1), 122–129.
Bastardi, A., Uhlmann, E.L., Ross, L., 2011. Wishful thinking: belief, desire, and the

motivated evaluation of scientific evidence. Psychol. Sci. 22 (6), 731–732.
Bateson, M., 2016. Optimistic and pessimistic biases: a primer for behavioral ecologists. Curr. Opin. Behav.Sci. 12, 115–121.
Beck, A.T., Rush, A.J., Shaw, B.F., Emery, G., 1979. Cognitive Therapy of Depression. Guilford Press, New York, NY.
Beck, A.T., 1976. Cognitive Therapy and the Emotional Disorders. Basic Books, New York, NY.
Berridge, K.C., Kringelbach, M.L., 2008. Affective neuroscience of pleasure: reward in humans and animals. Psychopharmacology (Berl.) 199, 457–480.
Berridge, K.C., Kringelbach, M.L., 2011. Building a neuroscience of pleasure and well-being. Psychol. Well-Being: Theory Res. Pract. 1 (3), 1–26.
Berridge, K.C., Robinson, T.E., 1998. What is the role of dopamine in reward: hedonic impact, reward learning, or incentive salience? Brain Res. Rev. 28 (3), 309–369.
Blair, K.S., Otero, M., Teng, C., Jacobs, M., Odenheimer, S., Pine, D.S., Blair, R.J.R., 2013. Dissociable roles of ventromedial prefrontal cortex (vmPFC) and rostral anterior cingulate cortex (rACC) in value representation and optimistic bias. Neuroimage 78, 103–110.
Bortolotti, L., Antrobus, M., 2015. Costs and benefits of realism and optimism. Curr. Opin. Psychiatry 28 (2), 194–198.
Bradley, B.P., Mogg, K., Lee, S.C., 1997. Attentional biases for negative information in induced and naturally occurring dysphoria. Behav. Res. Ther. 35 (10), 911–927.
Broadbent, D.E., 1958. Perception and Communication. Pergamon, London, UK.
Brydges, N.M., Leach, M.L., Nicol, K., Wright, R., Bateson, M., 2011. Environmental enrichment induces optimistic cognitive bias in rats. Anim. Behav. 81, 169–175.
Buehler, R., Griffin, D., MacDonald, H., 1997. The role of motivated reasoning in optimistic time predictions. Pers. Soc. Psychol. Bull. 23 (3), 238–247.
Bunford, N., Kujawa, A., Swain, J.E., Fitzgerald, K.D., Monk, C.S., Phan, K.L., 2016. Attenuated neural reactivity to happy faces is associated with rule breaking and social problems in anxious youth. Eur. Child Adolesc. Psychiatry. 26, 215–230.
Burra, N., Kerzel, D., 2013. Attentional capture during visual search is attenuated by target predictability: evidence from the N2pc, Pd, and topographic segmentation. Psychophysiology 50 (5), 422–430.
Calderon, T.G., 1993. Predictive properties of analysts' forecast of corporate earnings. Mid-Atlantic J. Bus. 29, 41–58.
Campbell, J., Greenauer, N., Macaluso, K., End, C., 2007. Unrealistic optimism in internet events. Comput. Hum. Behav. 23 (3), 1273–1284.
Chambers, J.R., Windschitl, P.D., Suls, J., 2003. Egocentrism, event frequency: and comparative optimism: when what happens frequently is 'more likely to happen to me' Pers. Soc. Psychol. Bull. 29, 1343–1356.
Chun, M.M., Turk-Browne, N.B., 2007. Interactions between attention and memory. Curr. Opin. Neurobiol. 17 (2), 177–184.
Chun, M.M., Golomb, J.D., Turk-Browne, N.B., 2011. A taxonomy of external and internal attention. Annu. Rev. Psychol. 62, 73–101.
Cichetti, D., Rogosch, F.A., 1996. Equifinality and multifinality in developmental psychology. Dev. Psychopathol. 8, 597–600.
Corbetta, M., Shulman, G.L., 2002. Control of goal-directed and stimulus-driven attention in the brain. Nat. Rev. Neurosci. 3, 210–215.
Craik, F.I.M., Rose, N.S., 2012. Memory encoding and aging: a neurocognitive perspective. Neurosci. Biobehav. Rev. 36, 1729–1739.
Cunningham, W.A., Brosch, T., 2012. Motivational salience: amygdala tuning from traits, needs, values, and goals. Curr. Direct. Psychol. Sci. 21 (1), 54–59.
Damasio, A.R., 1994. Descarte's Error: Emotion, Reason and the Human Brain. Grosset/Putnam, New York, NY.
Davidson, K., Prkachin, K., 1997. Optimism and unrealistic optimism have and interacting impact on health-promoting behavior and knowledge changes. Pers. Soc. Psychol. Bull. 23 (6), 617–625.
Desimone, R., Duncan, J., 1995. Neural mechanisms of selective visual attention. Annu. Rev. Neurosci. 18, 193–222.
Dillard, A.J., Midboe, A.M., Klein, W.M.P., 2009. The dark side of optimism: unrealistic optimism about problems with alcohol predicts subsequent negative event experiences. Pers. Soc. Psychol. Bull. 35 (11), 1540–1550.
Dolcos, F., Denkova, E., Dolcos, S., 2012. Neural correlates of emotional memories: a review of evidence from brain imaging studies. Psychologia 55 (2), 80–111.
Douglas, C., Bateson, M., Walsh, C., Bédué, A., Edwards, S.A., 2012. Environmental enrichment induces optimistic cognitive biases in pigs. Appl. Anim. Behav. Sci. 139, 65–73.
Duque, A., Vázquez, C., 2015. Double attention bias for positive and negative emotional faces in clinical depression: evidence from an eye-tracking study. J. Behav. Ther. Exp. Psychiatry 46, 107–114.
Engelmann, J.B., Damaraju, E., Padmala, S., Pessoa, L., 2009. Combined effects of attention and motivation on visual task performance: transient and sustained motivational effects. Front. Hum. Neurosci. 3, 4.
Everaert, J., Koster, E.H.W., 2015. Interactions among emotional attention, encoding, and retrieval of ambiguous information: an eye-tracking study. Emotion 15 (5), 539–543.
Everaert, J., Koster, E.H.W., Derakshan, N., 2012. The combined cognitive bias hypothesis in depression. Clin. Psychol. Rev. 32 (5), 413–424.
Everaert, J., Tierens, M., Uzieblo, K., Koster, E.H.W., 2013. The indirect effect of attention bias on memory via interpretation bias: evidence for the combined cognitive bias hypothesis in subclinical depression. Cogn. Emot. 27, 1450–1459.
Everaert, J., Duyck, W., Koster, E.H.W., 2014. Attention, interpretation, and memory biases in subclinical depression: a proof-of-principle test of the combined cognitive biases hypothesis. Emotion 14 (2), 331–340.
Everaert, J., Grahek, I., Duyck, W., Buelens, J., Van den Bergh, N., Koster, E.H.W., 2016. Mapping the interplay among cognitive biases, emotion regulation, and depressive symptoms. Cogn. Emot. 31 (4), 726–735.
Fallon, J.H., Moore, R.Y., 1978. Catecholamine innervation of the basal forebrain. IV. Topography of the dopamine projection to the basal forebrain and neostriatum. J. Comp. Neurol. 180 (3), 545–580.
Field, M., Cox, W.M., 2008. Attentional bias in addictive behaviors: a review of its development, causes, and consequences. Drug Alcohol Depend. 97, 1–20.
Fossati, P., 2008. Neural signatures of cognitive and emotional biases in depression. Dialogues Clin. Neurosci. 10 (3), 358–361.
Fougnie, D., 2008. The relationship between attention and working memory. In: Johansen, N.B. (Ed.), New Research on Short-term Memory. Nova Science Publishers, Inc, Hauppauge, NY.
Franken, I.H.A., 2003. Drug craving and addiction: integrating psychological and neuropsychopharmacological approaches. Prog. Neuro-Psychopharmacol. Biol. Psychiatry 27, 563–579.
Fromme, K., D'Amico, E.J., 2000. Measuring adolescent alcohol outcome expectancies. Psychol. Addict. Behav. 14 (2), 206–212.
Garrett, N., Sharot, T., Faulkner, P., Korn, C.W., Roiser, J.P., Dolan, R.J., 2014. Losing the rose tinted glasses: neural substrates of unbiased belief updating in depression. Front. Hum. Neurosci. 8, 639.
Godijn, R., Theeuwes, J., 2002. Programming of endogenous and exogenous saccades: evidence for a competitive integration model. J. Exp. Psychol. Hum. Percept. Perform. 28 (5), 1039–1054.
Goldberg, J., Fischhoff, B., 2000. The long-term risks in the short-term benefits: perceptions of potentially addictive activities. Health Psychol. 19 (3), 299–303.
Gotlib, I.H., Krasnoperova, E., Yue, D.N., Joormann, J., 2004. Attentional biases for negative interpersonal stimuli in clinical depression. J. Abnorm. Psychol. 113 (1), 121–135.
Hahn, S., Gronlund, S.D., 2007. Top-down guidance in visual search for facial expressions. Psychon. Bull. Rev. 14 (1), 159–165.
Hamann, S., 2001. Cognitive and neural mechanisms of emotional memory. Trends Cogn. Sci. 5 (9), 394–400.
Harding, E.J., Paul, E.S., Mendl, M., 2004. Cognitive bias and affective state. Nature 427, 312.
Hevey, D., McGee, H.M., Horgan, J.H., 2014. Comparative optimism among patients with coronary heart disease (CHD) is associated with fewer adverse clinical events 12 months later. J. Behav. Med. 37 (2), 300–307.
Hickey, C., Chelazzi, L., Theeuwes, J., 2010. Reward changes salience in human vision via the anterior cingulate. J. Neurosci. 30 (33), 11096–11103.
Hirsch, C.R., Clark, D.M., Mathews, A., 2006. Imagery and interpretations in social phobia: support for the combined cognitive biases hypothesis. Behav. Ther. 37 (3), 223–236.
Holmes, E.A., Lang, T.J., Shah, D.M., 2009. Developing interpretation bias modification as a cognitive vaccine for depressed mood: imagining positive events makes you feel better than thinking about them verbally. J. Abnorm. Psychol. 118 (1), 76–88.
Hutchinson, J.B., Turk-Browne, N.B., 2012. Memory-guided attention: control from multiple memory systems. Trends Cogn. Sci. 16 (12), 576–579.
Jefferson, A., Bortolotti, L., Kuzmanovic, B., 2016. What is unrealistic optimism? Conscious. Cogn. 50, 3–11.
Johnson, J.S., Woodman, G.F., Braun, E., Luck, S.J., 2007. Implicit memory influences the allocation of attention in visual cortex. Psychon. Bull. Rev. 14 (5), 834–839.
Joorman, J., Gotlib, I.H., 2007. Selective attention to emotional faces following recovery from depression. J. Abnorm. Psychol. 116 (1), 80–85.
Joorman, J., Yoon, K.L., Zetsche, U., 2007. Cognitive inhibition in depression. Appl. Prev. Psychol. 12 (3), 128–139.
Keil, A., Sabatinelli, D., Ding, M., Lang, P.J., Ihssen, N., Heim, S., 2009. Re-entrant projections modulate visual cortex in affective perception: evidence from granger causality analysis. Hum. Brain Mapp. 30 (2), 532–540.
Korn, C.W., Sharot, T., Walter, H., Heekeren, H.R., Dolan, R.J., 2014. Depression is related to an absence of optimistically biased belief updating about future life events. Psychol. Med. 44 (3), 579–592.
Koster, E.H., de Raedt, R., Goeleven, E., Franck, E., Crombez, G., 2005. Mood-congruent attentional bias in dysphoria: maintained attention to and impaired disengagement from negative information. Emotion 5 (4), 446–455.
Kraemer, H.C., Stice, E., Kazdin, A., Offord, D., Kupfer, D., 2001. How do risk factors work together? Mediators, moderators, and independent, overlapping, and proxy risk factors. Am. J. Psychiatry 158, 848–856.
Kress, L., Bristle, M., & Aue, T. (submitted). Seeing through rose-colored glasses: How optimistic expectancies guide visual attention.
Kuzmanovic, B., Jefferson, A., Vogeley, K., 2016. The role of the neural reward circuitry in self-referantial optimistic belief updates. Neuroimage 133, 151–162.
LeDoux, J., 2003. The emotional brain, fear: and the amygdala. Cell. Mol. Neurobiol. 23, 727–738.
Leyman, L., Raedt, R., de Schacht, R., Koster, E.H.W., 2007. Attentional biases for angry faces in unipolar depression. Psychol. Med. 37 (3), 393–402.
Li, W., Howard, J.D., Parrish, T.B., Gottfried, J.A., 2008. Aversive learning enhances perceptual and cortical discrimination of indiscriminable odor cues. Science 319, 1842–1845.
Liang, C., Hsu, W., Hung, F., Wang, W., Lin, C., 2011. Absence of a positive bias in social anxiety: the application of a directed forgetting paradigm. J. Behav. Ther. Exp. Psychiatry 42 (2), 204–210.
Liberzon, I., Phan, K.L., Decker, L.R., Taylor, S.F., 2003. Extended amygdala and emotional salience: a PET activation study of positive and negative affect. Neuropsychopharmacology 28 (4), 726–733.
Linnet, J., Frøslev, M., Ramsgaard, S., Gebauer, L., Mouridsen, K., Wohlert, V., 2012. Impaired probability estimation and decision-making in pathological gambling poker players. J. Gambl. Stud. 28 (1), 113–122.
Marín, O., Smeets, W., Gonzáles, A., 1998. Evolution of the basal ganglia in tetrapods: a new perspective based on recent studies in amphibians. Trends Cogn. Sci. 21,

487–494.
Matheson, S.M., Asher, L., Bateson, M., 2008. Larger, enriched cages are associated with 'optimistic' response biases in captive European starlings (Sturnus vulgaris). Appl. Anim. Behav. Sci. 109, 374–383.
McNaughton, N., Corr, P.J., 2004. A two-dimensional neuropsychology of defense: fear/anxiety and defensive distance. Neurosci. Biobehav. Rev. 28 (3), 285–305.
Mehrabian, A., Ljunggren, E., 1997. Dimensionality and content of optimism-pessimism analyzed in terms of the pad temperament model. Personal. Indiv. Diff. 23, 729–737.
Mendl, M., Burman, O.H.P., Parker, R.M.A., Paul, E.S., 2009. Cognitive bias as an indicator of animal emotion and welfare: emerging evidence and underlying mechanisms. Appl. Anim. Behav. Sci. 118, 161–181.
Menon, V., Uddin, L.Q., 2010. Saliency, switching, attention and control: a network model of insula function. Brain Struct. Funct. 214 (5–6), 655–667.
Metcalfe, J., 1998. Cognitive optimism: self-deception or memory-based processing heuristics? Pers. Soc. Psychol. Rev. 2 (2), 100–110.
Miendlarzewska, E.A., Bavalier, D., Schwartz, S., 2016. Influence of reward motivation on human declarative memory. Neurosci. Biobehav. Rev. 61, 156–176.
Mohanty, A., Gitelman, D.R., Small, D.M., Mesulam, M.M., 2008. The spatial attention network interacts with limbic and monoaminergic systems to modulate motivation-induced attention shifts. Cereb. Cortex 18 (11), 2604–2613.
Mohanty, A., Egner, T., Monti, J.M., Mesulam, M.M., 2009. Search for threatening target triggers limbic guidance of spatial attention. J. Neurosci. 29, 10563–10572.
Morris, J.S., Ohman, A., Dolan, R.J., 1998. Conscious and unconscious emotional learning in the human amygdala. Nature 393 (6684), 467–470.
Murphey, F.H., Sahakian, B.J., Rubinsztein, J.S., Micheal, A., Rogers, R.D., Robbins, T.W., Paykel, E.S., 1999. Emotional bias and inhibitory control processes in mania and depression. Psychol. Med. 29, 1307–1321.
Murray, E.A., 2007. The amygdala: reward and emotion. Trends Cogn. Sci. 11, 489–497.
Naghavi, H.R., Nyberg, L., 2005. Common fronto-parietal activity in attention, memory, and consciousness: shared demands on integration? Conscious. Cogn. 14 (2), 390–425.
Ochsner, K.N., Silvers, J.A., Buhle, J.T., 2012. Functional imaging studies of emotion regulation: a synthetic review and evolving model of the cognitive control of emotion. Ann. N. Y. Acad. Sci. 1251, E1–24.
Padmala, S., Pessoa, L., 2011. Reward reduces conflict by enhancing attentional control and biasing visual cortical processing. J. Cogn. Neurosci. 23 (11), 3419–3432.
Paul, E.S., Harding, E.J., Mendl, M., 2005. Measuring emotional processes in animals: the utility of a cognitive approach. Neurosci. Biobehav. Rev. 29, 469–491.
Peckham, A.D., McHugh, R.K., Otto, M.W., 2010. A meta-analysis of the magnitude of biases attention in depression. Depress. Anxiety 27, 1135–1142.
Pessoa, L., Engelmann, J.B., 2010. Embedding reward signals into perception and cognition. Front. Neurosci. 4.
Pessoa, L., McKenna, M., Gutierrez, E., Ungerleider, L.G., 2002. Neural processing of emotional faces requires attention. PNAS 99 (17), 11458–11463.
Pessoa, L., 2005. To what extent are emotional visual stimuli processed without attention and awareness? Curr. Opin. Neurobiol. 15 (2), 188–196.
Peters, M.L., Vieler, J.S., Lautenbacher, S., 2015. Dispositional and induced optimism lead to attentional preference for faces displaying positive emotions: an eye-tracker study. J. Positive Psychol. 1–12.
Phan, K.L., Wager, T., Taylor, S.F., Liberzon, I., 2002. Functional neuroanatomy of emotion: a meta-analysis of emotion activation studies in PET and fMRI. Neuroimage 16, 331–348.
Phelps, E.A., Delgado Nearing, K.I., LeDoux, J.E., 2004. Extinction learning in humans: role of the amygdala and vmPFC. Neuron 43 (6), 897–905.
Phelps, E.A., 2006. Emotion and cognition: insights from studies of the human amygdala. Annu. Rev. Psychol. 57, 27–53.
Pictet, A., Coughtrey, A.E., Mathews, A., Holmes, E.A., 2011. Fishing for happiness: the effects of generating positive imagery on mood and behaviour. Behav. Res. Ther. 49 (12), 885–891.
Pligt, J., 1998. Perceived risk and vulnerability as predictors of precautionary behaviour. Br. J. Health Psychol. 3 (1), 1–14.
Pool, E., Brosch, T., Delplanque, S., Sander, D., 2016a. Attentional bias for positive emotional stimuli: a meta-analytic investigation. Psychol. Bull. 142 (1), 79–106.
Pool, E., Sennwald, V., Delplanque, S., Brosch, T., 2016b. Measuring wanting and liking from animals to humans: a systematic review. Neurosci. Biobehav. Rev. 63, 124–142.
Rao, R.P.N., Ballard, D.H., 1999. Predictive coding in the visual cortex: a functional interpretation of some extra-classical receptive-field effects. Nat. Neurosci. 2 (1), 79–87.
Richter, S.H., Schick, A., Hoyer, C., Lankisch, K., Gass, P., Vollmayr, B., 2012. A glass full of optimism: enrichment effects on cognitive bias in a rat model of depression. Cogn. Affect. Behav. Neurosci. 12, 527–542.
Rinck, M., Becker, E.S., 2005. A comparison of attentional biases and memory biases in women with social phobia and major depression. J. Abnorm. Psychol. 114 (1), 62–74.
Rolls, 2013. A biased activation theory of the cognitive control and attentional modulation of emotion. Front. Hum. Neurosci. 7, 1–15.
Roy, M.M., Christenfeld, N.J.S., McKenzie, C.R.M., 2005. Underestimating the duration of future events: memory incorrectly used or memory bias? Psychol. Bull. 131 (5), 738–756.
Sabatinelli, D., Fortune, E.E., Li, Q., Siddiqui, A., Krafft, C., Oliver, W.T., Beck, S., Jeffries, J., 2011. Emotional perception: meta-analyses of face and natural scene processing. Neuroimage 54 (3), 2524–2533.
Scheier, M.F., Carver, C.S., Bridges, M.W., 1994. Distinguishing optimism from neuroticism (and trait anxiety, self-mastery, and self-esteem): a reevaluation of the Life Orientation Test. J. Pers. Soc. Psychol. 67 (6), 1063–1078.
Schiller, D., Freeman, J.B., Mitchell, J.P., Uleman, J.S., Phelps, E.A., 2009. A neural mechanism of first impressions. Nat. Neurosci. 12 (4), 508–514.
Schultz, W., 2004. Neural coding of basic reward terms of animal learning theory, game theory: microeconomics and behavioral ecology. Curr. Opin. Neurobiol. 14, 139–147.
Sharot, T., Riccardi, A.M., Raio, C.M., Phelps, E.A., 2007. Neural mechanisms mediating optimism bias. Nature 450 (7166), 102–105.
Sharot, T., Korn, C.W., Dolan, R.J., 2011. How unrealistic optimism is maintained in the face of reality. Nat. Neurosci. 14 (11), 1475–1479.
Sharot, T., Guitart-Masip, M., Korn, C.W., Chowdhury, R., Dolan, R.J., 2012a. How dopamine enhances an optimism bias in humans. Curr. Biol. 22 (16), 1477–1481.
Sharot, T., Kanai, R., Marston, D., Korn, C.W., Rees, G., Dolan, R.J., 2012b. Selectively altering belief formation in the human brain. Proc. Natl. Acad. Sci. U. S. A. 109 (42), 17058–17062.
Sharot, T., 2011. The optimism bias. Curr. Biol. 21 (23), R941–5.
Shepperd, J.A., Waters, E., Weinstein, N.D., Klein, W.M.P., 2015. A primer on unrealistic optimism. Curr. Direct. Psychol. Sci. 24 (3), 232–237.
Small, D.M., Gitelman, D., Simmons, K., Bloise, S.M., Parrish, T., Mesulam, M.-M., 2005. Monetary incentives enhance processing in brain regions mediating top-down control of attention. Cereb. Cortex 15 (12), 1855–1865.
Soto, D., Hodsoll, J., Rotshtein, P., Humphreys, G.W., 2008. Automatic guidance of attention from working memory? Trends Cogn. Sci. 12 (9), 342–348.
Strunk, D.R., Lopez, H., DeRubeis, R.J., 2006. Depressive symptoms are associated with unrealistic negative predictions of future life events. Behav. Res. Ther. 44 (6), 861–882.
Summerfield, C., Egner, T., Greene, M., Koechlin, E., Mangels, J., Hirsch, J., 2006a. Predictive codes for forthcoming perception in the frontal cortex. Science 314, 1311–1314.
Summerfield, J.J., Lepsien, J., Gitelman, D.R., Mesulam, M.M., Nobre, A.C., 2006b. Orienting attention based on long-term memory experience. Neuron 49, 905–916.
Theeuwes, J., Belopolsky, A.V., 2012. Reward grabs the eye: oculomotor capture by rewarding stimuli. Vis. Res. 74, 80–85.
Torkan, H., Blackwell, S.E., Holmes, E.A., Kalantari, M., Neshat-Doost, H.T., Maroufi, M., Talebi, H., 2014. Positive imagery cognitive bias modification in treatment-Seeking patients with major depression in Iran: a pilot study. Cogn. Ther. Res. 38, 132–145.
Tran, T.B., Hertel, P.T., Joormann, J., 2011. Cognitive bias modification: induced interpretive biases affect memory. Emotion 11 (1), 145–152.
Wassum, K.M., Izquierdo, A., 2015. The basolateral amygdala in reward learning and addiction. Neurosci. Biobehav. Rev. 57, 271–283.
Watkins, P.C., Vache, K., Verney, S.P., Mathews, A., 1996. Unconscious mood-congruent memory bias in depression. J. Abnorm. Psychol. 105 (1), 34–41.
Weinstein, N., Slovic, P., Gibson, G., 2004. Accuracy and optimism in smokers' beliefs about quitting. Nicot. Tob. Res. 6 (6), 375–380.
Weinstein, N.D., Marcus, S.E., Moser, R.P., 2005. Smokers' unrealistic optimism about their risk. Tob. Control 14 (1), 55–59.
Weinstein, N.D., 1980. Unrealistic optimism about future life events. J. Pers. Soc. Psychol. 39 (5), 806–820.
Williams, J.M.G., Watts, F.N., MacLeod, C.M., Mathews, A., 1997. Cognitive Psychology and Emotional Disorders. John Wiley and Sons, New York, NY.
Williams, M., Moss, S., Bradshaw, J., Mattingley, J., 2005. Look at me, I'm smiling: visual search for threatening and nonthreatening facial expressions. Vis. Cogn. 12 (1), 29–50.
Zelano, C., Mohanty, A., Gottfried, J.A., 2011. Olfactory predictive codes and stimulus templates in piriform cortex. Neuron 72, 178–187.