**Abstract**

Selective attention is thought to prioritize object features related to high rewards by increasing their saliency and decreasing the saliency of other features. This mechanism is proposed to be linked to the activity of the visual cortex. Electrophysiological studies have provided support for this account, but have focused on transient attention and neural activity when either high- or low-rewarded feature is present. In this study, we investigated the influence of reward presence and probability on the allocation of sustained feature-based attention using steady-state visual evoked potentials (SSVEPs). SSVEPs represent oscillatory responses of the visual cortex and allow for tracking of simultaneous allocation of attention toward multiple features. We recorded EEG in 40 participants while they completed the Random Dot Kinematogram task. Dots of two colors were tagged with different frequencies. On each trial, participants were instructed to attend one of the colors and detect coherent movements. After the first block (baseline), participants were informed that they could earn rewards (acquisition), and that the two colors were paired with high or low probability of earning a reward. In the third block (extinction) participants could not earn any rewards. Participants were faster and more accurate in the training and test blocks compared to baseline. No effect of reward probability on behavior was found. SSVEP amplitudes were increased for attended compared to unattended color. The amplitudes were decreased in training compared to baseline and test blocks. While the amplitude of the high-reward color remained the same across the blocks, the amplitude of the low-reward color was reduced in the training block. These results provide first evidence that SSVEPs can be used to detect the influence of rewards on feature-based sustained attention. Also, they provide an insight into the dynamics and trade-offs related to processing of features linked to different reward probabilities.

Keywords: attention; EEG; feature-based attention; reward; motivation; steady-state visually evoked potentials; frequency tagging

# Introduction

We are limited in the amount of information that we can process. Selective attention is crucial in choosing which stimuli will be processed (Chun, Golomb, & Turk-Browne, 2011; Desimone & Duncan, 1995). Long standing theories of attention postulate that stimuli are selected based on our current goals (top-down) or based on their physical salience (bottom-up) (Corbetta & Shulman, 2002; Posner, 1980; Theeuwes, 2010). Research on the influence of rewards on visual selective attention has provided a potential third mechanism that doesn’t fit in either of the two categories.

The most widely used experimental approach used to demonstrate that reward history can counteract goal-directed attention is the training-test design (for reviews see: Anderson, 2016; Chelazzi, Perlato, Santandrea, & Della Libera, 2013; Failing & Theeuwes, 2017). During training (reward phase) participants are doing an attention task in which different features (e.g. colors or shapes) are paired with different reward magnitudes or frequencies. For example, correct detection of a red stimulus in a visual search array is always followed by receipt of a high monetary reward, while other colors are paired with low or no reward. In the following test phase (extinction phase) participants are informed that they cannot earn any more rewards. Using this design it was demonstrated that objects paired with high rewards are easier to select as targets and harder to ignore as distractors, while the opposite is true for objects related to low rewards (Della Libera & Chelazzi, 2009). In a series of studies using a visual search task, it was demonstrated that distractors related to high rewards are harder to ignore even when no more rewards can be earned and participants are instructed to ignore the color information (Anderson, Laurent, & Yantis, 2011). This effect, termed the value-driven attentional bias, was present if the training and test phase are separated by several weeks (Anderson & Yantis, 2013). Similar results were found in a visual search task even when the distractor stimuli related to rewards were always task-irrelevant (Pearson, Donkin, Tran, Most, & Le Pelley, 2015) and using the spatial cueing task (Failing & Theeuwes, 2014).

Neuroimaging studies have mainly focused on the effects of rewards on attention during the training phase. In an fMRI experiment it was demonstrated that the representation of objects (cars, trees, or people in naturalistic images) object-selective visual cortex paired with high rewards was enhanced, while the representation of objects paired with low rewards was suppressed (Hickey & Peelen, 2015). Using electroencephalography in a visual search task it was demonstrated that previous rewards facilitate perpetual activity and lead to an increase in the deployment of attention (Hickey, Chelazzi, & Theeuwes, 2010). They have shown an amplification of early visual processing in extrastriate visual cortex (increased P1 component) and an increase in visuospatial attention (increased N2pc component) contralateral to the color associated with a high reward on the previous trial. This effect was present when that color was in the location of either the distractor or a target. A similar modulation of the N2pc component was also found when object categories were linked to different reward schedules (Donohue et al., 2016). An ERP study used a training-test design and found a larger P1 component for stimuli associated with high rewards up to 7 days after the training (MacLean & Giesbrecht, 2015). Serences??? Anderson, Laurent, Yantis, 2014 extrastriate cortex and the Anderson paradigm

The behavioral and neuroimaging studies such as these have led to the proposal that rewards can teach visual selective attention, and guide it despite the current goals and with no changes in physical salience of the stimuli (Anderson, Laurent, & Yantis, 2011; Awh, Belopolsky, & Theeuwes, 2012; Chelazzi, Perlato, Santandrea, & Della Libera, 2013; Failing & Theeuwes, 2017). This idea has generated a a lot of research and has important implication for both cognitive theory, as well as clinical translations (Anderson on addiction, depression, etc.). However, the current studies leave a number of issues unanswered. First, most of the studies, especially the electrophysiological ones, have focused on transient attention: they have investigated the quick processing of the briefly presented stimuli. This approach could favor the fast and automatic effects of reward history on attention. Second, most of the studies on the value-driven attentional bias have used the visual search task and introduced rewards related to the features (in most cases colors) present in the search array. In this way, it is hard to rule out the possibility that spatial and feature-based attention are confounded. Finally, the studies showing the superiority of the reward effects over goal-directed attention have done so in the settings in which the goals of the participants are assumed (i.e. they are aware that they cannot earn any more money, so it is assumed that their goal is to pay equal amount of attention to all of the stimuli). However, this idea hasn’t been tested in a more rigorous setting in which participants still have a clear goal that is in collision or in line with the reward-driven effect. Additionally, the attentional capture in the existing paradigms is always inferred: trials with and without the distractor associated with a reward are compared. In contrast, our paradigm enables us to look at the simultaneous processing of both target and distractor associated with different reward schedules.

In this study we have set out to directly compare the influence of goal-directed attention and value-driven attention and to investigate the simultaneous deployment of attention to the stimuli linked to high or low reward probability. We have used the steady-state visual evoked potentials (SSVEPs) to track stimulus processing in the early visual cortex. SSVEPs represent the oscillatory response of the visual cortex to flickering stimuli (Norcia, Appelbaum, Ales, Cottereau, & Rossion, 2015). They provide a continuous measure of feature-based attention deployed across multiple stimuli simultaneously, and are a reliably modulated by goals such as paying attention to a certain stimulus feature. For example, in a random-dot kinematogram (RDK) task, dots of different colors can be frequency-tagged with different flickering rates. If participants are instructed to pay attention to red dots, the amplitude in their frequency is reliably increased, while the amplitude in the frequencies of the other stimuli is decreased (Andersen & Müller, 2010). Using the RDK task, we investigated the simultaneous deployment of attention to two features (red and blue dots) across three phases of the experiment. On each trials participants were instructed to pay attention to one of the two colors, and they first did the task without any rewards (baseline), then rewards were introduced and the two features were linked with different probabilities of earning a rewards (reward). In the last phase participants were informed that they will not be able to earn any more rewards (extinction). This design enabled us to investigate the influence of rewards on attention simultaneously for both features. Further on, it allowed us to compare the goal-directed deployment of attention with the value-driven attention in the extinction phase.

The graveyard:

We show that:

1) Introduction of rewards affects feature-based attention both behaviorally and in SSVEPs

2) Leads to lower levels of attention for the low rewarded stimuli, while high rewarded stimuli stay at the same level

3) The lingering effect of reward is present in the absence of rewards, even though our measure of feature-based attention goes back to baseline

“Alternative formulation: humans are more efficient to select targets associated with high rewards, but relatively inefficient at ignoring them when they are shown as distractors. Interestingly, the ability to ignore a given distractor also improved when this was consistently followed by high (as opposed to low) rewards, whereas the ability to select the same items as targets became relatively impaired.” “In summary, the present results provide evidence that reward has a direct impact on human vision that is independent of its role in strategy and endogenous attentional set. Our results suggest that the anterior cingulate cortex—a cortical expression of the mesolimbic dopamine system—plays a crucial role in this source of attentional control.”

This method has already been successfully used to explore the “attention grabbing” by irrelevant emotional stimuli (Attar, Andersen, & Müller, 2010) and is particularly interesting because it provides not just a measure of which stimuli capture attention, but also a continuous measure of how much attention is simultaneously being paid towards different stimuli.

These issues can be overcome by using an electrophysiological technique that has been reliably shown to trace the deployment of visual selective attention.

Corbetta & Shulman, 2002:

“Uninformative sensory stimuli are not effective in drawing attention when we are carefully attending to a specific location rather than diffusely attending over a broad spatial extent”.

*Broad theoretical introduction*

Given the limited processing capacity, selective attention is crucial in choosing which stimuli will be processed (Chun et al., 2011; Desimone & Duncan, 1995). Visual selective attention (VSA) prioritizes stimuli in accordance with current goals and knowledge based on previous learning (Chelazzi et al., 2013). The exact mechanisms through which rewards influence selective attention are a matter of intensive empirical and theoretical work. However, most researchers in the field agree that rewarded locations, objects, and object features are prioritized by increasing their saliency, while the saliency of the other locations, objects, and object features is reduced. This mechanism is commonly linked to the activity of the neurons in the visual cortex (Roelfsema, van Ooyen, & Watanabe, 2010).

*Description of the current results and tasks used including the ERP results and the fMRI study*

Della Libera and Chelazzi were the first to show that objects paired with high rewards are easier to select as targets and harder to ignore as distractors, while the opposite is true for objects related to low rewards (Della Libera & Chelazzi, 2009). Similar results were found for features and locations related to different reward contingencies (for recent reviews see: Anderson, 2016; Failing and Theeuwes, 2017). The most often used task in this domain is the visual search task. In this task participants are searching for a target among distractors. Typically, the feature related to high rewards can be either a target or a distractor.

In a series of studies Anderson and colleagues have demonstrated that the reward-related effects in such a task remain even when participants are aware that they cannot earn any more rewards (Anderson & Yantis, 2013; Anderson, Laurent, & Yantis, 2011). They have designed a visual search task in which the participants go through a training phase in which one color is consistently paired with high probability of earning a high reward, while another color is paired with high probability of earning a low reward. After the training phase participants were still slower on the trials in which the distractor was in the high reward color. Surprisingly, they have observed this effect even after weeks from the initial experiment. They have termed this effect the value driven attentional bias.

Using electroencephalography in a similar task Hickey and co-authors have demonstrated that the facilitation of perceptual activity and increase in deployment of attention for the stimuli related to high rewards (Hickey, Chelazzi, & Theeuwes, 2010). They have shown an amplification of early visual processing in extrastriate visual cortex (increased P1 component) and an increase in visuospatial attention (increased N2pc component) contralateral to the color associated with a high reward on the previous trial. This effect was present when that color was in the location of either the distractor or a target.

Hickey and Peelen (Hickey & Peelen, 2015) demonstrated that the representation of objects paired with high rewards was enhanced, while the representation of the objects paired with low rewards was suppressed. They found this effect in the object-selective visual cortex using fMRI while participants were searching for object categories (cars, trees, or people) in naturalistic images.

*Introduction of the main unresolved issues*

It is known that there is a bottom-up effect, but here we wanted to look at what happens when participants strategically change their attentional set.

In this we can compare the influence of a strategic attentional set with the influence of a more bottom-up factors.

However, most of the existing studies were not able to test the prediction of the simultaneous facilitation and inhibition.

*Introduction of the SSVEPs and how they can help resolve the issues*

A technique that can be used to track the voluntary deployment of attention simultaneously across different features.

This study is focusing on the steady state visually evoked potentials (SSVEPs) which represent the oscillatory responses of the visual cortex to flickering stimuli (Norcia, Appelbaum, Ales, Cottereau, & Rossion, 2015). This method has already been successfully used to explore the “attention grabbing” by irrelevant emotional stimuli (Attar, Andersen, & Müller, 2010) and is particularly interesting because it provides not just a measure of which stimuli capture attention, but also a continuous measure of how much attention is simultaneously being paid towards different stimuli.

*The present study*

Our goal is to use SSVEPs in order to, for the first time, assess the influence of reward probability on sustained feature-based attention. How this fits with the theoretical models presented in the first part of the intro? Present the main idea and design of the study. We manipulate reward probability, not magnitude (Maunsell, 2004).