Modulation of sensory processing under different modes of reward cueing

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Abstract

Rewards not only shape our value-based choices but also affect our simple perceptual decisions. Accordingly, behavioral and neural correlates of reward-driven effects on perception have already been identified at the earliest stages of sensory processing. However, it still needs to be determined how reward effects arise and are regulated under a multitude of variable contexts that characterize natural environments. To identify the general principles that govern the reward-driven modulation of sensory perception, we compared these effects under different contingencies of reward on performance and sensory modalities of the reward-associated stimuli (i.e. either visual, auditory, or audiovisual modalities) using behavioral, pupillometry, and neuroimaging techniques. We hypothesized that whereas some reward effects exhibit context-dependency, others, such as the dependence on attention and reliance on the long-range communication of signals across the brain, follow a general, context-independent principle. Our results in a first behavioral study revealed that whereas performance-contingent reward cues and previously rewarded stimuli both improved perceptual discrimination, performance-contingent rewards elicited stronger effects on the response times and pupil dilation compared to previously rewarded stimuli, indicating a dependency on the mode of reward delivery. However, no difference between the sensory modalities was found for either performance-contingent or previously rewarded stimuli. Interestingly, when we tested the previously rewarded stimuli in a second fMRI study, we found evidence for modality-specific changes in the effective connectivity between the reward and attention networks and the early visual areas. Specifically, cross-modal rewards engaged brain areas involved in integrating information across sensory modalities, namely the Superior Temporal cortex, in addition to those involved in reward and attentional processing. This finding inspired a third behavioral and fMRI study, where we tested whether the same principles apply to the contexts where reward cues were signaled from multiple sensory modalities, i.e., both auditory and visual, and were delivered continuously after correct responses. Here, we specifically tested whether reward influences the integration of information across visual and auditory modalities. The results of this last study revealed overall similar patterns of reward-driven modulations for unisensory and multisensory stimuli at the behavioral level. Furthermore, although we found evidence for differences between unisensory and multisensory rewards both in classical reward coding regions and in higher sensory areas, these differences were overall smaller than the supra-additive threshold predicted by classical models of multisensory integration. This finding hence indicates that

reward effects, in the setting that we tested, occur at an independent and later stage compared to multisensory integration, hence affecting the sensory processing in a context-independent manner. Taken together, this thesis identified key characteristics of reward-associated stimuli and their mode of delivery that give rise to either dependence or independence from the specific contexts. Specifically, when rewards were contingent on performance and were delivered continuously, they mobilized resources to optimize behavior irrespective of the specific sensory features. However, when rewards were not performance-contingent or were discontinued, they exhibited modality-specificity, particularly in the way that reward was broadcasted across the brain. Our findings therefore indicate that the regulation of reward effects on sensory perception is tightly linked with the optimization of final choices, suggesting that both reward and sensory systems influence each other to establish adaptive behavior.

Chapter 1: General Introduction

1.1 Reward theory

Reward shapes our behavior and choices through mechanisms that in principle seek to optimize behavior by maximizing our gains (Schultz, 1992; Elliott et al., 2000; Gold and Shadlen, 2002; Rangel et al., 2008; Gottlieb et al., 2014). Rewarding events can be expressed in multifaceted ways, which leads to distinct functionality of reward in shaping behavior. For instance, when an employee is awarded for their performance at work, the employee will likely maintain their performance at a satisfactory level. In this example, reward acts as a *reinforcer*, which tries to increase the frequency or the intensity of a behavior (Schultz, 2000). Through this award, the next time the employee remembers specific tasks that were praised, the corresponding behavior will likely be repeated and maintained. Here, reward prevents an *extinction* by maintaining a learned behavior. Afterwards, the employee might have gone to eat their favorite dish to celebrate the event, where the dish gave them a feeling of pleasure. Reward here acts as a goal itself which leads to a consummatory behavior. Schultz (2000) describes that objects that signal rewards are given a *motivational value* as a label.

As illustrated above, reward signals can serve various functions that underlie our behavior and decision-making processes. Rangel and colleagues (2008) provided a framework to explain how reward guides decision-making processes. In order for a decision to be made, the problem that has to be tackled should first be represented, identifying the internal and external state of a problem. For instance, a monkey is hungry (internal state) and to get fruits on a tree, it needs to consider how many monkeys are already in the proximity of each tree (external). Then, a set of actions are available for the monkey to get the fruit, considering how hungry it is and how competitive the environment is. At this stage, the organism undergoes a valuation process, where it assesses possible actions and assigns a value to each action. The next step is action selection, where the monkey chooses an action that is optimal to fulfill its hunger with the minimum possible competition. When the monkey finally gets the fruit, it evaluates the outcome and whether it fulfills its expectation, and if not, the chosen strategy needs to be changed for future behavior. At all stages, a learning process might occur to determine whether an update in representing the problem might be needed or the values of the action sets have to be re-assigned.

Learning through reward has been explained by many theories, where one of the pioneer works is by Pavlov (1927, as reviewed in Schultz, 2000) in *classical conditioning*. He proposed a model that promotes behavioral learning through an association, where a cue that does not elicit a behavioral response on its own (i.e. neutral stimulus) is paired with a cue that naturally elicits a response (i.e. unconditioned stimulus). After the organism is exposed to the pairings multiple times, the mere exposure of the neutral stimulus will now elicit a response, changing the neutral stimulus into a conditioned stimulus. Furthermore, Wagner and Rescorla (1972) criticized and extended this theory, where they argued that pairing two cues by mere exposure is inadequate to explain the change in behavior. Instead, they focused on the associative strength between the two cues, where the co-occurrence of the two cues will change the current associative strength depending on the predictability of the pairing. As noted by Schultz (2000), the importance of the Rescorla-Wagner model was in introducing an uncertainty factor in associative reward learning, which is further quantified as a reward prediction error. When a reward is delivered unpredictably following an action or event, the prediction error will be positive. However, once the action has been learned and therefore reward deliveries are predictable, the prediction error will fall to zero. In contrast, when the action has been learned (i.e. reward is still expected to occur), but no reward was delivered, then the prediction error will fall to negative and the behavior starts to extinguish.

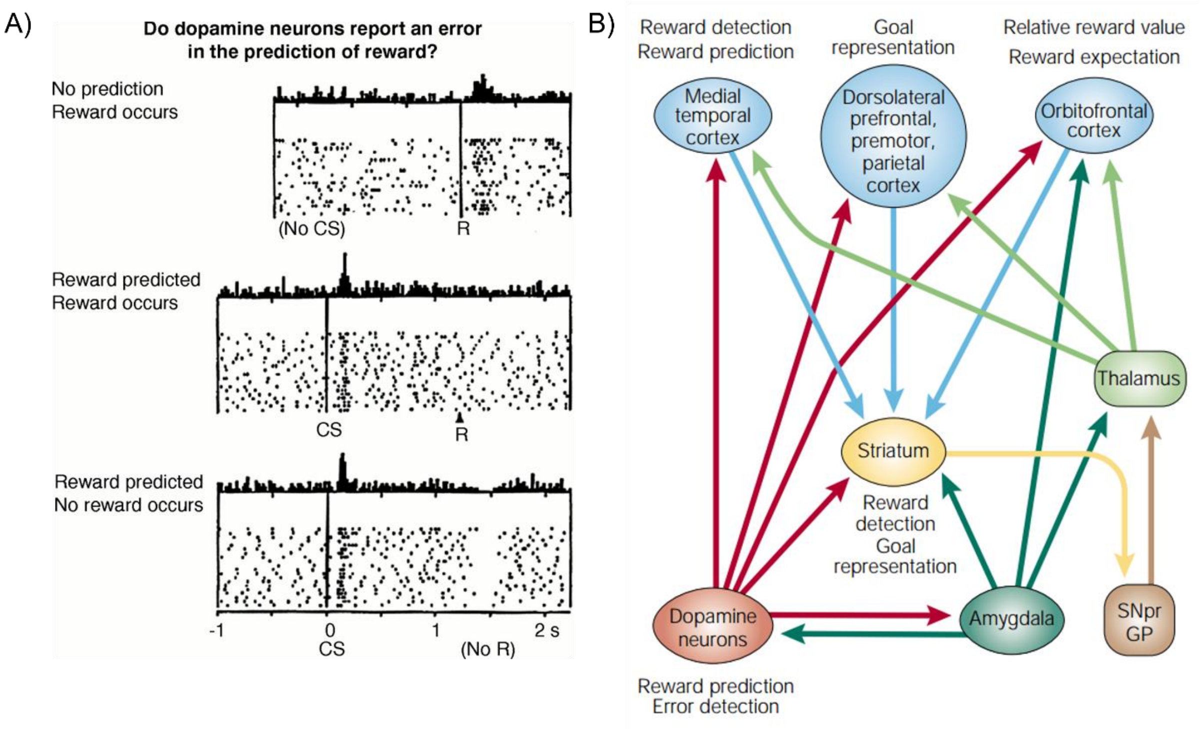

Figure 1. (A) Response of dopaminergic neurons to reward prediction error recorded in the monkey striatum (Schultz et al., 1997). The top panel shows the neural response as the monkey received reward (R) juice without any prediction (i.e. without cues signaling the reward (CS – conditioned stimulus)). The middle panel shows the neural response after the monkey learned the association between reward and the reward predicting cues (CS), and the neural response shifted to the time of CS occurrence. The bottom panel shows when reward deliveries were omitted following the reward-predicting cues. (B) Dopaminergic projections (red) in the brain to the cortical areas in the frontal and parietal (blue) and subcortical areas in the striatum (yellow) and amygdala (green). However, the areas receiving dopaminergic projections are also interconnected with each other and with other brain areas that carry sensory information, such as the thalamus (light green). Panel A is adopted from Schultz and colleagues (1997) and Panel B from Schultz (2000).

To illustrate further how reward prediction error is regulated in the brain, we will look into the underlying neural mechanism of reward prediction error that has been investigated based on the phasic activities of dopaminergic neural activities. Schultz (1997) recorded neural response in a monkey’s striatum, as it is a structure that receives direct projections of the dopaminergic neurons located in the ventral tegmental areas. As the monkey was learning the pairing of a visual stimulus with a reward (i.e. liquid), the neural response showed higher firing rates upon receiving the reward cue. This shows that when the organism did not expect a reward and obtained it, the prediction error will be positive and is expressed as a higher firing rate in the dopaminergic neurons at the time of reward delivery (**Figure 1A** *top panel*). However, after the monkey learned the association between the cues, the striatum was activated upon receiving the visual stimuli that were predictive of reward (i.e. Conditioned Stimulus, CS), as shown in the higher firing rate after the onset of the cues, but not at the time of reward delivery (**Figure 1A** *middle panel*). This indicates that when the organism established an association between a stimulus and reward and therefore predicted reward upon receiving the CS cue, there is no reward prediction error and no change in the activity of the dopaminergic neurons. Furthermore, in the case that upon receiving the cues, the reward was omitted, they observed a decreased firing rate of the dopaminergic neurons (Schultz et al., 1997). Here, the organism experiences an extinction, where the associations of the cue and reward are being unlearned, as their expectancy of reward was violated (i.e. reward prediction error is negative, see **Figure 1A** *bottom panel*).

1.1.1 Reward prediction error is broadcasted through dopaminergic projections across the brain

The reward prediction error signals originate from the midbrain ventral tegmental areas. Upon calculating the prediction error in the expected and obtained reward, the dopamine neurons will emit a global reinforcement signal to the striatum (**Figure 1B**), where the neural responses in this subcortical structure show a reward-expectation correlates (Schultz, 2000). Similarly, the amygdala, another subcortical structure that receives dopaminergic projections, also responds to reward-related activities, specifically upon reward receipts. Furthermore, the parietal cortex also receives dopaminergic projections, where the modulation is linked to task-related activity where the choice associated with reward would be prioritized and an appropriate action to obtain the reward is coordinated (Platt and Glimcher, 1999; Bendiksby and Platt, 2006). Moreover, through a cortico-basal ganglia-cortico pathway, dopaminergic projections are also received in the frontal areas, such as the orbitofrontal cortex and the dorsolateral parts of the prefrontal cortex (Schultz, 2000). While the orbitofrontal cortex is associated with detecting, perceiving, and expecting rewards that are related to the decision-making process (Schultz, 2000; O'Doherty, 2004), the dorsolateral parts of the prefrontal cortex are engaged in preparing the desired behavior that would acquire or optimize the reward.

Therefore, the reward signals in each brain area are responding to different aspects of reward, where two major categories can be observed: neurons that are detecting the reward prediction error and other neurons that can differentiate between the rewards and might be involved in assessing the identity of individual rewards, thus underlying the perception of reward (Schultz, 2000). Although each area is tuned to a specific aspect of reward, altogether, these areas create a reward coding mechanism in the brain that underlies reward learning, where a reward is utilized as a teaching signal to adapt our behavior (Schultz, 2000; Chelazzi et al., 2013).

1.1.2 Reward representation in the brain underlies different functions

As introduced in the previous section, dopaminergic projections are routed to the cortical areas, where each area represents different aspects of reward. For instance, the frontal areas represent a common coding of reward value, which means that they are independent of the sensori-motor contingencies of the choice and are not affected by other aspects such as ambiguity, quantity, cost, and others (i.e. domain-general) in the medial part of the orbitofrontal cortex (Padoa-Schioppa, 2011) and ventromedial prefrontal cortex, where the reward encoding in this area does not separate different types of reward stimuli (Levy and Glimcher, 2011, 2012). Moreover, O'Doherty (2004) showed that the orbitofrontal cortex also encodes reward values coming from different sensory modalities. For instance, in a study where sensory inputs were held constant, but only the values changed, the medial part of the orbitofrontal cortex was modulated by the change of reward value, showing that this area is encoding reward value and not affected by the sensory properties (Rolls et al., 1981).

The evidence above identifies neurons that respond to rewards in a domain-general manner, where reward signals are not differentiated based on the property of the predictive cues or the properties of the reward itself. There are also neurons showing specificity to the reward identity. For instance, Yacubian and colleagues (2007) showed that reward properties have different representations in the striatum, where reward magnitude and reward probabilities modulate different areas in the striatum. Moreover, the striatum and also the prefrontal areas have been observed to show general and specific reward modulations, depending on the identity of the reward (Levy and Glimcher, 2011) and the context of how the reward was delivered (Elliott et al., 2000). This evidence indicates that within areas receiving dopaminergic projections, there are neurons responding to reward indifferently (i.e. in a domain-general manner), while there are also neurons that respond to specific properties of the reward predicating cues or the reward itself, showing there are functional segregations in reward coding, which will be further explained.

1.2 Interactions between the reward and the sensory systems

So far, we have discussed how reward signals are processed in the brain and how the principle of reward learning is established. However, in practice, we experience reward through the inputs from our sensory system, as reward does not have its own receptors in the environment (Schultz, 2006). Hence, one possibility is that reward information is received through sensory inputs. Although sensory cortices do not receive a direct dopaminergic projection, reward modulation has been known to reach the sensory cortices. Therefore, reward processing is not only limited to the areas receiving dopaminergic projections, but also involves a mechanism that engages sensory processing. Therefore, it is important to understand the interactions between the two systems. There are two major lines of evidence supporting the inter-relatedness of reward and sensory processing that I would like to highlight: 1) how the sensory properties of the cues are represented in reward-related areas and vice versa, and 2) how reward is represented in sensory-related areas.

1.2.1 Sensory representation in the reward-related areas

The first line of evidence demonstrates that areas that receive dopaminergic projections, such as the striatum and the frontal areas, are also responding to the sensory signals. For instance, Zink and colleagues (2003) showed that the striatum plays a role in encoding sensory properties, as the striatum was modulated by a salient stimulus that had no values attached to it. Further studies showed that salient cues associated with monetary rewards had higher modulation in the striatum compared to the less salient cues that were also associated with the same amount of reward signaled from visual (Zink et al., 2004) and auditory modalities (Zink et al., 2006), indicating that the modulation in the striatum was driven more by the saliency of the sensory properties. Moreover, other reward-related areas, such as the orbitofrontal cortex, have been shown to receive inputs from all sensory modalities (Carmichael and Price, 1995; Frey et al., 2000; Aharon et al., 2001; Kringelbach, 2005; Kveraga et al., 2007; Rolls, 2007) and play a role in integrating sensory cues (Kringelbach, 2005). Moreover, the neurons receiving sensory inputs in the orbitofrontal cortex are dissociated from the neurons receiving dopaminergic projections (i.e. reward processing) (Rolls, 2007), indicating a different functional organizational within the orbitofrontal cortex regarding reward and sensory processing.

1.2.2 Reward representation in the sensory-related areas

Furthermore, not only were reward signals observed in the fronto-parietal areas that are linked to higher cognitive functions, but also reward signals were observed in areas regulating sensory inputs or the translation of sensory inputs to a behavior. For instance, in their early studies, Platt and Glimcher (1999) investigated how sensorimotor decision-making is affected by reward in monkeys. The monkey was instructed to do a visual spatial task by making a saccade towards one of two possible positions to obtain a juice reward. As the visual stimuli cued gradients of probabilities and the magnitude of the juice reward, they observed an area involved in transforming visual signals into eye-movement commands in the lateral intraparietal (LIP) was modulated. Their findings suggest that reward signals are reaching the sensorimotor areas that are linked to action selection, hence affecting more basic aspects of cognitive processing.

Further studies have investigated the relationship between reward and sensory areas systematically and observed that the process where reward affects perceptual decision-making could be traced back to brain areas as early as the primary sensory areas. For instance, Shuler and Bear (2006) observed that the neuronal responses of the primary cortex (area V1) are predictive of the timing of reward delivery in rats. Furthermore, it has been shown that neurons in rat's V1 improve their perceptual discriminability through the learning of reward, where neurons in the primary visual area were able to adjust their sensitivity (i.e. anticipation) to task-relevant property of the cue (Poort et al., 2015). Serences (2008) found that human's early visual areas are modulated by the magnitude of reward, in that the Blood Oxygenation Level Dependent (BOLD) responses showed a larger difference between two stimuli as the value difference between them increased. Weil and colleagues (2010) demonstrated that the reward receipt enhanced the activities of neurons in the primary visual areas (V1), both within as well outside of the retinotopic representation of the visual stimuli, to improve the upcoming representation of the stimuli. Although most studies have been done in the visual domain, studies examining other sensory domains have also observed reward modulation in the primary sensory cortices. For instance, observations in the auditory domain revealed that the primary auditory cortex represents a sound frequency better when it is paired with reward (Beitel et al., 2003). Moreover, primary somatosensory cortices have also been observed to respond to the delivery of reward (Pleger et al., 2008). The studies above showed various early sensory responses to the many features of reward, such as the timing, value difference, and probabilities, across different sensory modalities.

Furthermore, Komura and colleagues (2001) extended these findings, as they observed that rewards affected sensory processes in the thalamus. The thalamus has been known to relay sensory information to the primary and secondary sensory cortices. In their study, they found that reward modulated the thalamus in two ways: the early, phasic responses occurred shortly following the stimulus presentation and depended on the sensory modality of the cue, while the late responses gradually increased during the cue until the time of reward delivery, and this modulation of reward in the thalamus was independent of the sensory modality. This finding showed that reward modulation not only reached the primary sensory cortices, but already affected the thalamus, a structure that crosses the sensory input pathway.

The studies mentioned above have shown various observations of reward modulation of different sensory processes that are relevant for behavior or decision-making (Beitel et al., 2003; Pleger et al., 2008; Serences, 2008). Some studies demonstrated that in order to modulate the sensory cortices to optimize the goal-directed behavior, reward signal targeted sensory processing in a non-specific manner, where both the stimulus-related responses and stimulus-unrelated representations were enhanced (Weil et al., 2010). In contrast, other studies observed that reward signals targeted specifically the sensory areas relevant for goal-directed behavior (Schiffer et al., 2014). Hence, it is still debatable whether reward learning mechanism in the sensory cortices interacts in a stimulus-specific or stimulus-unspecific manner.

To provide a perspective on this uncertainty, Gold and Shadlen (2002) proposed a framework for how reward and sensory processing interact. In their review, they discussed that in order for an action or decision to be made, there are neurons responsible for forming perceptual decisions by linking sensory evidence accumulated over time to motor intentions. For instance, association areas in the frontal and parietal cortex, such as the lateral intraparietal areas (LIP) and the prefrontal cortex, showed sustained activities during a visually guided saccade task and are examples of neurons that appear to be responsible for forming the perceptual decisions (Kim and Shadlen, 1999; Platt and Glimcher, 1999). Moreover, these areas appear to be also sensitive to other psychological factors that can affect the decision-making process. For instance, the neural activity in the sensorimotor association areas such as LIP has been modulated by the prior probabilities and the expected magnitude of the reward (Platt and Glimcher, 1999), or the areas involved in oculomotor decisions such as the superior colliculus are affected by the prior probabilities of rewards (Dorris and Munoz, 1998). Gold and Shadlen (2002) suggested that these regions are likely to access information about the accuracy and the rate of reward, thus extending their role from sensorimotor processing to also encompass reward processing. Hence, their proposal suggested that reward signals engage a mechanism promoting goal-directed behavior, in which when reward can be measured in a gain, such as in the motoric output (e.g. in faster eye movement), reward modulates the areas that are related to the sensorimotor processing. Although, in a matter where reward is measured in the tuning specificity of the sensory cortices (e.g. in perceptual acuity), *it is still unclear whether reward modulates sensory perception in a target-specific or target-unspecific manner*.

1.3 Mechanisms of interaction between the reward and the sensory systems

In order to understand the standpoint of the current knowledge of possible mechanisms through which reward and sensory systems interact, we will discuss the two broad categories of mechanisms, namely cognitive and neurophysiological mechanisms, involved.

1.3.1 Cognitive mechanisms

Reward guides our behavior and perception by increasing the salience of the sensory stimuli. For instance, it has been observed that the visual system was modulated monotonically as reward value increased (Engelmann et al., 2009). This modulation in the visual system is similar to the modulation observed in the attentional and reward networks in the brain (Pessoa and Engelmann, 2010). This might indicate that the sensory system is affected in a similar way as the higher cognitive processes, such as those that encode and represent the reward value, or it might reflect that reward modulation occurs in addition to the primary role of these areas in representing sensory processing, likely through top-down, feedback signals from reward coding areas. Moreover, as reward network was modulated in a similar way as the attentional network, there is a strong indication that reward and attention jointly affect sensory perception. In this context, how reward impacts sensory processing depends on how reward is cued, similar to the dependencies of cueing context affecting how attention is engaged (Van Der Stigchel and Theeuwes, 2007). Furthermore, Pessoa (2015) distinguished two major reward manipulation and their difference in modulating perception: the proactive and reactive paradigms (Braver, 2012). In proactive paradigms, reward acts as a motivational factor, in which reward mobilizes cognitive resources to solve the task at hand, including the deployment of attention (Chelazzi et al., 2013; Pessoa, 2015). Meanwhile, in reactive paradigms, reward has an intermediate effect on attention or cognitive resources deployment. In order to accommodate the goal-directed behavior, the learning mechanism in the reactive paradigm does not only affect how reward impacts the stimulus representation, but also how the attentional prioritization process will impact stimulus representation. Specifically, reward adaptively allocates more attentional prioritization when the reward cues are placed on the target, while when reward acts as a distractor, the system will enhance the rejection of the distractor (Libera and Chelazzi, 2009). This extensive training in the reactive paradigm can also be referred to as the selection history of reward. Adopting from attentional studies, Awh and colleagues (2012) argued further that selection history is another category that relies on a previous association or selection of a stimulus, leading to a more efficient encoding of the stimuli despite the fact that the stimulus is irrelevant or not-contingent to the task.

In summary, studies have identified distinct characteristics of responses in proactive and reactive paradigms. This distinction may derive from a dissociable neural mechanism underlying the two processes. Specifically, proactive paradigms engage higher control areas, such as reward-related or attention-related areas, while reactive paradigms may rely on the physical saliency of the stimulus or a long-lasting effect of the previous reward association to optimize behavior.

1.3.2 Neurophysiological mechanisms

The studies mentioned above demonstrate that reward signals can spread across the brain, from the typical dopaminergic projections to the association areas and further to the primary sensory cortices. Interestingly, direct projections to the primary sensory areas have been observed to be scarce (Oades and Halliday, 1987). However, reward is still observed to modulate the earliest stage of information processing in the primary sensory areas. Given these, the question arises of how do the reward signals reach early sensory areas?

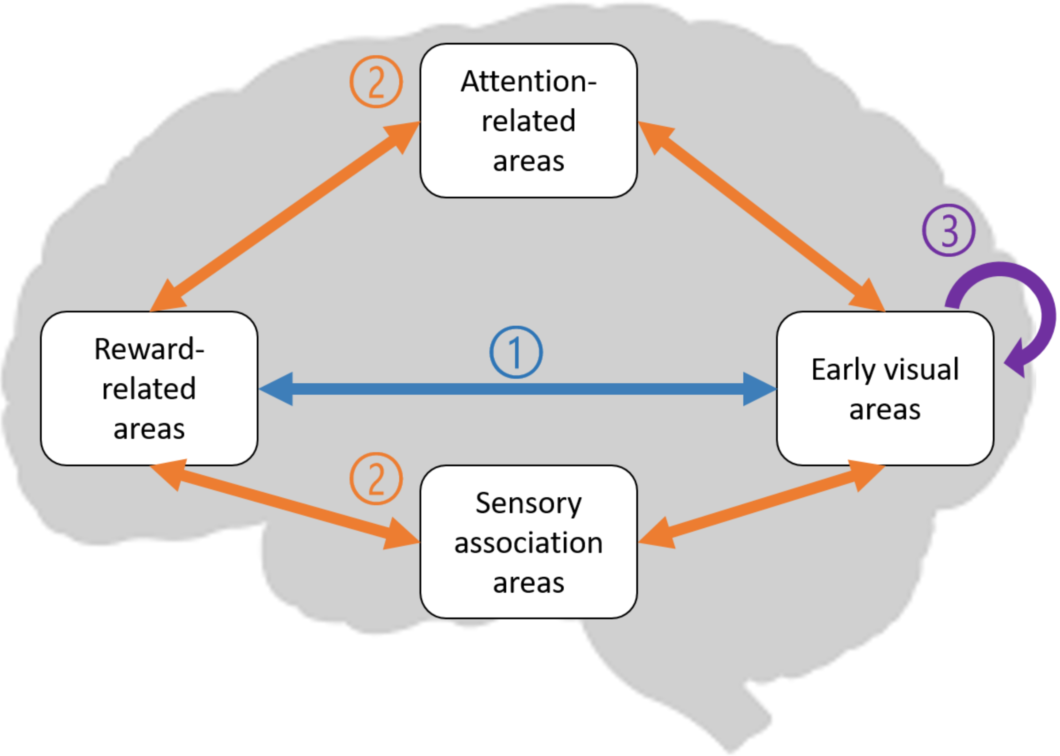

Figure 2. Illustrative scenarios of the communication between the reward-related and early visual areas. Previous studies have demonstrated different possible pathways that may underlie the reward effects on early visual areas. (1) a *direct* communication through long-range projections between the early visual areas and the frontal reward areas, (2) a *mediated* communication through attention and/or association areas, or (3) reward modulation relies on the long-lasting effect of reward on neural plasticity *within* the early visual areas.

One possibility is that reward signals are communicated directly from reward areas to the primary sensory areas. Although scarce, there have been studies investigating and reporting the neurophysiological pathways between the reward and sensory cortices. For instance, Khibnik and colleagues (2014) found direct projections from the primary visual areas to the striatum in mice, suggesting that early visual processing may shape reward/striatal-related behavior. Moreover, Kveraga and colleagues (2007) also found a pathway between the early visual areas and the orbitofrontal cortex (OFC), an area known to receive dopaminergic projections and be involved in the encoding and representation of reward value (Schultz, 2000). They suggested that the early visual areas deliver magnocellular information (i.e. low spatial frequency information) to the OFC in order for OFC to signal other areas, such as the fusiform gyrus, to give an early prediction to identify an object (Kveraga et al., 2007). Other studies also showed that the OFC sent teaching signals directly to the primary somatosensory areas (S1) (Wang et al., 2022). In their study, they observed that the contribution of the OFC to the S1 areas differs depending on the laterality. Specifically, reward teaching signal is projected within the ipsilateral S1, while contralateral S1 reflected more sensory processing. Altogether, these studies demonstrated that there is a long-range projection and communication between the earliest stages of information processing in the primary sensory areas and the areas that are related to higher cognitive processing.

Another possibility is that reward signals can be mediated through other brain areas/mechanisms to be communicated across the brain. Apart from the reward-related regions, reward signals have been observed to also modulate the fronto-parietal regions that are related to attention and occipito-temporal cortices that are responsive to higher sensory mechanisms (Pessoa and Engelmann, 2010). Moreover, Pessoa (2015) proposed that depending on the task employed, improved perceptual performance might rely on areas from the frontal and parietal regions, exerting top-down modulations on sensory areas. For instance, an area that is relevant for reorienting attention in the temporo-parietal junction was involved in detecting a target, and this effect was enhanced by the reward, accompanied by activities in the reward-related area such as the OFC (Small et al., 2005). Another study by Platt and Glimcher (1999) showed that attentional mechanisms might gate the reward signals to modulate early sensorimotor mechanisms. They observed the lateral intraparietal areas in monkeys, an area that is related to translating visual signals into eye-movement, which was modulated by the probabilities of the reward/gain the monkey could obtain. These two examples showed that areas relevant for goal-directed behavior are modulated by reward signals, indicating that there is a mechanism that links a value to the cognitive system that regulates behavior, such as attention or movement control. Furthermore, in a study by Pooresmaeili and colleagues (2014), reward was cued from the auditory sensory modality, while the target was in the visual domain. They observed reward modulation in the early visual areas. Additionally, they also observed reward modulation in the ventromedial prefrontal cortex (vmPFC) and the superior temporal sulcus (STS). This might indicate that the reward communication to the early visual areas might be enabled through both the classical frontal reward coding areas as well as the higher sensory areas such as STS.

Finally, reward effects induced by extensive learning might change the local plasticity of the primary visual areas, as shown both empirically (Chubykin et al., 2013; Kim and Anderson, 2019) and through computational modeling (Wilmes and Clopath, 2019). Specifically, a training period with rewards enables the primary visual area to reorganize itself to maximize its output in different ways. For instance, the training of perceptual discriminability will sharpen the orientation tuning of the trained orientation, while training of detection will change the gain of some neural populations (Furmanski et al., 2004) and this learning-induced effect is established by the association of learned stimuli with rewards (Poort et al., 2015). This mechanism might occur through the cholinergic mechanisms (Chubykin et al., 2013) or through sparse dopaminergic projections in the visual cortex (Arsenault et al., 2013).

In this section, we discussed the possible underlying neural mechanism of reward-driven modulation on behavior and perception: whether the reward signals travel through a long-range projection from the reward-related areas to modulate early visual areas, mediated through attention or association areas, or the modulation relies on the local plasticity change in the early visual areas. *So far, there has been no consensus on these models and on how reward-related information is communicated to the early visual areas.* Interestingly, the dopaminergic projections in the early visual cortex are sparse (Oades and Halliday, 1987). Hence, reward signals need to rely on one of the alternative communication possibilities to reach early visual areas.

1.3.2 Measurement of reward and sensory system

Studies investigating different modes of reward cueing can be distinguished into two lines. The first line of studies investigated reward effects when the delivery of rewards was contingent on the performance of a task (Engelmann et al., 2009; Padmala and Pessoa, 2011). In these settings, typically, a *proactive paradigm* is used where reward can mobilize other cognitive resources in order to facilitate the performance and thereby optimize the outcomes (Fröber and Dreisbach, 2016; Qin et al., 2020). When such paradigms involve a perceptual task, the underlying mechanism relies on the top-down communication of information between brain regions that play a role in high-level control and valuation (Botvinick and Braver, 2015) in the frontal and parietal cortices (Padmala and Pessoa, 2011) and early motor or sensory areas to facilitate performance or improve perceptual decision making (Weil et al., 2010).

On the contrary, when reward effects were tested using *reactive paradigms*, in which reward signal relied on either previous associations (Le Pelley et al., 2015; Watson et al., 2020) and/or did not provide information related to the target of the task (Hickey et al., 2010; Anderson et al., 2011; MacLean and Giesbrecht, 2015; Gong et al., 2017), the predominant effect was a capture of attention to the reward cues but not necessarily a facilitation of performance. For instance, in settings where distractors signaled past reward associations, they captured attention away from the target and impaired performance (Sali et al., 2013; Anderson et al., 2014; Rusz et al., 2020).

There has been a general criticism of the proactive paradigms stating that in these settings, the effects of reward and attention cannot be distinguished from each other (Maunsell, 2004). Reactive paradigms, on the other hand, try to remedy this issue as goal-directed attention and reward processing are kept separated from each other (through previous associations or task-irrelevant cueing of rewards). However, the reactive paradigms also involve the capture of bottom-up attention and may therefore convolute the separation of attentional target processing and reward.

To identify which aspects of perceptual processing specifically involve reward-related rather than attention-related mechanisms, a second line of studies used a different method (Leo and Noppeney, 2014; Pooresmaeili et al., 2014). Here, the reward information was learned in the past and, more importantly, was signaled from a different sensory modality than the target stimulus (i.e. target was in the visual domain, while reward cue was in the auditory domain). Using similar paradigms, where reward information was irrelevant to the current task, these studies observed a reward-driven facilitation of visual discriminability (Leo and Noppeney, 2014) and an improved representation of the target in the early visual areas (Pooresmaeili et al., 2014), although reward information was signaled through the auditory modality and could not directly influence the processing of a visual target.

In summary, reward-driven effects on perception are often observed in the form of a facilitation in task performance when rewards are contingent on the task performance. However, it is not clear whether reward effects in these settings are driven by rewards or by task-relevant attentional processes. To minimize the involvement of task-relevant processes, reward effects can be tested in reactive paradigms that rely on previous associations between the task and rewards. Here, reward effects are more inhomogeneous than the proactive paradigms: in some instances, a facilitation of performance is observed, whereas in other instances, reward-driven capture of attention to non-targets impairs performance. Moreover, reactive paradigms do not still allow a complete separation between attentional and reward mechanisms. This shortcoming can be further improved by signaling rewards from a different sensory modality (i.e. cross-modal reward cueing), which has been a novel direction used in recent years (Leo and Noppeney, 2014; Pooresmaeili et al., 2014). Due to its novelty, many aspects of these latter lines of research are still unknown. For instance, *we have not yet clearly understood how reward-driven modulation of behavior and perception interact with the sensory properties of* *reward cues in general and their sensory modality in particular*. As diverging results were demonstrated using reactive paradigms, *it is not known whether contingencies of reward on task performance interact with the sensory modality of rewards*.

1.4 Aims of the thesis

We live in a multisensory environment, where sensory inputs play an important role in shaping our perception of the environment. Moreover, reward guides our perception towards choices that maximize our gains, be it better perceptual performance or higher rewards. However, the link between reward mechanism and sensory perception has been underexplored. *It is not clearly known how reward processing interacts with the sensory system to facilitate our behavior and perception*. The sensory system is mapped in its hierarchical organizational function (Felleman and Van Essen, 1991), regulating the processing of sensory inputs, and reward system through dopaminergic projections to cortical areas (Schultz, 2000), regulating how reward signals modulate different aspects of behavior and perception. The investigation of the two systems shows how each of the two independent mechanisms organizes itself. However, in order for an organism to be able to adapt to its environment, our behavior and perception should be shaped by both factors simultaneously and coherently. This indicates that most likely an interaction between the sensory and reward processing should occur at each and every stage of information processing in the two systems, but the exact nature of such interactions is poorly understood. Given the ubiquity of sensory processing and the importance of rewards in shaping behavior, it is important to expand our current knowledge and gain a better understanding of their interaction, at the same level of precision that the two systems, reward (Schultz, 2000) and sensory system (Felleman and Van Essen, 1991), have been characterized in the past. This knowledge will allow a better understanding of behavior in natural environments that are rich both in their sensory as well as in their motivational content and require flexible adjustment of behavior.

In the previous sections, I have discussed how reward is an important factor that shapes our behavior and decision-making. A framework by Rangel and colleagues (2008) demonstrated how learning through reward occurs in every stage of the decision-making process. As reward does not have its own sensory inputs, its influence on behavior and perception is tightly linked with the inputs of the sensory system. For instance, several studies provided evidence on how reward signals reached the earliest stage of information processing and shaped the representation, thus altering perception (Beitel et al., 2003; Shuler and Bear, 2006; Pleger et al., 2008; Serences, 2008). Considering a scarce dopaminergic projection to the early sensory areas (Oades and Halliday, 1987), further studies proposed principles of how reward may interact with the sensory system: through a *direct* communication between the reward-related areas and the primary sensory areas, *mediated* through attention or association areas, or reward signals alter the *local* neural plasticity in the primary sensory areas. *However, as to date, there has been no consensus on the mechanisms of the interaction between the reward and sensory systems. Considering how reward has been adapting our behavior to ensure survivability, it is important to identify the principles governing its interaction with the low-level sensory processing which provides the inputs from the external world.* As an implication, understanding how information is altered by reward would benefit, for instance, some clinical cases when reward sensitivity and processing is disrupted, such as in gambling, as therapeutical interventions can be more expanded not only to regulate the reward sensitivity and processing, but also to utilize the sensory inputs to accommodate the effectivity of the therapy. Previously, the methods of taking advantage of the cross-modal plasticity have been investigated to improve a sensory integration deficit of letter-to-speech (Gori and Facoetti, 2014). In the case of gambling, in addition to medical therapy regulating the dopaminergic activities, patients can be desensitized to the sensory triggers that are associated with the gambling activity by associating the sensory triggers with a neutral stimulus or re-directing the attention to other feature of the sensory properties by associating other sensory feature with a rewarding stimulus that promotes recovery. Furthermore, understanding how reward shapes our multisensory perception is also beneficial for vital infrastructures. For instance, positive feedback for a safe choice of driving could be implemented using multisensory cues, where when a driver does not drive above the speed limit, a visual and/or audiovisual cue can be delivered to reinforce the safe behavior in the future.

Therefore, this thesis aims to systematically answer the open question as to *how reward-related and perceptual processing systems interact?* To answer this question, in my thesis I compared reward effects on sensory processing under different contexts. Firstly, I tested rewards with different relationships to the performance in a task (i.e. performance-contingent or previously rewarded). Secondly, I examined effects when rewards were signaled from the same (intra-modal), different (cross-modal), or a combination (inter-modal) of sensory modalities used to carry out a task. Examining these different contexts will allow us to identify whether reward effects follow a domain-general or a context-specific principle while interacting with the sensory processing system. Towards this aim, this thesis tries to achieve three objectives:

1) Understanding how reward cues modulate visual perceptual decision-making when signaled through visual (intra-modal) or auditory (cross-modal). I hypothesize that reward-driven modulation followed a dissociable mechanism depending on which sensory modality the cues were signaled from. Specifically, reward cues would enhance the visual perceptual decision-making by increasing the neural representation in the early visual cortex, regardless of the sensory modality of the cues. However, in order to enhance this representation, reward cues will follow dissociable neural pathways depending on the sensory modality of the cues.

2) Understanding how intra-modal and cross-modal reward effects interact with the performance-contingency of rewards. I hypothesize that reward effects exhibit dissociations based on the degree to which they are contingent on the performance. Specifically, as reward is contingent on the performance, reward cues mobilize resources from the higher-level areas to modulate the visual perceptual decision-making, irrespective of the sensory properties of reward cues. However, as reward deliveries are halted, reward cues will rely on the previous associations, engaging more limited resources based on the plasticity formed in the sensory-dependent areas. Hence, the reward effects observed from performance-contingent reward cues are stronger than those of previously rewarded cues.

3) Understanding how reward-driven modulation of perception can be combined across sensory modalities when reward is cued from multiple sensory modalities. As reward effects have already been observed to modulate the early sensory areas, I hypothesize that reward and sensory signals are merged at the same early stage of processing. Accordingly, I predict that reward effects will be integrated similarly as the sensory integration (i.e. according to a *supra-additive* rule of multisensory integration).

Below I will provide a preview of the methods we used and the results we obtained in each chapter to achieve these objectives.

In order to achieve objective 1 and 2, two studies were conducted. In the **first study (chapter 2)**, we compared intra- and cross-modal reward modulation of early visual areas when reward was either contingent on the performance being delivered continuously after correct responses or was learned in the past and was then halted. We expected that reward-driven modulation in the performance-contingent case relies on the higher-level areas and therefore will be stronger than previously associated reward. In contrast, we expected that the effect of previously associated reward cues would rely on another mechanism, such as sensory-dependent areas, and consequently the reward effects would be weaker. In this study, we found a similar facilitatory effect of reward under both contexts, but importantly we also identified differences between the two modes of reward cueing. Specifically, when reward was contingent on the performance, behavioral response speed and pupillary dilation exhibited a stronger reward-driven modulation compared to when reward deliveries were halted.

In the **second study (chapter 3)**, we used previously rewarded stimuli, which allow a better distinction between task-related and reward-driven effects, and compared the reward effects at the neural level using fMRI. Specifically, we tested whether a difference can be observed based on whether rewards were signaled intra- or cross-modally relative to a visual target. In this study, we found an overall enhancement of behavioral and neural correlates of target processing across intra- and cross-modal rewards. Specifically, using multivariate voxel pattern analysis of the fMRI data, we further observed areas related to reward, attention, and sensory association areas, such as the lateral orbitofrontal cortex, intraparietal areas, and superior temporal areas that were modulated by reward effect, indicating a possible communication might occur for reward effect to modulate the early visual areas. To test this, we conducted an effective connectivity analysis of the fMRI data and observed intra- and cross-modal reward modulation followed a distinct pathway, where intra-modal reward-associated cues relied on the attention-related areas to modulate the early visual areas, while cross-modal reward-associated cues relied on both attention-related and sensory association areas. Interestingly, we observed further dissociation between the two modes of reward cueing on the direction of reward modulation at the communication between the early visual areas to the attentional or sensory association areas in intra- and cross-modal conditions, respectively.

Furthermore, to answer the third objective, we conducted the **third study (chapter 4),** where we compared reward effects and its modulation of early visual areas when reward was cued through unisensory or multisensory stimuli using neuroimaging methods. We expected that reward effects would be integrated similarly as sensory information, as previous studies demonstrated a reward modulation occurring at the earliest stage of sensory processing. To compare the integration of reward effects and sensory, we employed the parameter as stated in the multisensory integration, where the behavioral and neural response of multisensory reward cues should be more than the sum of the reward effects from the unisensory cues. Behaviorally, we found that reward effects did not differ between uni- or multisensory cues, indicating that reward mechanism followed the same principle irrespective of the sensory configuration of the cues. In contrast, sensory processing showed a distinct modulation depending on the configuration of the stimuli, indexed by the multisensory integration, where the responses of multisensory cues exceeded the sum of the unisensory cues. Our neuroimaging results, based on the univariate analysis of fMRI data, supported these findings. We found distinct areas that were modulated by reward and multisensory integration, ruling out an early integration model.

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Chapter 2: Value-driven modulation of visual perception by visual and auditory reward cues: the role of performance-contingent delivery of reward

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2.1 Abstract

Perception is modulated by reward value, an effect elicited not only by stimuli that are predictive of performance-contingent delivery of reward (PC) but also by stimuli that were previously rewarded (PR). PC and PR cues may engage different mechanisms relying on goal-driven versus stimulus-driven prioritization of high value stimuli, respectively. However, these two modes of reward modulation have not been systematically compared against each other. This study employed a behavioral paradigm where participants' visual orientation discrimination was tested in the presence of task-irrelevant visual or auditory reward cues. In the first phase (PC), correct performance led to a high or low monetary reward dependent on the identity of visual or auditory cues. In the subsequent phase (PR), visual or auditory cues were not followed by reward delivery anymore. We hypothesized that PC cues have a stronger modulatory effect on visual discrimination and pupil responses compared to PR cues. We found an overall larger task-evoked pupil dilation in PC compared to PR phase. Whereas PC and PR cues both increased the accuracy of visual discrimination, value-driven acceleration of reaction times and pupillary responses only occurred for PC cues. The modulation of pupil size by high reward PC cues was strongly correlated with the modulation of a combined measure of speed and accuracy. These results indicate that although value-driven modulation of perception can occur even when reward delivery is halted, stronger goal-driven control elicited by performance-contingent reward cues additionally results in a more efficient balance between accuracy and speed of perceptual choices.

Keywords: visual perception, reward, pupil response, sensory modality

2.2 Introduction

Stimuli associated with rewards have a strong influence on our behavior as they trigger the expectation of desirable outcomes, thereby driving agents to optimize their goal-directed actions (Schultz, 2015) and value-based choices (Delgado, 2007; Wallis, 2007; Schultz, 2015). Accordingly, brain areas underlying action planning and value-based decisions are strongly modulated by rewards. Moreover, reward effects even extend to the earliest stages of information processing in the brain as reward associations of stimuli influence their representation in the primary sensory areas (Shuler & Bear, 2006; Serences, 2008). Understanding the underlying mechanisms of value-driven modulation of perception is important since it allows a better understanding of how experience-related and contextual factors in general influence sensory perception (Pessoa and Engelmann, 2010; Seriès and Seitz, 2013).

Reward effects on perception are typically investigated using paradigms where correct detection or discrimination in a perceptual task (Engelmann and Pessoa, 2007) or efficient orienting responses in a motor task (Milstein and Dorris, 2007) lead to higher magnitude or probability of rewards. In such scenarios, prioritization of reward cues, through engaging mechanisms such as selective attention or preparation of oculomotor responses, aligns with the goal-driven mechanisms that help agents to maximize their obtained rewards (Chelazzi et al., 2013; Failing and Theeuwes, 2018). Using such tasks, value-driven modulations have been observed at the early stages of sensory processing in the brain. For instance, Weil et al., (2010) provided evidence that rewarding feedbacks improved behavioral performance in a visual discrimination task and also increased the activity in the human primary visual cortex during the discrimination phase following a reward feedback. Another study by Pleger, et al. (2008) also demonstrated that reward facilitated somatosensory judgments. There, high reward cues improved tactile performance and enhanced the hemodynamic response in the primary somatosensory cortex, indicating that reward signals can influence early sensory areas when a decision is based on the sensory features of stimuli. Thus, reward signals, during the delivery of reward or during the presentation of reward-predicting cues, can be propagated not only within the classical reward-related regions, but also to sensory areas, especially when the reward delivery is contingent on the accuracy of sensory judgments (i.e. performance-contingent). One criticism to these designs is that value-driven effects cannot be distinguished from attentional (Maunsell, 2004) or cognitive control mechanisms (Botvinick and Braver, 2015) that are involved in processing of the task-relevant feature of a task. Accordingly, such paradigms do not allow a differentiation between value-driven effects due to voluntary, goal-driven mechanisms from effects due to stimulus-driven and involuntary mechanisms.

Another line of research has shown that value-driven modulation of perception also occurs when reward cues are not the relevant feature of the task or when reward delivery and hence the motivation to strategically optimize performance has been removed. For instance, the delivery of reward in response to a saccadic target in some trials can affect the oculomotor performance in subsequent unrewarded trials when a non-target stimulus contains a similar feature as the rewarded target in the past (Hickey and van Zoest, 2012). It has also been shown that reward effects outlast the delivery of reward so that previously rewarded features automatically affect participants’ performance (Yantis et al., 2012; De Tommaso et al., 2017). The latter experiments typically employ a two-phase paradigm (De Tommaso and Turatto, 2021), where in the first training or conditioning phase participants learn the association of stimulus features with certain amount or probability of reward, and in the subsequent test phase previously rewarded cues are presented without the actual delivery of reward (i.e. during extinction). Although during the test phase reward associated cues are not reinforced anymore, it has consistently been shown that they can still involuntarily capture participants’ attention, a phenomenon called value-driven attentional capture (VDAC) (Anderson et al., 2011), and thereby influence perceptual judgments across a variety of tasks (Anderson et al., 2011; Yantis et al., 2012; Camara et al., 2013; Failing and Theeuwes, 2015; Bucker and Theeuwes, 2017; Tankelevitch et al., 2020). The typical finding of these studies is that when previously rewarded stimuli are the same as the target of a task they facilitate performance (accuracy or RT) but importantly when they are irrelevant to the task or assigned to distractors, they can impair performance (Anderson et al., 2014; Asutay and Västfjäll, 2016; Gong et al., 2017; Bucker and Theeuwes, 2018; Qin et al., 2020; Watson et al., 2020), a so-called value-driven distraction (Rusz et al., 2020). Such effects likely arise as a result of the enhanced representation of distractors in visual cortex (Itthipuripat et al., 2019), which limit the processing resources that are available to the target.

Interestingly, it is not always the case that task-irrelevant reward cues capture attention away from the target and suppress performance. For instance, Pooresmaeili et al. (2014) utilized one sensory modality (audition) to signal the reward value while keeping the target of the task in another modality (vision). Using this design, it was shown that task-irrelevant auditory cues that were previously associated with high reward enhanced the visual sensitivity compared to low reward cues. A follow-up study (Vakhrushev et al., 2021) used a similar design and compared task-irrelevant reward cues from the same (vision) or different (audition) sensory modality in terms of their effect on perceptual decisions made about a visual target. In this study, it was found that previously rewarded auditory and visual cues had distinct effects on behavioral and electrophysiological correlates of visual perception, suggesting that reward-driven modulations may have dependencies on the sensory modality of task-irrelevant stimuli.

Overall, across different paradigms employed to investigate the effects of reward on sensory perception, performance-contingent rewards have been often found to be associated with the facilitation of sensory processing, whereas divergent effects were observed for cues previously associated with rewards based on whether the target or the task-irrelevant distractors contained a rewarded feature. Another factor that also seems to weigh in is where the reward information was signaled from, with different effects for rewards cued intra-modally or cross-modally. However, a systematic investigation of these factors where the same perceptual judgement is tested under different modes of reward delivery and cuing has been missing. Therefore, in the current study, we designed a paradigm that tested the effect of three factors on visual perception: reward magnitude, sensory modalities of reward cues, and the contingency of reward delivery on task performance. Specifically, a similar design as two previous studies from our lab (Pooresmaeili et al., 2014; Vakhrushev et al., 2021) was used where auditory or visual cues were first associated with either high or low monetary reward during a training phase (referred to as conditioning). During the test phase, auditory and visual cues were presented at the same time as the target of a visual discrimination task but did not carry any information about the task at hand (i.e., orientation discrimination). Importantly, participants either obtained rewards upon correct responses or did not receive any reward feedback in any condition. In the first case, participants' rewards depended on the identity of auditory or visual stimuli and these cues were *performance-contingent* predictors of rewards (PC), whereas in the second case auditory and visual stimuli were *previously associated with rewards* (PR) and did not predict the delivery of reward anymore. We hypothesized the two modes of reward cuing are linked to distinct processes: goal-driven (voluntary) and stimulus-driven (involuntary) attention. In result, when the cues were performance-contingent, the voluntary control would dominate and therefore the cues would benefit performance. However, when the cues were associated with rewards in the past and did not lead to reward feedbacks during the test phase, they would only involve the involuntary capture of attention and lead to weaker reward-driven modulations, which may differ between the intra- and cross-modal rewards. Pupil responses can be used as a sensitive readout of changes in the motivational state due to salient events (Chiew and Braver, 2013; Schneider et al., 2018; Pietrock et al., 2019), even when such events are not consciously detected (Bijleveld et al., 2009). Pupil responses have also been recently linked to the level of cognitive effort exerted in a task (van der Wel and van Steenbergen, 2018). We therefore hypothesized that performance-contingent reward cues are associated with higher goal-directed cognitive effort in prospect of higher rewards, hence producing a stronger value-driven modulation of pupillary responses compared to cues that were previously associated with rewards.

Our results demonstrate that reward associated cues enhance the accuracy of visual discrimination irrespective of the sensory modality and whether the reward delivery was continued (PC) or halted (PR). Additionally, performance-contingent reward cues (PC) energized behavior, as indexed by reaction times and pupil responses, an effect that was absent in previously rewarded cues.

2.3 Materials and Methods

2.3.1 Participants

43 subjects participated in the experiment to fulfil a target sample size of N=36 based on a previous study(Vakhrushev et al., 2021). They were invited via an online recruiting system (http://www.probanden.eni-g.de/orsee/public/). All participants were naïve to the hypothesis of the project, had no history of neurophysiological or psychiatric disorders according to a self-report, had normal or corrected-to-normal vision, and performed the key presses during the task with their dominant hands (5 left handed). Eight participants were removed from the final sample, as due to technical problems the experiment had to be terminated before the complete dataset was collected (N = 4), the psychometric method used to estimate the orientation discrimination thresholds did not converge on a reliable value (N = 2, based on our previous work the QUEST method needed to converge on a stimulus orientation < 2° and performance during the baseline phase needed to be < 90%), the participant did not learn the reward associations (N = 1) or had a strong bias for one of the colors or sounds prior to learning the reward associations (N = 1, estimated as a bias towards high reward colors or sounds > 2.5 SD of the group mean). Thus, the final sample comprised data from 35 participants (18 female; age: 18-45, 27 ± 5 SD years).

Participants were informed that after the experiment they would obtain a reward comprising a fixed hourly rate (~ 8 Euros per hours) plus an added bonus that depended on their performance. To calculate the total reward, the fixed hourly rate was added to the money participants obtained during the experiment and a fraction of the total amount (4%) was handed over to the participants in cash.

Before the experiment started and after all procedures were explained, participants gave their oral and written consent. The study was approved by the local ethics committee of the "Universitätsmedizin Göttingen" (UMG), under the proposal number 15/7/15.

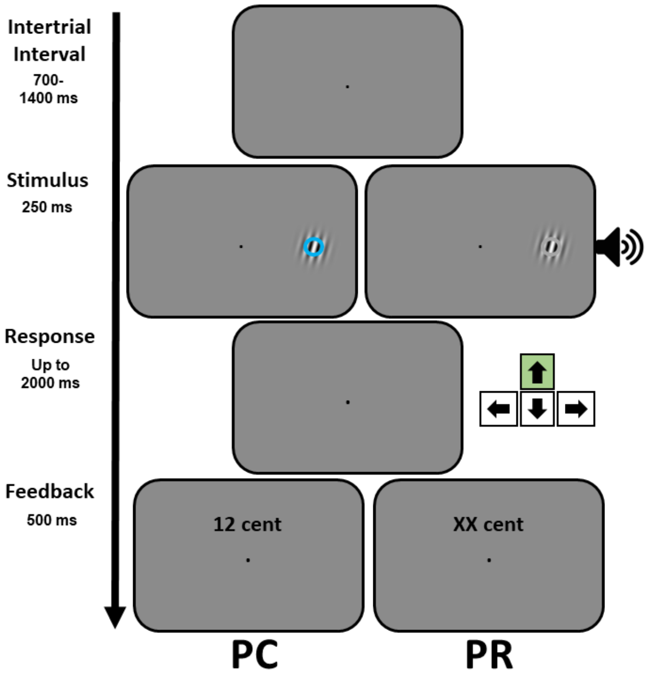

Figure 3. Behavioral paradigm employed during the test phase. An example trial of the visual discrimination task, illustrating the Gabor target and the task-irrelevant visual (left) or auditory (right) stimuli, is shown. Participants reported the orientation of the Gabor target by pressing either the up or down arrow keys (the correct response for the example trial is illustrated symbolically by the arrow in the green box). Prior to the test phase, participants learned to associate different visual (blue or orange circles) or auditory (high or low pitch tones) stimuli, counter-balanced across participants, with different reward magnitudes during a conditioning phase (see **Figure S1**). The test phase comprised two parts with different reward contingencies (PC and PR). In case of a correct response, during the performance-contingent reward (PC) phase, the monetary reward associated with a specific stimulus was displayed (for instance 12 cent). In a subsequent phase, previously reward-associated (PR) stimuli were not predictive of reward delivery, but to keep the layout of the feedback display similar across the two phases the letters XX were shown for all conditions.

2.3.2 Stimulus presentation and apparatus

The behavioural paradigms used during the reward associative learning (conditioning) and test phase were identical to a previous study (Vakhrushev et al., 2021). The paradigm employed during the conditioning was a spatial localization task (see Figure S1 and the Experimental procedures) where participants reported the side (left or right) from which visual or auditory stimuli were presented. During the test phase, a visual orientation discrimination task was used in which the tilt direction of a Gabor patch (a Gaussian-windowed sinusoidal grating with SD = 0.33°, a spatial frequency of 3 cycles per degree, subtending 2° diameter, displayed at 9° eccentricity to the left or right side of the fixation point) had to be reported (**Figure 1**). The tilt orientation of the Gabor patch was set to each participant's perceptual threshold estimated after the initial training. To determine this threshold, we employed a QUEST algorithm (Watson and Pelli, 1983) to estimate the Gabor tilt orientation for which participants' performance was at 70%. In each trial, a task-irrelevant semi-transparent ring (alpha 50%, 0.44° in diameter) was superimposed on the Gabor patch. The color of the rings (orange or blue for visual conditions, or grey for auditory and neutral conditions) was adjusted individually for each participant in such a way that they were perceptually isoluminant. Perceptual thresholds for the visual discrimination task were determined when Gabors were superimposed with a grey circle. For auditory cues, two pure tones with different frequencies (350 Hz or 1050 Hz) were presented at 70 dB simultaneously with the Gabor patch and at the same side.

The timing of events was identical across the experiment (see **Figure 1** and **Figure S1**). As soon as participants fixated (within 1° of the fixation point) a trial started. After an additional fixation period of 700-1400 ms, a target stimulus appeared (either a colored circle or a tone during conditioning or a Gabor patch together with a colored circle or a tone during the test phase). The target stimulus disappeared after 250 ms and participants had to indicate its side (conditioning) or the orientation of the Gabor patch (during the test phase) within 2000 ms from the onset of the target. Finally, a feedback display was presented for 500 ms. The feedback display contained the reward magnitude that participants received (in numbers) during conditioning and performance-contingent phase (see the Experimental procedures). To keep the visual layout of the feedback display similar across PC and PR phases, in the latter phase "xx cent" was shown for all conditions.

Throughout the experiment, visual stimuli were displayed on a calibrated ViewPixx monitor (refresh rate = 120 Hz, resolution 1080x1920 pixels, and placed at a viewing distance of 60 cm). The auditory tones were delivered through an over-ear headphone (HAD 280 audiometry headphones, Sennheiser).

2.3.3 Experimental procedure

The experiment consisted of a practice session (32 trials) for the orientation discrimination task and three phases. In the first phase, referred to as the *baseline phase* (160 trials), participants were required to report the tilt direction of a Gabor patch relative to the horizontal meridian by pressing a keyboard button (either the down or up arrow keyboard button for clockwise and counter-clockwise directions, respectively; see **Figure 1**). They were additionally instructed to ignore the simultaneously presented visual or auditory cues that accompanied the Gabor. Afterwards, participants completed a *conditioning* task to learn the reward associations of auditory and visual cues (see **Figure S1**). In this task, participants decided whether a colored circle or an auditory tone was perceived to be on the left or right side by pressing the corresponding arrow key buttons. Upon correct response, participants saw the magnitude of the reward that was paired with a certain cue and thereby learned whether a visual or auditory stimulus was associated with high (mean = 25 Cents) or low (mean = 2 Cents, drawn from a Poisson distribution) monetary reward. In the third phase, referred as the *test phase*, participants performed the same orientation discrimination task as in the baseline phase, but in the presence of task-irrelevant visual or auditory cues that had been associated with different amounts of reward during conditioning. As the main task was a visual discrimination task, task-irrelevant visual and auditory stimuli will be referred to as intra- and cross-modal, respectively. Additionally, the test phase was split into two parts: in the first part (320 trials, the phase with *performance-contingent reward cues*, *PC*), upon correct response, similar reward feedbacks as in the conditioning phase were presented, i.e. reward depended on the identity of cues and was either high or low. In the second part (320 trials, referred to as the phase with *previously associated reward cues, PR*), the delivery of rewards was halted. Here, participants were instructed similarly to the performance-contingent phase with the exception that they were informed about a different feedback display shown after each trial. Specifically, they were told that in the PR phase the differential reward deliveries would be halted and instead after each trial they would see a feedback in the form of “xx cent” indicating a constant amount of reward that would be added to their total earning in case they responded correctly.

In order to determine whether participants learned the reward-cue association, they were asked to indicate which cue from each modality presented to them sequentially had been associated with more money. This question was completed in multiple parts following the conditioning, performance-contingent, and previously rewarded phases. Additionally, we also repeated the question in the questionnaire after the experiment was completed. If a participant did not provide any correct response across all experimental phases (*conditioning*, PC, and PR), then the participant was removed from further analysis (N = 1).

2.3.4 Pupillometry

An EyeLink 1000 Plus system with a desktop mount (SR Research) was used to track the right eye. The EyeLink camera was controlled by the corresponding toolbox in MATLAB (Cornelissen, et al., 2002). Before each block, the eye tracking system was calibrated using a 9-point standard EyeLink calibration procedure.

Pupil responses were acquired at a sampling frequency of 1000 Hz. The pupil data of each trial was extracted from 100 ms prior to the target onset until the end of the trial (i.e. the end of the feedback display). Trials in which more than 50% of data was lost were removed from further analysis. For the missing data due to blinks, a linear interpolation was applied, where the missing data was interpolated based on the samples within a window of 10 ms before and after the blink. The data was then low-pass filtered (fourth order Butterworth with a cut-off frequency of 2 Hz), normalized to z-score (across all samples recorded for each participant) and subsequently corrected for baseline (i.e. 100 ms). For the statistical analysis, the average stimulus-evoked response in a window from the target onset until the end of each trial (the end of the feedback display as shown in **Figure 1**) was examined. Note that a trial's timing depended on how fast the participant responded. Therefore, to examine the relation between the pupil size and the behavioural measures, pupil responses were estimated from the data of the first 500 ms interval after the target onset. This was done to ensure that for all participants and all experimental conditions the same number of pupil samples were considered.

2.3.5 Data analysis

The data obtained from all parts of the experiment was analyzed using custom-written scripts in MATLAB (version R2015a). We analyzed accuracies, reaction times (RT: median reaction time across correct and incorrect trials), inverse efficiency scores (median RT of correct trials divided by the accuracy) d-prime (d') and pupil size. We removed trials in which any of the following conditions were met: lack of stable fixation during the presentation of the target (i.e. the distance of eye gaze from the fixation point exceeded 0.9°), no response, reaction times exceeding the 2.5 SD of each phase, or loss of more than 50% of pupil data. This resulted in 2.98% (±1.20 SD), 2.62% (±2.25 SD), 3.01% (±1.04 SD), and 3.64% (±2.97 SD) trials removed from baseline, conditioning, performance-contingent and previously rewarded phases, respectively. For each response variable, we calculated the average across all trials of each condition per subject during the baseline and test phases separately. D-prime was measured based on the probability of hits and false-alarms, as $d' = Z(PHit) - Z(PFA)$, where one of the tilt directions was arbitrarily treated as “target-present” as in formal Signal Detection Theory analysis of discrimination tasks (Macmillan and Creelman, 1991). Extreme values of PHit or PFA were slightly up- or down-adjusted (i.e., a probability equal to 0 or 1 was adjusted by adding or subtracting $\frac{1}{2 \times N}$, where N is the number of trials, respectively). Afterwards, the difference in response variables (accuracies, reaction times, d’ and pupil size) between baseline and test phase was entered to a 2x2x2 repeated measures ANOVA, with the reward contingency (performance-contingent: PC and previously associated: PR), reward magnitude (high and low), and sensory modality (visual or auditory, i.e., intra- and cross-modal, respectively) as within-subjects factors. Significant effects in RM ANOVA were followed up by post-hoc tests (*multcompare* in MATLAB with *Bonferroni* correction). To test whether the value-driven modulation of pupil size is predictive of the modulation of the behavioral measures a robust regression method (*robustfit* with default settings in MATLAB) was employed.

2.4 Results

The main objective of this study was to examine whether visual discrimination is influenced by co-occurring visual and auditory stimuli which did not carry any information about the dimension over which the discrimination was performed (i.e. the orientation of a Gabor stimulus, see Figure 1) but were either predictive of the reward delivery upon correct performance (i.e. performance-contingent: PC phase) or were previously associated with the reward delivery (i.e. previously rewarded: PR phase). Participants first learned the reward associations of visual and auditory stimuli during a conditioning phase by performing a localization task (see the Supplementary Information and **Figure S1**). We found a weak effect of reward on the behavioural performance and pupil responses (see the Supplementary Information and **Figure S2**) during the conditioning phase. Nevertheless, the conditioning task was successful in establishing the associations between stimuli and rewards, as according to the debriefings performed after this phase, all participants had learned the reward associations of tones and colors correctly. Therefore, we next examined the behavioral and pupillometric responses during the visual discrimination task, testing whether the learned reward associations affected the visual perception during the PC and PR phases compared to the baseline (i.e. done prior to the conditioning).

2.4.1 Effect of performance-contingent and previously associated reward cues on the accuracy of visual discrimination

Overall, during the initial baseline phase where the cues were not associated with any reward magnitude, participants performed on average across all conditions with 78.78% accuracy (± 0.94 s.e.m) (Figure 2A-B), while in the performance-contingent phase (PC), mean accuracy increased to 79.44% (± 1.23 s.e.m) and in the last phase with previously rewarded cues (PR) increased to 80.06% (± 1.32 s.e.m). This indicated that with time, participants became more proficient in the task. However, the improvement of accuracy across time (Baseline, PC and PR) did not reach statistical significance ($F(2,34) = 1.04$, $p = 0.35$, $\eta_p^2 = 0.03$).

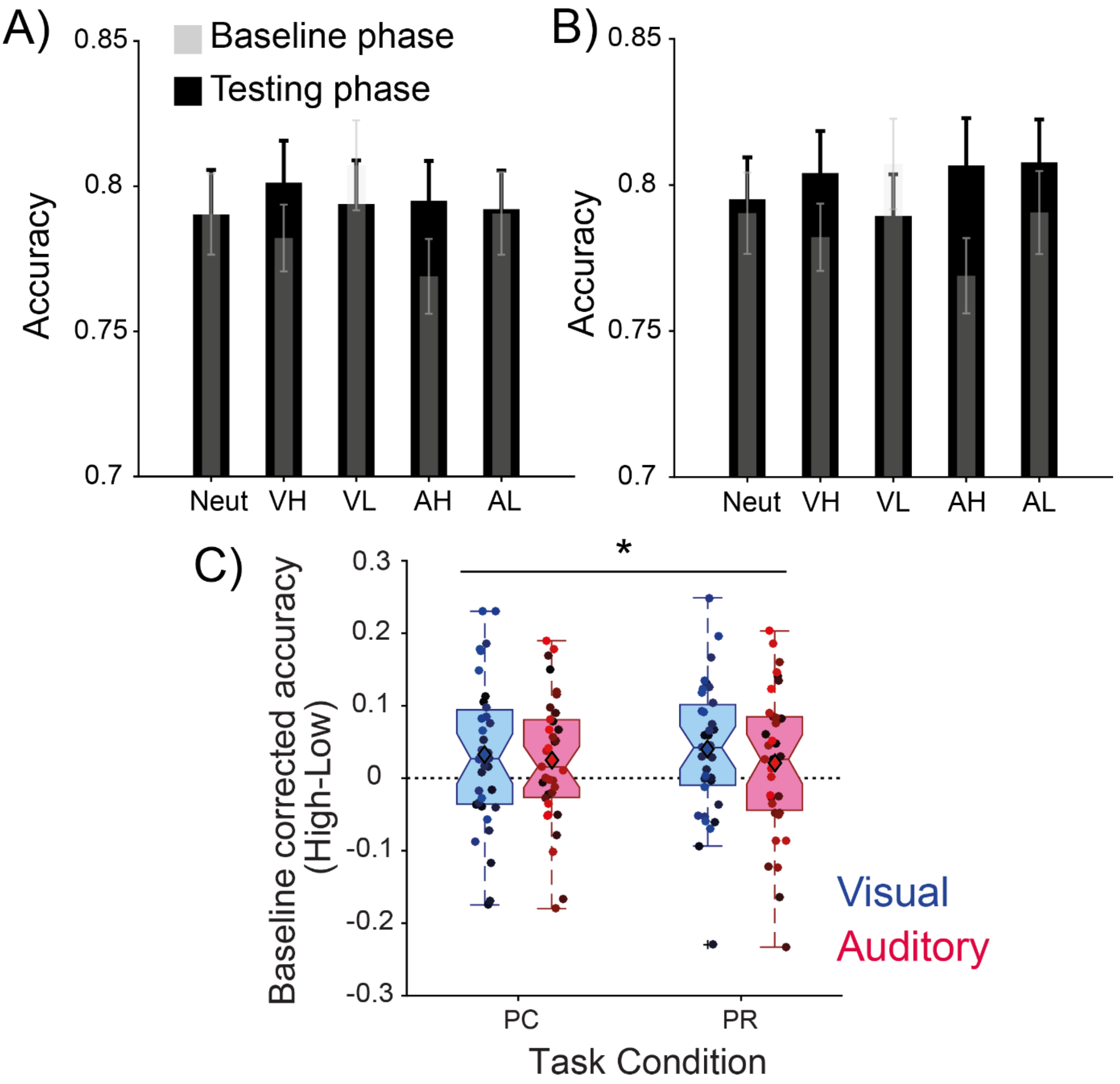

Figure 2. Value-driven modulation of discrimination accuracy. **A)** Accuracies of the baseline and performance-contingent reward (PC) phase. **B)** Same as A for the previously associated rewards (PR) phase. The transparent grey shades represent the baseline performance before learning the reward associations, overlaid on the test phase performance in black for each condition (neut: neutral, VH: visual high-, VL: visual low-, AH: auditory high-, and AL: auditory low-reward). **C)** Baseline -corrected reward effect (high – low) for intra-modal (visual) and cross-modal (auditory) reward cues during the two phases. Error bars in A and B represent s.e.m., circles with different

color shades in C correspond to the data of individual participants, and * stands for the main effect of reward at p < .05.

In the test phase, a repeated measures 2 x 2 x 2 ANOVA conducted on the baseline corrected accuracy rates showed a significant main effect of reward magnitude across PC and PR phases (**Figure 2C**): F(1,34) = 7.37, $p = 0.01$, $\eta_p^2 = 0.18$. All other main and interaction effects were non-significant (all *p*s>0.1). Post-hoc tests revealed a significant increase in accuracies by high- compared to low-reward visual cues in PR ($p = 0.016$, Cohen's d = 0.430), a trend in PC ($p = 0.068$, Cohen's d = 0.319) and non-significant effects in auditory conditions (PC: $p = 0.108$, Cohen's d = 0.279; and PR: $p = 0.235$, Cohen's d = 0.204). We obtained similar results when d-prime (d') scores instead of accuracies were used (F(1,34) = 6.75, $p = 0.01$, $\eta_p^2 = 0.17$), indicating that the improvement in participants' performance was not driven by an enhanced false-alarm rate.

The main effect of reward is in line with our hypothesis predicting that high-reward cues improve the perceptual discriminability. Contrary to our predictions, we did not find a significant interaction effect with reward contingency or sensory modality, although the effect sizes were larger for intra-modal (visual) cues.

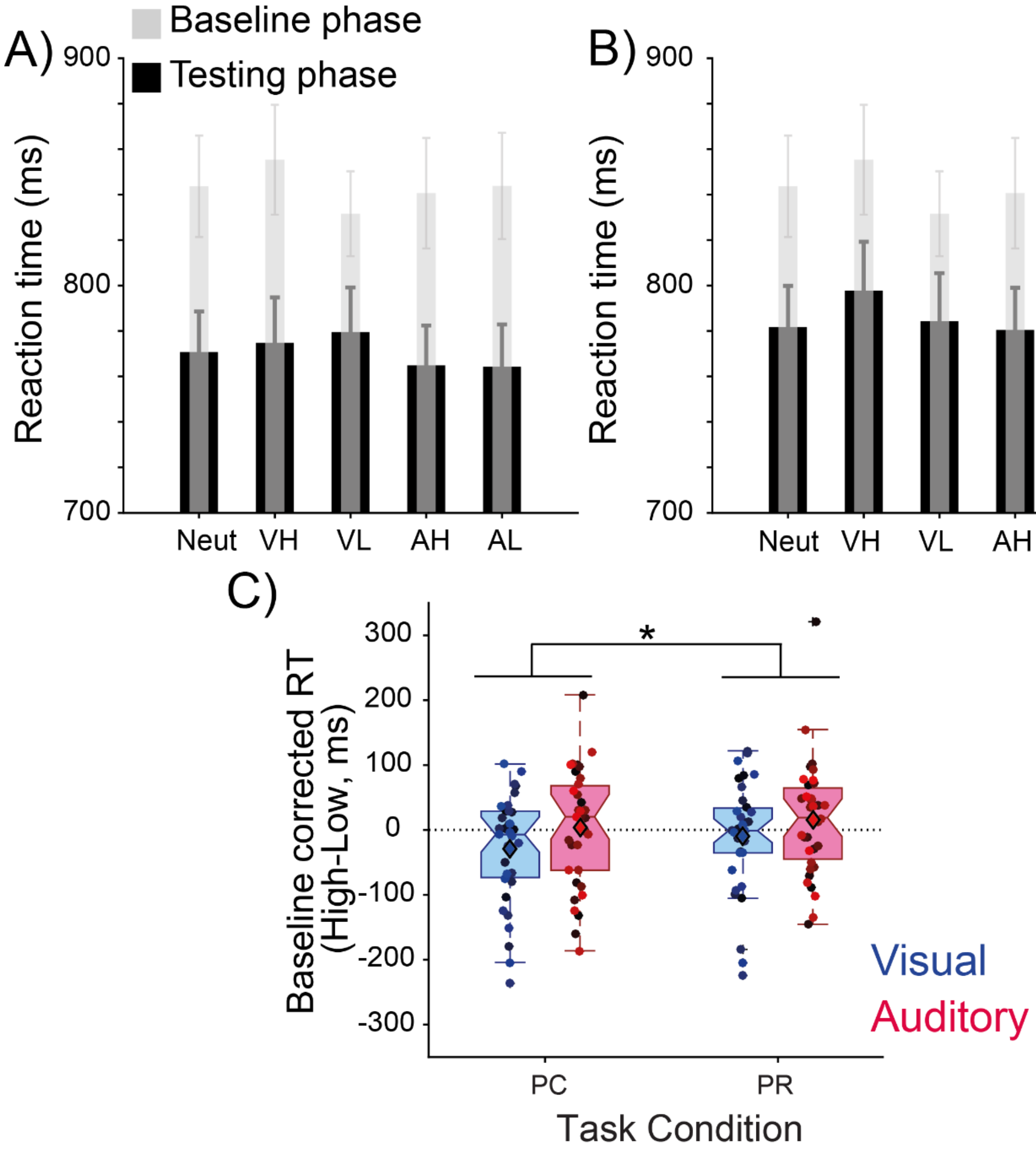

Figure 3. Value-driven modulation of discrimination speed. **A)** Reaction times (ms) of the baseline and performance-contingent reward (PC) phase. **B)** same as A for the previously associated rewards (PR) phase. The transparent grey shades represent the baseline reaction times before learning the reward associations, overlaid on the test phase performance in black for each condition (neut: neutral, VH: visual high-, VL: visual low-, AH: auditory high-, and AL: auditory low-reward). **C)** Baseline -corrected reward effect (high – low) for intra-modal (visual) and cross-modal (auditory) reward cues during the two phases. Error bars in A and B represent s.e.m., circles with different color shades in C correspond to the data of individual participants, and * stands for the interaction effect between reward and task phase at p < .05.

2.4.2 Effect of performance-contingent and previously associated reward cues on the speed of visual discrimination

The analysis of reaction times (RTs) across all conditions demonstrated that participants became overall faster as they proceeded through the experiment (**Figure 3A-B**), an effect that reached statistical significance when tested with an ANOVA with phase (Baseline, PC and PR) as the independent factor (F(2,34) = 21.39, $p < 10^{-7}$, $\eta_p^2 = 0.39$). Participants' RTs in both PC

(M = 770.83 ms, s.e.m = 18.24 ms) and PR phases (M = 782.41 ms, s.e.m = 18.93 ms) were significantly faster than the baseline phase (M = 843.01 ms, s.e.m = 21.33 ms, both *p*s$<10^{-4}$).

A repeated measures 2 x 2 x 2 ANOVA on the baseline corrected reaction times revealed a significant interaction between reward magnitude and task contingency (F(1,34) = 4.61, p = 0.039, $\eta_p^2 = 0.12$, Figure 3C). This effect demonstrates that when cues associated with higher value were predictive of the reward delivery, participants reacted faster than when reward delivery was halted. Specifically, post-hoc tests revealed that this effect was more pronounced for performance-contingent, high-reward visual cues (p = 0.048, Cohen's d = 0.33) than other conditions (visual/PR: p = 0.47, Cohen's d = 0.123; auditory/PR: p = 0.30, Cohen's d = 0.178; auditory/PC*:* p = 0.80, Cohen's d = 0.043). Although mostly driven by the visual cues, this finding is in line with our hypothesis predicting that performance-contingent rewards have a stronger influence on the speed of perceptual decisions.

2.4.3 Effect of performance-contingent and previously associated reward cues on pupil responses

We next examined the pupil responses using a 2 x 2 x 2 repeated measure ANOVA with three factors: reward magnitude (high and low), sensory modality (auditory and visual), and reward contingency (performance-contingent: PC and previously associated: PR). Pupil responses were the baseline corrected average pupil size (z-score) extracted from the target onset until the trial end (**Figure 4**). Across all visual and auditory conditions, task-evoked pupil responses were significantly higher in PC compared to PR phase (F(1,34) = 61.32, $p < 10^{-8}$, $\eta_p^2 = 0.643$). Additionally, a significant interaction effect was observed between the reward magnitude and contingency (F(1,34) = 7.17, p = 0.011, $\eta_p^2 = 0.174$), as higher rewards increased the pupil size compared to lower rewards only in PC (p = 0.04, Cohen's d = 0.354) but not in PR phase (p = 0.94, Cohen's d = 0.014). A weaker interaction effect (F(1,34) = 4.80, p = 0.035, $\eta_p^2 = 0.124$) was also observed between the sensory modality and reward contingency, corresponding to larger pupil responses evoked by cross-modal (auditory) compared to intra-modal (visual) stimuli in PC phase and an opposite effect in PR phase. The effect of sensory modality in each phase did not reach significance (PC: auditory-visual = 0.02 ± 0.02 s.e.m, p = 0.31; PR: auditory-visual = -0.01 ± 0.02 p = 0.34, p = 0.34).

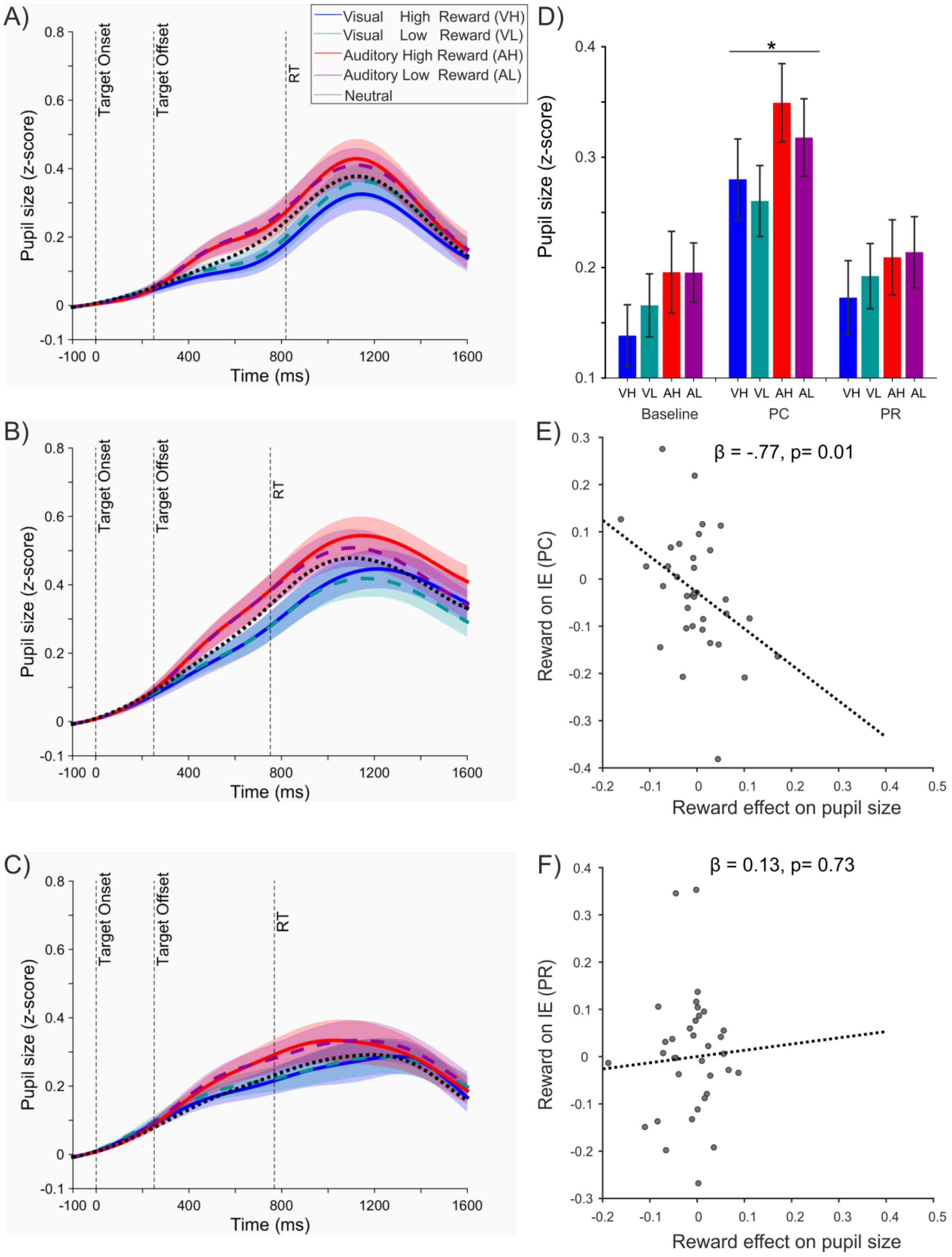

Figure 4. **A)** Time course of pupil response for each condition during the baseline phase **B)** same as A during the performance-contingent phase (PC). **C)** Same as A during the previously associated rewards (PR). In A-C the vertical dashed line denoted as RT shows the mean reaction time across all conditions and across all participants. **D)** Bar plots represent the mean task-evoked pupil size measured from the target onset until the trial end (i.e. the end of feedback phase, see Figure 1) for each condition (VH: visual high-, VL: visual low-, AH: auditory high-, and AL: auditory low-reward. **E)** Relation of the value-driven modulation of pupil size (in the first 500 ms after the target onset) and inverse efficiency scores during the PC phase. **F)** Same as E during the PR phase. In E and F regression lines are estimated based on a robust regression analysis.

The lack of reward-driven effects in the PR phase could be due to a time-dependent habituation of pupil responses to reward rather than the termination of reward delivery, since the previously rewarded (PR) phase consistently occurred after the performance-contingent (PC) phase. However, we ruled out this possibility by examining the pupil responses of the first and second half of each phase (see the Supplementary Information and Figure S3).

We next examined whether the value-driven modulation of pupil responses observed in the performance-contingent (PC) phase exhibited any correlation with the modulation of our behavioural measures. Since we observed both a modulation of accuracy (**Figure 2**) and RTs (**Figure 3**), we combined these measures into one single parameter, i.e. inverse efficiency score (IE) defined as the ratio of reaction times of correct trials to accuracy (Vandierendonck, 2021). This parameter provides a measure of how well participants adjust their speed-accuracy trade-off. We found a strong linear relation ($\beta = -0.77$, $t_{33} = -2.59$, $p = 0.01$, **Figure 4E**) between the net effect of reward on pupil size (i.e. pupil size in high reward condition of both modalities minus pupil size in low reward of both modalities) and on IE scores. This effect indicates that a stronger value-driven pupil dilation was predictive of a stronger value-driven acceleration of visual discrimination across participants. This correlation was non-existent in the PR phase ($\beta = 0.13$, $t_{33} = 0.35$, $p = 0.73$, Figure 4F).

2.5 Discussion

This study aimed to compare performance-contingent (PC) and previously associated (PR) reward cues from visual or auditory modality in terms of their modulatory effects on visual perception and task-evoked pupil responses. Our results showed that reward associated cues exert a persistent effect, in that once the reward associations are learned, reward cues improved the accuracy of perceptual judgments even when rewards were not delivered anymore (i.e. during the PR phase). Performance-contingent cues (PC) were overall associated with larger task-evoked pupil responses indicating that they invoke more engagement with the task and higher goal-driven control. Furthermore, in contrast to PR, PC cues especially in visual modality, also sped up perceptual choices when a higher reward was expected and this effect was correlated with the value-driven modulation of pupil responses. These results suggest that despite the persistent effects of reward even when reward delivery is halted, some aspects of value-driven effects are specific to performance-contingent cues.

Previous research has provided evidence for a value-driven modulation of perception when the task-relevant features of stimuli are associated with high reward (Chelazzi et al., 2013; Pessoa, 2015; Failing and Theeuwes, 2018), an effect that also persists when the reward delivery is halted (De Tommaso et al., 2017). Conversely, it has been shown that the association of task-irrelevant stimuli with rewards inflicts a cost on performance, likely due to capturing attention away from the target and exhausting the cognitive control mechanisms (Sali et al., 2013; Anderson et al., 2014; Rusz et al., 2020; Watson et al., 2020). Although the majority of past research has focused on visual modality, recent studies have also examined the cross-modal effects of rewards (Leo and Noppeney, 2014; Pooresmaeili et al., 2014). Interestingly, the latter studies showed that cross-modal (auditory) stimuli that have been previously associated with higher rewards facilitated visual perception compared to low reward stimuli, despite being irrelevant to the task at hand. These findings suggest that the value-driven increase in the salience of task-irrelevant stimuli is not necessarily associated with costs on performance. What determines whether rewards boost or impair perception in light of findings of the current study and the past research?

To understand the divergent effects observed across studies and thereby provide a unifying explanation for reward effects on perception, it is important to point to differences in the design and experimental procedures that were employed. There is a critical difference between the current study and previous studies showing that task-irrelevant reward cues captured attention away from the target and were thus associated with a cost on performance (Sali et al., 2013; Anderson et al., 2014; Rusz et al., 2020; Watson et al., 2020). In those previous studies, the majority of which employed a visual search paradigm, the target and the reward associated task-irrelevant stimuli were spatially separated. This separation might be the factor explaining the capture of attention to a different location than the target by reward cues, thereby competing with the task goal. In our study however, both target and task-irrelevant reward cues were presented at the same spatial location, hence the capture of attention by task-irrelevant high reward cues may have spilled over to the target, increasing its representation and therefore optimizing behavior compared to low reward cues. This is in line with the findings of MacLean & Giesbrecht (2015) showing that when task-irrelevant cues were in the same location as the probed target, cues associated with higher reward magnitude improved visual search performance compared to low reward magnitude. Another related possibility is that higher reward may in fact promote perceptual grouping between the reward- associated cues and the target, as reward has been shown to interact with object-based attention (Shomstein and Johnson, 2013; Stanisor et al., 2013; Zhao et al., 2020). Therefore, in our paradigm high-reward task-irrelevant cues may have enhanced the processing of the target through a combination of space-based and object-based selection mechanisms, especially since during the PC phase these cues were predictive of the reward delivery.

The results of the current study show that previously rewarded stimuli can have long-lasting facilitatory effects on perception. However, we note that PR phase in our experiment was only tested after the PC phase, and therefore participants had a long exposure to the reward cues in a setting when they were predictive of the reward delivery when orientation discrimination task was performed correctly (i.e., the PC phase). In contrast, in our previous work (Vakhrushev et al., 2021), we tested the PR phase only after a conditioning phase which employed a different task (i.e., cue localization) than the test phase (i.e., orientation discrimination), and found that reward effects were most prominent for cross-modal cues. Together, the current results and results of our previous study indicate that the effects of reward critically depend on the training mode (Jahfari and Theeuwes, 2017; Failing and Theeuwes, 2018) and the relation between the rewarded stimuli and the task-relevant features.

Although accuracies were enhanced by high reward cues in both PC and PR phase, speed of visual discrimination was only modulated by rewards in the performance-contingent phase, especially for intra-modal cues. It is important to note that our task instructions encouraged accuracy over speed, as participants received a reward only for correct responses and independent of RT. Therefore, speeding up choices in PC occurred without an explicit instruction for speedy responses or an impact of doing so on reward magnitudes. However, by increasing the speed of choices during the PC phase for high reward cues, participants could increase their total reward rate, i.e. the amount of reward obtained in a given time for a self-paced task, a factor that has been shown to play an important role in perceptual decision making (Gold and Shadlen, 2002). When reward delivery is halted increasing the reward rate is not at stake anymore and hence in PR we did not find a speed enhancement. The motivation to increase speed in high reward PC trials however did not lead to a decrement in accuracy due to speed-accuracy-trade-off, suggesting that the goal-driven control mechanisms invoked by PC cues may increase the overall efficiency of perceptual choices.

Examination of pupil responses provided further evidence that performance-contingent (PC) reward cues invoke a stronger engagement of goal-driven mechanisms, as demonstrated by two key findings. Firstly, we found a stronger task-evoked pupil dilation in PC across all conditions, suggesting that in this phase participants exerted overall higher cognitive effort compared to the previously rewarded (PR) phase. Recruiting higher cognitive effort is known to increase the activity of noradrenergic neurons in Locus Coeruleus (LC) and thereby induce pupil dilation (van der Wel and van Steenbergen, 2018). Accordingly, previous studies have shown that large pupils predict the higher cognitive control required before goal-directed eye movements (Mathôt et al., 2015), reflect the higher effort required for task switching (da Silva Castanheira et al., 2021), and are indicative of the degree to which endogenous orientating of spatial attention is invoked by a task (Lasaponara et al., 2019). Importantly, the degree to which humans engage in a cognitively effortful task depends on the inherent relation between costs and benefits that ensue from performing a task (Shenhav et al., 2021) and whether the cost-benefit relations remain predictable over time (Manohar et al., 2017). In our experiment, the continuous and consistent delivery of reward upon correct performance in PC may have allowed a more direct estimation of how much rewards could compensate for the cost of extra cognitive effort, hence encouraging participants to maintain a sustained heightened level of goal-directed attention across all conditions. Secondly, in addition to the overall heightened dilation of pupils in PC phase, we found that only in this phase value-driven modulation of pupil size was significant, and this effect was predictive of the behavioural speed modulation. Modulation of pupil responses by reward value is in line with a number of previous findings (Chiew and Braver, 2013, 2014; Massar et al., 2016; Koelewijn et al., 2018; Pietrock et al., 2019; Walsh et al., 2019) and indicates that when the delivery of reward is contingent on task performance, higher reward incentives could efficiently mobilize the processing resources, and settle an efficient relationship between the speed and accuracy of choices, effects that are also reflected in the task-evoked pupil dilatation and have been reported across motor (Naber and Murphy, 2020), perceptual (Walsh et al., 2019) and cognitive (Kozunova et al., 2022) tasks. On the other hand, the lack of value-driven modulation of pupil responses for PR cues is in line with effects reported in previous studies, where reward-driven modulations of pupil size were only found during the learning of reward associations (Anderson and Yantis, 2012) but were absent during the test phase when reward-associations were implicit (Hammerschmidt et al., 2018). Taken together, these findings suggest that pupillary responses are not modulated by the mere exposure to the associative value of stimuli, but rather depend on the context in which rewards are delivered (Preuschoff et al., 2011; Cash-Padgett et al., 2018).

In the current study, the previously rewarded (PR) phase consistently occurred after the performance-contingent (PC) phase. Although our results in the PR phase could be directly compared to the previous studies that used a similar design (Vakhrushev et al., 2021), future studies would benefit from counterbalancing the task order across participants to confirm whether the results in each phase and the differences observed between PC and PR phases could be replicated. In fact, comparing our results to those reported previously (Vakhrushev et al., 2021), suggests that the reward-driven effects in the PR phase, especially for intra-modal cues, could be boosted when preceded by a phase when the delivery of rewards is contingent on performance (PC), although this conclusion awaits future replications. In doing so, future studies may also benefit from using a larger sample size, as across experiments the effect sizes that we observed were relatively small. However, we also notice that small effect sizes could be due to the nature of the task we employed, as unlike previous studies, we used reward cues that did not carry information about the target of the visual discrimination task, a scenario when rewards and attentional requirements of the task align and larger reward driven effects are expected. Furthermore, studies on pupillometric correlates of value-driven effects can make use of paradigms in which the timing of events in each trial is tailored to the sluggish nature of pupil responses. Specifically, in our study the trial duration was relatively short (1450 ms - 2150 ms), which might have been insufficient to isolate the sluggish pupil modulations evoked by some of the conditions. This can be achieved by introducing a delay between the target offset and the appearance of the feedback display (see Figure 1) and by prolonging the intertrial intervals (ITI). Another important direction for future studies would be to further investigate which neural mechanisms give rise to the behavioural and pupillary effects that were observed here, through using neuroimaging or electrophysiological methods. This direction is important as it will allow to test whether the stronger involvement of goal-driven control during PC phase occurs through the same mechanisms that underlie attentional and reward-driven selection, namely an enhanced engagement of fronto-parietal attentional regions (Corbetta and Shulman, 2002; Padmala and Pessoa, 2011) or changing the temporal profile of attentional control (Krebs et al., 2013). Moreover, future neuroimaging studies should investigate how the sensory modality of rewards interacts with the value-driven modulations of perception, as intra-modal and cross-modal reward effects may rely on distinct neural mechanisms (Vakhrushev et al., 2021).

In summary, our findings demonstrate a persistent effect of intra- and cross-modal rewards on visual perception. The stronger goal-driven control invoked by performance-contingent rewards and reflected in pupil responses, can additionally enhance the overall efficiency of perceptual choices by increasing the speed without sacrificing the accuracy.

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Authors' contributions

JEA and AP conceptualized the project. JEA, RV and AP designed the task. JEA conducted the experiments. JEA, RV and AP analyzed the data. JEA and AP interpreted the results and wrote the first draft of the manuscript. All authors revised the manuscript. AP acquired funding.

The datasets and analysis scripts will be provided upon request addressed to the corresponding author (AP) and will be stored on Open Science Framework data repository (https://osf.io/).

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2.7 Supplementary Information

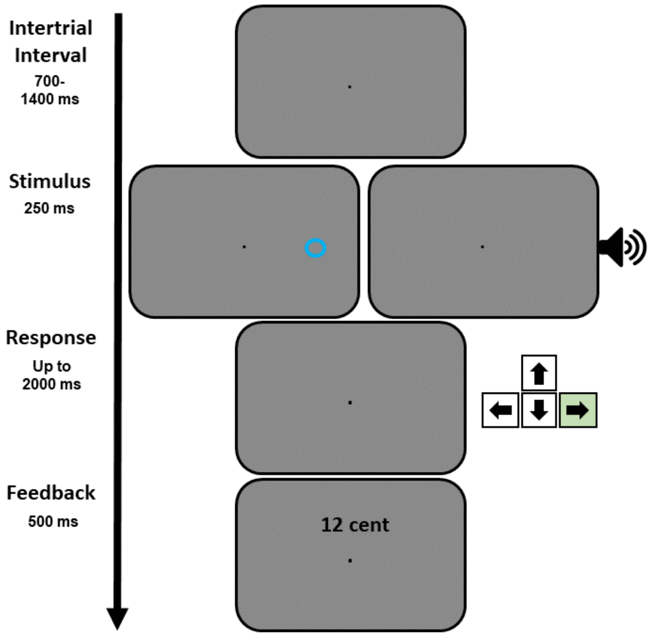

Figure S4. Behavioral paradigm employed during the conditioning phase. Participants were asked to report whether a visual (left) or an auditory (right) stimulus was presented to the left or right side and indicate their responses by pressing the corresponding left or right arrow keys on the keyboard. Here, two example trials are shown in which the stimulus is presented to the right side and hence the correct response was to press the right arrow key (highlighted arrow box in green). In case of a correct response, the monetary reward associated with a specific stimulus was displayed (for instance 12 cent), and thereby participants learned the reward associations of different colors and auditory tones.

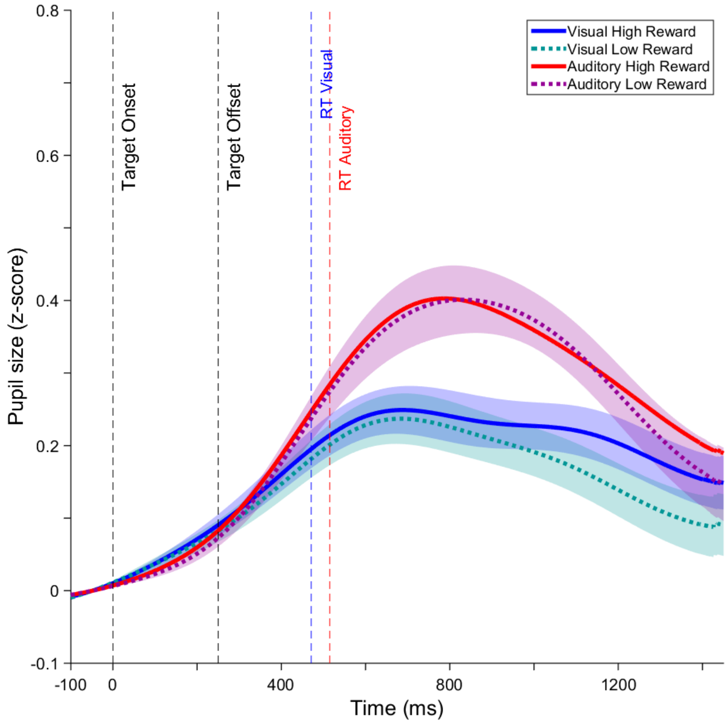

Figure S2. Pupil responses during the conditioning phase. The vertical dashed light in blue shows the mean reaction time across all visual cues across all participants and the red dashed line shows the mean reaction time across all auditory cues across all participants. For more details see the section “Behavioral and pupillometry results during the conditioning” in the Supplementary Text.

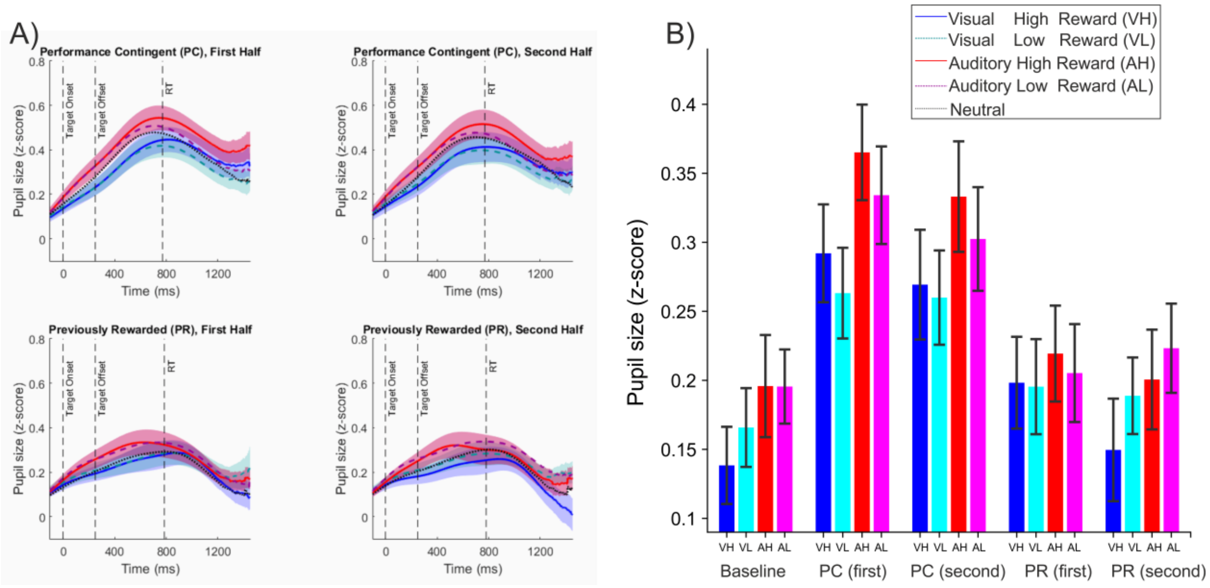

Figure S3. Pupil responses in the first and second half of the performance-contingent (PC) and previously rewarded (PR) phases. A) Time course of pupil responses in the first and second half of PC phase (upper row) and in the first and second half of PR phase (lower row). The vertical dashed line denoted as RT shows the mean RT across all conditions and across all participants. B) Bar plots represent the mean task-evoked pupil size measured from the target onset until the trial end for each condition (VH: visual high-, VL: visual low-, AH: auditory high-, and AL: auditory low-reward) for different phases. The data in PC and PR phases is separately shown for the first and second half of all trials (as in A). For more details see the section “Examining the changes in reward-driven effects on pupil responses with time” in Supplementary Text and Figure 4 in the main text.

2.7.1 Behavioral and pupillometry results during the conditioning

During the conditioning, participants performed a localization task and thereby learned the reward associations of the tones and colors, as each correct response led to a monetary reward that depended on the identity of stimuli (see the Material and Methods and **Figure S1**). Participants’ overall performance in this task was nearly perfect for both modalities (99.75% ± 0.11 s.e.m and 99.53% ± 0.21 s.e.m for visual and auditory stimuli, respectively), with no significant difference between the modalities (F(1,34) < 1), as intended. Additionally, a small but significant main effect of reward value on increasing the localization accuracies (by 0.02% ± 0.17 s.e.m and by 0.61% ± 0.25 s.e.m for high compared to low reward cues in visual and auditory modality, respectively, F(1,34) = 4.43, p = 0.04, η_p^2 = 0.12) and a trend for an interaction with modality (F(1,34) = 3.74, p = 0.06, η_p^2 = 0.10) were found.

Analysis of reaction times (RTs) only revealed a significant main effect of modality (F(1,34) = 40.76, p = 0.28, η_p^2 = 0.55) corresponding to the faster RTs for the localization of visual stimuli compared to the auditory tones (472.22 ms ± 16.80 s.e.m and 517.11 ms ± 16.95 s.e.m, respectively), an effect that is in line with the superior performance of vision for spatial localization (Welch and Warren, 1980). Although in both modalities response times were decreased for high compared to low reward stimuli (-2.34 ms ± 6.48 s.e.m, and -7.60 ms ± 5.14

s.e.m, for the decrease of RTs in visual and auditory high reward cues, respectively), this effect did not reach statistical significance ($F(1,34) = 1.203$, $p = 0.28$, $\eta_p^2 = 0.03$) and no interaction was found between the reward effect and the stimulus modality ($F(1,34) < 1$).

Analysis of pupil size during conditioning (Supplementary **Figure S2**), revealed a main effect of modality ($F(1,34) = 18.23$, $p < 0.001$, $\eta_p^2 = 0.35$) corresponding to a larger pupil size in response to auditory compared to visual stimuli and a smaller main effect of reward ($F(1,34) = 4.43$, $p = 0.046$, $\eta_p^2 = 0.11$). The effect of reward did not reach significance in individual sensory modalities (ps>0.1).

Overall, we found a small effect of rewards on increasing the localization accuracies and increasing the task-evoked pupil responses but no effect on the performance speed (RTs). The lack of a behavioural effect of rewards on RTs during the conditioning is likely due to the fact that the localization of visual and auditory stimuli was done as a nearly perfect level.

2.7.2 Examining the time-dependence of reward-driven effects on the pupil responses

We observed a significant reward-driven enhancement of pupil responses only during the performance-contingent (PC) phase. The lack of reward effects during the previously rewarded (PR) phase could potentially be due to a time-dependent habituation of pupil responses to reward, as PR phase consistently happened after the PC phase, and not due to the termination of reward delivery. To rule out this possibility, we divided the trials in each phase to two halves and examined whether the reward-driven effects were different across time (**Figure S3**). An ANOVA on pupil responses during the performance contingent phase revealed only a main effect of reward value ($F(1,34) = 4.20$, $p = 0.048$, $\eta_p^2 = 0.11$), but no interaction with time ($F(1,34) = 0.33$, $p = 0.57$, $\eta_p^2 = 0.01$). In a second analysis, we entered the pupil data of both halves of the two phases to the analysis. This analysis reproduced our results reported in the main text when all trials were included: we again observed a significant interaction between the reward value and phase ($F(1,34) = 6.28$, $p = 0.017$, $\eta_p^2 = 0.01$) corresponding to a stronger reward-driven modulation in the performance-contingent phase and importantly no interaction ($F(1,34) = 1.51$, $p = 0.227$, $\eta_p^2 = 0.043$) of this effect with time (first or second half of the data). These results thus rule out the possibility that the lack of reward effects in the previously rewarded phase is solely driven by a time-dependent habituation to reward delivery.

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Chapter 3: Distinct mechanisms underlie value-driven modulation of visual cortex by previously rewarded visual and auditory stimuli

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Chapter 3

In the previous chapter, we have identified how reward-driven modulation of perceptual discriminability was regulated by both the performance contingencies of reward and the sensory modality of the reward-associated cues. We observed that rewards overall enhanced the accuracy of perceptual discrimination, although some aspects of reward-driven modulations such as the acceleration of response times and pupillary dilation were stronger in performance contingent compared to the previously rewarded cues. Our observation confirmed previous studies demonstrating that reward-driven enhancement of speed and accuracy of perceptual decisions and the pupil-linked arousal, especially when rewards are relevant to the task at hand (Chelazzi et al., 2013; Pessoa, 2015). However, consistent with our findings, past research has also reported divergent effects for previously reward-associated cues, where reward may enhance (Leo and Noppeney, 2014; Pooresmaeili et al., 2014; De Tommaso and Turatto, 2021) or impair (Anderson et al., 2011; MacLean and Giesbrecht, 2015; Watson et al., 2020) performance. As our previous study indicated a long-lasting reward effect, where previously rewarded cues continued to enhance perceptual discriminability, we attempted to replicate this observation and investigate further the neural correlates governing reward-driven effects of previously reward associated cues.

3.1 Abstract

Past reward associations may be signaled by stimuli from different sensory modalities, however it remains unclear how different types of reward-associated stimuli modulate perception. In this human fMRI study, we employed a paradigm involving a visual discrimination task, where a visual target was simultaneously presented with either an intra- (visual) or a cross-modal (auditory) cue that was previously associated with rewards. We hypothesized that depending on the sensory modality of the cues distinct neural pathways underlie the value-driven modulation of visual areas. Two steps of analyses were conducted: first, using a multivariate approach, we confirmed that previously reward-associated cues enhanced the target representation in the early visual areas. Then, using effective connectivity analysis, we tested three possible patterns of communication across the brain regions that could underlie the modulation of visual cortex: a direct pathway from the frontal valuation areas to the visual areas, a mediated pathway through the attention-related areas, and a mediated pathway that additionally involved distinct sensory association areas for auditory and visual rewards. We found evidence for the third model and demonstrate that reward-related information is communicated across the valuation and attention-related brain regions such as the intraparietal sulcus across for both visual and auditory cues. Additionally, the long-range communication of reward information also involved the superior temporal areas in case of auditory reward-associated stimuli. These results suggest that in the presence of previously rewarded stimuli from different sensory modalities, a combination of domain-general and domain-specific mechanisms are recruited across the brain to adjust visual processing.

Keywords: reward, value, visual perception, sensory modality, fMRI

3.2 Introduction

Rewards modulate information processing in the brain at multiple stages, from decision making where an organism's behavior is optimized to maximize reward outcomes (O'Doherty et al., 2001, 2007), to perception where the representations of sensory stimuli are altered depending on their current or past associations with rewards (Cicmil et al., 2015; Hickey et al., 2010; Rangel et al., 2008; Serences, 2008; Stanisor et al., 2013; Arsenault et al., 2013). Previous literature has demonstrated that a network encompassing the ventral striatum and prefrontal cortex plays a crucial role in learning and representation of reward value, thereby informing the subsequent decision-making stages about the best course of action to choose (Schultz, 2000; Rangel et al., 2008). On the other hand, a more recent line of research has provided evidence for a value-driven modulation of neuronal responses in almost all primary sensory areas (Rutkowski and Weinberger, 2005; Shuler and Bear, 2006; Pleger et al., 2008; Weil et al., 2010; Goltstein et al., 2013; Stanisor et al., 2013), a mechanism through which stimuli associated with higher rewards or better realization of the goals of the task are prioritized for perceptual processing. Despite the wealth of knowledge regarding the neuronal underpinnings of valuation in the brain and the emerging evidence for the value-driven alteration of perception, it is unclear how these processes interact.

Unravelling the mode of interaction between valuation and perception is a crucial step towards understanding how information processing in the brain is adapted to the rich and dynamic characteristics of the naturalistic environments. In such settings, objects have multiple features; from the same or different sensory modality; which may have different associations with rewards, and these associations may change over time. Therefore, to form a robust representation of reward value despite the multitude of stimulus features in the environment, the valuation network should constantly receive information from sensory areas (Komura et al., 2001; Reig and Silberberg, 2014). On the other hand, sensory areas should be efficiently re-regulated as reward associations of stimuli and task requirements undergo changes so that in each instance the stimuli that lead to better outcomes gain advantaged processing (Haber, 2011; Pessoa and Engelmann, 2010).

Different models have been put forward to explain the communication of information across the brain's valuation network and the sensory areas. Pessoa & Engelmann (2010) for instance, proposed that reward signals are embedded into perceptual processing through either direct or indirect inputs from the valuation network to sensory areas. Direct inputs rely on a connectivity between the valuation network and sensory areas, whereas indirect inputs are likely to be first broadcasted to the frontoparietal attentional network (Corbetta and Shulman, 2002; Pessoa, 2009) and then be fed back to the sensory areas. Additionally, recent studies have identified other sensory association areas which may be involved in routing information between the valuation and perception networks. For instance, Pooresmaeili et al., (2014) found an increase of neural responses in the superior temporal cortex, known to be involved in multisensory processing (Calvert et al., 2000, 2001; Stein and Stanford, 2008), when auditory stimuli had been associated with higher rewards and modulated visual perception cross-modally. This finding suggested that areas involved in combining information across different features of a multisensory object may additionally integrate reward signals into the perceptual processing (Cheng et al., 2020). This proposal is also in line with the findings from another study (Anderson, 2017) showing that lateral occipital complex (LOC), an area that is involved in representation of perceived objects (Kourtzi and Kanwisher, 2001) and integration of local features to global shapes (Grill-Spector, 2003) especially when attention is biased to visual object features (Martin et al., 2018), plays a role in the value-driven changes in attentional control. Yet another possibility is that a history of privileged processing and preferred selection confers high reward stimuli a long-lasting processing gain already at the level of encoding of information at the early visual areas (Kim and Anderson, 2019), and hence value-driven modulation of perception occurs without the need for constant communication of information across the valuation and perception systems.

All mechanism outlined above have found support in the literature. For instance, direct inputs from the valuation network is plausible because previous studies have shown that lateral OFC and striatum have bilateral connections with the primary visual cortices (Barbas, 1993; Carmichael and Price, 1995; Kveraga et al., 2007; Khibnik et al., 2014). However, these connections may first be relayed to other areas as direct dopaminergic inputs to early visual areas such as area V1 are scarce (Oades and Halliday, 1987; Jacob and Nienborg, 2018) therefore supporting the proposal of a mediation through the sensory association (Macedo-Lima and Remage-Healey, 2021) or attentional (Noudoost and Moore, 2011) areas. The important role of attentional areas in mediation of value-driven effects is also supported by a host of previous studies (Pessoa, 2015), demonstrating that rewards guides attention to be allocated to the most valuable items in the scene (Chelazzi et al., 2013), and attention in turn gates the effects of reward by determining whether or not rewarded stimuli are aligned with the goal of the task and should be boosted or supressed (Roelfsema and Van Ooyen, 2005; Roelfsema et al., 2010; Gong et al., 2017). Finally, an effect of reward locally arising at the level of sensory areas due to the reward history and its resultant long-lasting changes in sensory representations is supported by computational modelling (Wilmes and Clopath, 2019) and experimental approaches (Chubykin et al., 2013; Kim and Anderson, 2019) showing that during learning, the task-relevant neural representations that are predictive of rewards are locally boosted in area V1 (Poort et al., 2015).

The aim of the current study was to shed light on the underlying mechanisms of value-driven modulation of perception and the mode of interaction between the valuation and perception systems. Specifically, we sought to test which of the mechanisms mentioned above can best explain the value-driven modulation of visual perception across different types of reward-associated stimuli. Towards this aim, we used a behavioral paradigm similar to previous studies (Pooresmaeili et al., 2014; Vakhrushev et al., 2021; Antono et al., 2022) that featured either cross-modal (Pooresmaeili et al., 2014) or both cross- and intra-modal reward-associated stimuli (Vakhrushev et al., 2021; Antono et al., 2022). In this paradigm, auditory or visual stimuli were first associated with either high or low monetary reward during a reward associative learning phase (referred to as conditioning). During the test phase (post-conditioning), auditory and visual reward-associated stimuli (cross- and intra-modal, respectively) were presented at the same time as the target of a visual discrimination task but were irrelevant to the task at hand and did not predict the delivery of reward anymore. By having a comparison between intra- and cross-modal reward associated cues, we aimed to identify reward-related mechanisms that are shared or disparate across sensory modalities. Furthermore, in order to disentangle reward- and goal-related mechanisms, we associated rewards to the features of the stimulus that were not the target of the visual discrimination task. Concurrently as participants performed the behavioral task, we recorded the brain activity using fMRI.

We hypothesized that higher reward improves performance by enhancing the neural representation of the task target in the early visual areas. In our task, the visual discrimination had to be done on a target stimulus (i.e., a Gabor patch) while the reward-associated stimuli were presented simultaneously and at the same spatial location but were irrelevant to the task. Therefore, to examine the target-specific modulation of visual processing, we inspected how the accuracy of a multivariate pattern classifier for target’s tilt orientation in the early visual areas was influenced by the value of reward-associated stimuli. Furthermore, to identify which brain areas were engaged in encoding the associated reward value of stimuli, we used a second set of multivariate pattern classifiers that decoded stimulus value, either dependent or independent of specific sensory features, across the brain. Finally, we tested possible models of whether and how the long-range communication of reward information between the valuation and early visual areas occurs. Our results showed that overall higher reward enhanced the accuracy of target-specific representations in the early visual areas but this effect involved distinct modes of long-range neuronal interactions across the brain for cross-modal and intra-modal reward-associated stimuli.

3.3 Materials and Methods

3.3.1 Participants

Thirty-six healthy participants were recruited (14 females; mean age 25.6 ± 4.48 SD, 20-40 years old) using an online local database (http://www.probanden.eni-g.de/orsee/public/). All participants had normal or corrected-to-normal vision, were right-handed, and gave oral and written informed consent after all procedures was explained to them. 3 participants were excluded from all analyses since their performance in the reward conditioning task was below a pre-defined criterion (<80%) indicating that they could not localize the visual or auditory stimuli. One additional participant was excluded from the fMRI analysis since the data acquisition inside the scanner could not be completed (see the *Procedures*). Participants were paid 10€ per hour for their participation in 2 scanning sessions (each 2.5 hours), and in addition received a bonus up to 10€ depending on their performance. The study was approved by the local ethics committee of the "Universitätsmedizin Göttingen" (UMG), under the proposal number 15/7/15.

3.3.2 Stimuli and apparatus

The target stimuli used for the main task in the pre- and post-conditioning were Gabor patches (a Gaussian-windowed sinusoidal grating with SD = 0.33°, a spatial frequency of 3 cycles per degree, subtending 2° diameter, displayed at 10° eccentricity to the left or right side of the fixation point), which were tilted clockwise or counter-clockwise relative to the horizontal meridian. In each trial, a semi-transparent ring (alpha 50%, 0.44° in diameter) was superimposed on the Gabor patch. The color of the rings (orange or blue for visual conditions, or grey for auditory and neutral conditions) was adjusted individually for each participant in such a way that they were perceptually isoluminant. For auditory cues, two pure tones (600 Hz or 1000 Hz) were presented at 90dB simultaneously with the Gabor patch and at the same spatial location (see the *Procedures*). To achieve the co-localization of the auditory tones and the visual stimuli, we convolved the tones with head-related transfer functions based on a recorded database (Algazi et al., 2001) so that they could be perceived at 10° distance to the left or right of the fixation point.

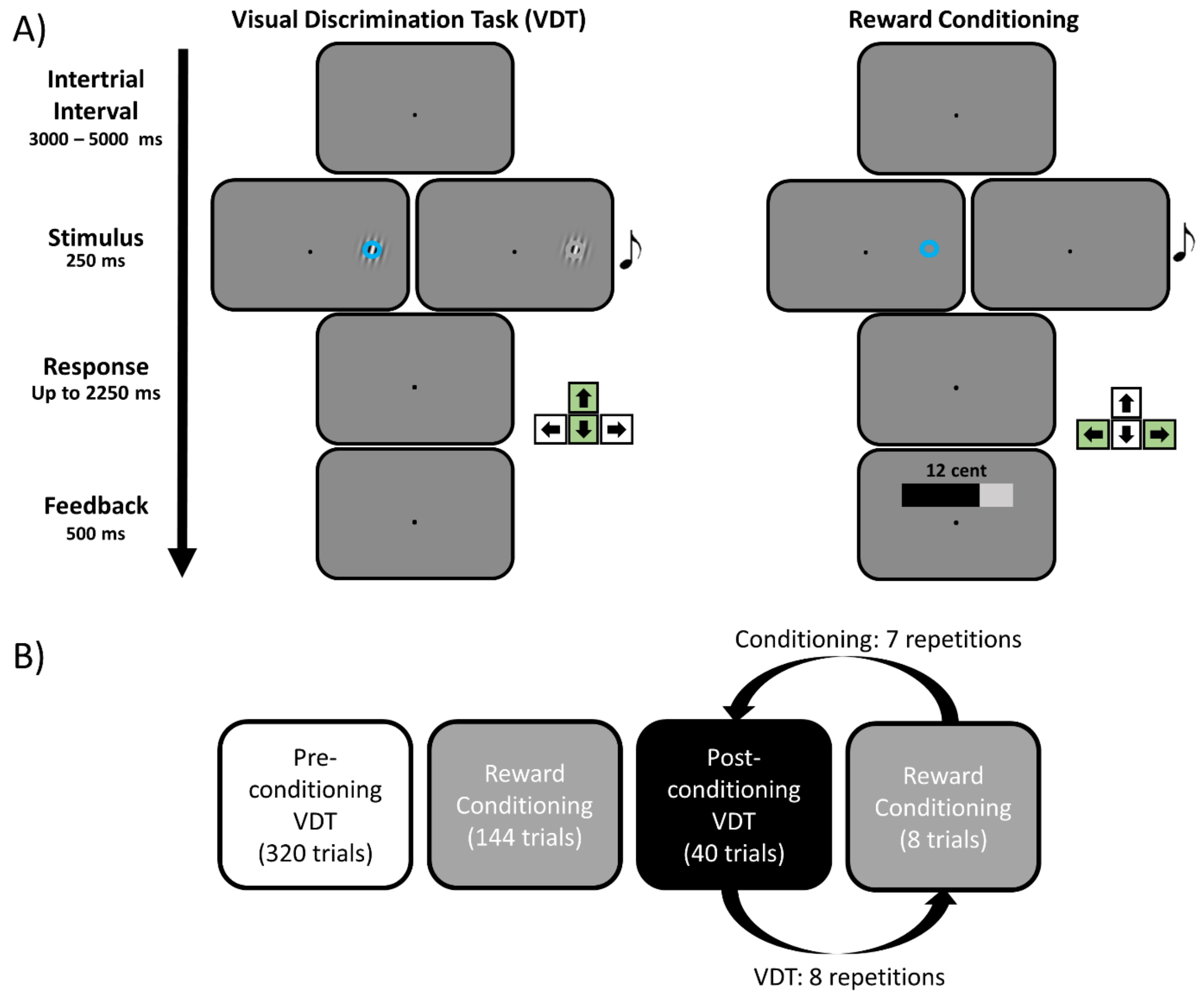

Figure 5. Behavioral paradigms. **A)** On the left side the visual discrimination task (VDT) used in the test phase is shown. Participants were instructed to discriminate the orientation of a Gabor patch (i.e. clockwise or counter-clockwise) overlaid with a semi-transparent ring by pressing upper or lower arrow keys on a response box, repectively. Simultaneously with the Gabor target, a task-irrelevant visual (intra-modal) or auditory (cross-modal) cue was also presented on the same location. The VDT task was employed both before and after a conditioing task (shown on the right side) where the reward associations of intra- and cross-modal cues were learned. During conditioing, participants were asked to indicate whether the cues (auditory or visual) were presented to the left or right side (by pressing the left or right arrow keys on a response box, repectively). The properties of the cues (color for the visual and pitch for the auditory tone) predicted different magnitudes of reward that was shown on the display during a feedback phase. During VDT, intra- and cross-modal cues were never predictive of reward delivery and accordingly the feedback display only contained a fixation point. **B)** The sequence of tasks employed during the experiment for each participant: first the VDT was completed before the cues were associated with rewards (referred to as the *pre*-conditioing phase recorded on day 1). Thereafter during the second session recorded on another day, participants first learned the reward associations of visual and auditory cues during the conditioing and then proceeded to the *post*-conditioning VDT with the cues that had been associated with rewards. To prevent the exinction of reward effects, the reward associations were reminded by interleaving the VDT with short conditioing blocks.

Throughout the experiment, visual stimuli were displayed on an MR-compatible projection screen using a calibrated ProPixx projector (VPixx Technologies, Saint-Bruno, QC, Canada) at a resolution of 1920x1080 pixels, and a refresh rate of 120 Hz. The screen was placed at the end of the scanner bore at a distance of 88 cm from the participants’ eyes. The full display size on the screen was 43 cm x 24 cm, i.e. the visible range from the central fixation spot was +/-

13.6° horizontally and +/-7.7° vertically. The auditory tones were delivered through MR compatible earphones (Sensimetric S15, Sensimetrics Corporation, Gloucester, MA) with an ear tip (Comply™ Foam Canal Tips) to maintain acoustic seal and reduce environmental noise.

For tracking the gaze position an MRC eye-tracker system mounted on the mirror on top of the MR head coil was used (MRC HiSpeed, MRC Systems GmbH, Heidelberg, Germany). Before each of the two scanning sessions, the eye-tracking system was calibrated using a 9-point standard MRC calibration procedure.

3.3.3 Procedures

The data collection was done over two scanning sessions (about 2.5 hours each). The first session consisted of a preparation phase (comprising a practice session for the visual orientation discrimination task: VDT, measurements of the sound localization, adjustment of colors' luminance and determining the perceptual threshold for the VDT) and an experimental phase referred to as pre-conditioning with the simultaneous acquisition of fMRI data. Prior to the scanning, participants completed a sound localization task, where they had to indicate whether a sound was played from the left or right side using their index and middle finger on a keyboard, and were included in the study if their localization accuracies were >95%. Afterwards, participants adjusted the luminance of both visual cues using a flicker task inside the scanner. The tilt orientation of the Gabor patch during the orientation discrimination task was set to each participant's perceptual threshold estimated after the initial training and inside the scanner. To determine this threshold, we employed a QUEST algorithm (Watson and Pelli, 1983) to estimate the Gabor tilt orientation for which participants' performance was at 75%. Thresholds were determined when Gabors were superimposed with a grey circle. The scanning session started with the pre-conditioning phase (320 trials) employing an orientation discrimination task shown in **Figure 1A**. Participants were asked to indicate whether a Gabor stimulus was tilted clockwise or counter-clockwise relative to the horizontal meridian by pressing one of the 2 vertical buttons on a 4-button response pad (Current designs Inc., Philadelphia, PA) and to ignore the simultaneously presented task-irrelevant visual or auditory cues. The first scanning session terminated after the completion of pre-conditioning and participants attended the second session after at least 24 hours.

In the second scanning session, participants first completed a conditioning task to learn the reward associations of auditory and visual cues (see **Figure 1B**). During conditioning, participants were instructed to localize the visual (orange or blue rings) and auditory cues (pure tones 600 or 1000 Hz) and indicate whether they were presented to the left or to the right, by pressing one of the 2 horizontal buttons on a 4-buttons response pad. Upon correct response, participants saw the magnitude of the reward that was paired with a certain cue and thereby learned whether a visual or auditory stimulus was associated with high (mean = 25 Cents) or low (mean = 2 Cents, drawn from a Poisson distribution) monetary reward. All reward-cue combinations were counterbalanced across participants. In the third phase, referred to as post-conditioning (320 trials), the same procedure as in the pre-conditioning was employed with the exception that the task-irrelevant auditory and visual cues had already been associated with different amounts of monetary rewards. Additionally, in both pre- and post-conditioning one additional condition referred to as the neutral condition was included. The neutral condition contained the Gabor target overlaid by a semi-transparent grey ring. Since the grey color was never associated with any reward value during the conditioning, the neutral stimulus served as a means to measure target-specific responses in the visual cortex. Participants were instructed that they would get a bonus for each correct response, independent of the identity of the visual or auditory cues, though they would not be able to see the reward feedback.

In order to prevent extinction, we interleaved the post-conditioning blocks (each block with 40 trials) with a short conditioning block (8 trials). To ensure that participants had learned the reward-cue associations, we asked a question during and after the experiment. Based on these, all participants could correctly identify which cue properties were associated with high compared to low reward magnitudes.

3.3.4 Behavioural data analysis

The data obtained from all parts of the experiment was analysed using custom-written scripts in MATLAB (version R2015a). For the behavioural analysis, we removed the trials in which participants did not respond or had extreme response times. To determine the extreme response times, we first log transformed each participant's reaction times to achieve a roughly normal distribution and then removed trials which had reaction times >2SD from the mean (across all trials of each phase). This procedure removed 4.55, 4.67 and 5.13% of trials as outliers from the pre- and post-conditioning and conditioning, respectively. From the remaining trials, we calculated the mean of each response variable (accuracy and reaction times of correct trials) for each condition (high and low reward in auditory and visual cues) per subject during the post- and pre-conditioning separately. Afterwards, we entered the difference of accuracies and reaction times between the two phases (i.e., pre- and post-conditioning) as dependent variables in a 2x2 repeated measures ANOVA, with sensory modalities (intra- or cross-modal) and reward magnitude (high or low) as independent factors.

3.3.5 MRI data acquisition

The imaging data was collected using Siemens Magnetom Prisma Fit (3T) with a 64 channels head coil at the University Medical Centre Göttingen. Structural images were acquired for each session using a MPRAGE T1-weighted sequence (FOV: 256 x 256mm; voxel size: 1 x 1 x 1mm; TR: 2250ms; TE: 3.3ms; number of slices: 176). Functional images were acquired using an EPI sequence (TR: 900ms; TE: 30ms; FOV: 210 x 210mm; voxel size: 3 x 3 x 3mm; slice thickness: 3mm; flip angle: 60°; number of slices: 45).

3.3.6 fMRI data preprocessing

The imaging data was processed using the Statistical Parametric Mapping software (version SPM12: v7487; https://www.fil.ion.ucl.ac.uk/spm/). The data preprocessing pipeline consisted of realignment of the slices to the mean image, unwarping the images according to the voxel displacement mapped image, slice time correction for multiband interleaved sequence, coregistration between the functional and the structural images, segmentation of brain tissues according to the tissue probability maps, spatial normalization to the MNI space, and spatial smoothing with a kernel size of 8 mm (FWHM: 8 mm). All preprocessing steps were undertaken for the images that entered to the univariate GLM. For the multivariate analysis (MVPA), all steps were done except for the spatial normalization and spatial smoothing (see also under the *MVPA analysis*). For one participant the image required for unwarping could not be acquired due to technical problems at the scanner and we excluded this participant from all further fMRI-related analyses, resulting in N = 32 for corresponding results.

3.3.7 Univariate GLM for effective connectivity

For the effective connectivity analysis, we designed a General Linear Model (GLM) with 10 regressors of interest for pre- and post-conditioning phases and 8 regressors of interest for the conditioning phase. These regressors were stick functions time-locked to the onset of the stimulus presentation in each trial (**Figure 1A**) and corresponded to the experimental conditions that varied in the reward magnitude (H-high or L-low), the sensory modality of the cues (V-visual or A-auditory), and the sides (L-left or R-right), plus the neutral trials (N: with no reward association) that was included in the pre- and post-conditioning in order to characterize the visual responses in the absence of reward associations.

Both scanning sessions were modelled in a single GLM, separated by a regressor marking session 1 (i.e. pre-conditioning phase) and session 2 (i.e. conditioning and post-conditioning phase). Moreover, we also modelled additional nuisance regressors such as six movement parameters for each session, three events of no interest (e.g. instructions) across the whole sessions, one regressor that marked the interleaved blocks of reward conditioning during the post-conditioing phase, and four regressors for marking each period of data acquisition (i.e. one regressor marked the pre-conditioning phase on day 1 and three regressors marked the three periods of data acquisition on day 2, one for conditioning and two for post-conditioning, each period corresponded to the time between the start and end of the scan).

3.3.8 Multivariate analysis (MVPA)

For the MVPA analysis, we created a GLM where each trial in the pre- and post-conditioning was modelled as a separate regressor with stick functions at the onset time of the target. Four extra nuisance regressors were also included to model the inter-leaved blocks of conditioning and the instruction display, plus six head motion nuisance regressors. The trials during the conditioning blocks were modelled similarly as explained under *univariate GLM for the effective connectivity*. For this GLM, we used the images that underwent all preprocessing steps except for the spatial normalization and smoothing. The parameter estimates of this GLM (t values) were then fed into several pattern classifiers using LibSVM's implementation of linear support vector machines (SVMs) (www.csie.ntu.edu.tw/~cjlin/libsvm). SVM classification was done using a whole-brain searchlight method, where the classification accuracy of each pattern classifier was computed based on the information contained in all voxels within a spherical searchlight region (radius: 6 mm) using a 10-fold cross-validation method. The searchlight was iteratively moved over every voxel in the whole-brain images and the calculated classification accuracy within each sphere was mapped to the voxel at the centre and normalized against the chance level accuracy (~ 50% for a two-class pattern recognition). The output of the classifiers was used to compute first-level contrast images (see the description of orientation and value decoders below), which were then spatially normalized to the MNI space and smoothed (FWHM, 3 mm). These contrast images were then entered into a second-level analysis, in which the statistical significance of each contrast was evaluated using one-sample t tests.

Our pattern classification analysis comprised two main types of decoders: *an orientation decoder* to classify the tilt orientation of the target stimulus (i.e. classifying clockwise or counter-clockwise tilt orientation) and several *value decoders* to classify the associated reward magnitude of visual or auditory stimuli (i.e. classifying high or low reward magnitudes). These classifiers were designed to identify the early visual areas that encoded information about the target (orientation decoder) and brain regions that contained information about the associated reward value of stimuli (value decoders), respectively. Orientation decoders classified the stimulus orientation separately for different reward (high or low), cue modality (auditory or visual) and side (left or right). To examine the effect of reward value on early visual areas, we inspected the classification accuracy of this decoder using the contrast *High Value* > *Low Value* across all conditions (side and modality) during the post-conditioning corrected for the effects that existed prior to the learning of reward associations during the pre-conditioning. To identify the regions that contained information about reward value after learning of reward values, we built 2 types of value decoders: 1) value decoders that classified stimulus value across all conditions (i.e., both modalities: auditory or visual and locations\sides: left and right 2) value decoders that classified stimulus value separately for each sensory modality and each side. These decoders thus identified brain regions that were invariant to sensory modality and spatial location (*value decoder*$_1$) or were sensitive to sensory modality and spatial location (*value decoder*$_2$). The results of value decoders in post-conditioning were corrected against the results prior to the learning of reward associations in the pre-conditioning.

3.3.9 Effective connectivity analysis (ECA)

In order to understand how cross- and intra-modal reward information is communicated across different brain regions to modulate early visual areas, we set up an effective connectivity analysis (ECA) using a dynamic causal modelling (DCM) approach (Friston et al., 2003; Friston, 2011). We hypothesized that there are three possibilities of how learned reward associations are communicated to modulate visual target processing. The first mechanism is based on a direct communication between the reward-related and the early visual areas, whereas the second mechanism relies on the involvement of either attention-related or sensory association areas to first process the reward information before it is further relayed to the early visual areas. Alternatively, reward-related information might be locally encoded in the early visual areas without the necessity of long-range communications across brain regions.

In order to test these hypotheses, we extracted the time series of regions of interest (ROIs) that were identified by our two types of MVPA decoders (i.e., orientation and value decoders) treating them as nodes in DCM networks to be modelled. Both types of decoders could potentially identify multiple brain regions (see the Results and **Table 2**). Therefore, we limited our analysis to ROIs that were most informative for testing our a priori hypotheses. These ROIs comprised the early visual areas (EVA) known to contain information about the stimulus orientation (Hubel and Wiesel, 1968; Grill-Spector and Malach, 2004) and valuation areas that based on previous literature are known to play a role in coding stimulus value and attentional or sensory processing. The visual ROIs (see **Table 2**, **Figure 2B** and **Supplementary Figure 2**) were defined as regions that had a significantly higher orientation classification accuracy in the presence of high compared to low reward stimuli across both modalities (i.e. the contrast: *High Value* > *Low Value*) in post- compared to pre-conditioning and were within an anatomical mask consisting of bilateral V1-V2 areas (Eickhoff et al., 2005). In order to define the ROIs that contained information about the stimulus associated value, we inspected the results of our two *value decoders* (see also the description of MVPA methods). The classification results of *value decoder*$_1$ revealed a right lateralized inferior orbitofrontal area ([51 26 -7], *p* uncorrected < .005, k = 20), an area known to encode stimulus associative value (Kringelbach, 2005; Zald et al., 2014). The output of the *value decoder*$_2$ was inspected either across sensory modalities or based on an interaction contrast that tested whether a region contained more information about the associated value of a specific sensory modality over the other (e.g. classification accuracy is higher for auditory than visual). Among the activations revealed by the first contrast (**see Table 2**), we selected both the strongest cluster at the right superior temporal areas (at [57 -28 8], *p* uncorrected < .005, k = 20), an area related to multisensory processing (Calvert et al., 2000; Stein and Stanford, 2008) and has been observed to be modulated by reward magnitude (Pooresmaeili et al., 2014), and the largest cluster that corresponded to the left anterior intraparietal sulcus (IPS) (at [-33 -58 53], *p* uncorrected < .005, k = 20), an area known to play a role in the allocation of attention (Corbetta et al., 2000; Corbetta and Shulman, 2002; Serences and Yantis, 2007) and has well-documented neuroanatomical connections with the frontal areas (Greenberg et al., 2012).

For each ROI, time series were extracted separately for pre- and post-conditioning by overlaying the group functional ROI on each participant's structural scan. Within this framework, we estimated 11 biologically plausible models for the pre- and post-conditioning phases in which the directed causal influences among brain regions could change by three types of parameters: driving inputs and intrinsic and modulatory connections. Driving inputs corresponded to the incoming visual information contained in the different experimental conditions. To estimate the driving inputs, we used the univariate GLM which provided us the estimated BOLD times series corresponding to our 5 experimental conditions: intra-modal high reward (VH), intra-modal low reward (VL), cross-modal high reward (AH), cross-modal low reward (AL), and neutral (N). For each input the data of two sides (left and right) were combined and fed to the DCM models. Furthermore, as all stimuli contained the same visual target (i.e. the Gabor patch), we fed all driving inputs to the visual ROI (EVA) which is the first stage of information processing in a visual task. Intrinsic (condition-independent) connections were defined between every pair of nodes in the network and as self-connections. The models differed from each other with respect to the modulatory connections, which varied with the experimental conditions (**Figure 4**). In the null model, only intrinsic connections were included and no condition-dependent modulatory connection existed. The rest of the models assumed different patterns of connectivity between the early visual areas and other ROIs. One class of models (model 1-4) assumed that the valuation ROI (i.e. lateral OFC) communicated with the early visual areas indifferently across intra- and cross-modal condition. Specifically, the communication might involve a long-range direct communication (model 1), where previous studies have shown that lateral OFC receives direct inputs from visual and auditory cortices (Kringelbach and Radcliffe, 2005), making the assumption of a direct connection between the two regions plausible. Another possibility was that the communication of the valuation and visual ROIs is indirect, with the information being first relayed to sensory-related ROI for cross-modal condition (model 2). Specifically, these models involved a modulatory connectivity between OFC-STS (Zald et al., 2014) and thereafter from STS to EVA (V1-V2 areas), comprising connectivity patterns that are supported by previous studies (Felleman and Van Essen, 1991; Lewis and Noppeney, 2010). The third possibility was that the valuation and visual ROIs influenced each other through engaging the attention-related areas, i.e. IPS in our case; (model 3) or both attentional and sensory areas (model 4). The pattern of inter-areal connectivity assumed by these models is in line with previous literature showing functional and structural connectivity between these areas: lateral OFC is functionally connected with IPS (Zald et al., 2014), IPS has connections to STS as demonstrated by diffusion tractography (Bray et al., 2013) and IPS has structural connections to early visual areas (Felleman and Van Essen, 1991; Bray et al., 2013). Moreover, STS has been known to have a functional connection with the primary visual area (Noesselt et al., 2007). So far, model 1-4 assumed that intra- and cross-modal cues behaved similarly. In order to capture the possibility of a dissociation between intra- and cross-modal pathways, we also modelled another class of models (model 5-10) where distinct pathways were involved in intra- and cross-modal reward processing. Lastly, we also included a *null* model (model 11), which assumed that the influence of reward on early visual areas occurred locally with these areas and did not require a constant log-range communication with other areas.

These models were therefore captured by a DCM model space consisting of 11 models per phase (pre- or post-conditioning). Each model was estimated for each participant and each phase (pre- and post-conditioning) separately. Then, models were compared using a group-level random effects Bayesian Model Selection (BMS) approach (Stephan et al., 2009) to select the most probable model given the observed BOLD time-series. We employed a random effect (RFX BMS) to select the winning model, as this method allows for the possibility that different participants may have different preferred models. Note that in all models (see **Figure 4**), high and low reward conditions in both phases are assumed to be processed by the same brain regions and involve the same inter-areal connectivity patterns, albeit the strength of these connections were hypothesized to differ depending on the reward magnitude (between phases: pre- and post-conditioning and reward conditions: high and low). To test this latter hypothesis, we next inspected the winning model detected by BMS approach and tested whether the connectivity strength of this model was modulated by reward magnitude using a Parametric Empirical Bayes (PEB) approach (Zeidman et al., 2019). The PEB approach is a hierarchical Bayesian model that uses both non-linear (first-level) and linear (second-level) analyses. The advantage of using this approach is that inter-individual variability in model parameters is parameterized at the second level. Hence, parameter estimates for subjects with noisy data are likely to be adjusted in order to conform to the group distribution. Combining BMS and PEB approaches allowed us to maximally capture the inter-individual variability while selecting models using BMS, while having a more sensitive measurement of parameter estimates of the winning models by using PEB that adjusts parameter estimates based on their distribution across the participants. As our model comparison analysis revealed that model 10 had the strongest evidence in the post-conditioning, while the *null* model had the strongest evidence in the pre-conditioning, we exclusively extracted the parameters of the winning model 10 for pre- and post-conditioning of each participant as the input of the design matrix in the PEB. Then, at the group level, we constructed a PEB model with a constant term (mean parameter estimates across participants) and an additional binary regressor to model the difference between pre- and post-conditioning. This allowed us to investigate how the connectivity strength was modulated by reward magnitude before and after participants had learned the reward-cue associations. As we were interested in the reward modulation of each connection between regions, we focused on the estimated parameters in the modulatory (i.e. B matrix) connectivity, specifically for both feedforward/bottom-up and feedback/top-down connections. Finally, for each connection, we report the reward modulation (high-low) posterior probabilities using a threshold of > 0.99, correcting for multiple comparisons across connections (Bonferroni correction).

3.4 Results

3.4.1 Conditioning phase: Recruitment of the classical brain regions involved in the reward associative learning

Participants exhibited near perfect accuracy in localizing both visual and auditory stimuli (both > 95%), however there was no significant effect of reward on either the response accuracies or the reaction times (for details see the Supplementary Information). Analysis of the BOLD responses revealed the classical brain areas that are involved in the associative learning of rewards, such as the ventral striatum and insula (see the **Supplementary Figure 1**). The effect of reward on the BOLD responses was largely independent of the sensory modality, except for the higher activations observed for the auditory compared to visual reward value found in the right caudate (see the **Supplementary Table 1**).

Table 1. Behavioral results during the visual discrimination task performed in pre- and post-conditioning

Condition	**RT** **(pre-conditioning)**	**Accuracy** **(pre-conditioning)**	**RT** **(post-conditioning)**	**Accuracy** **(post-conditioning)**
High Reward Intramodal (HV)	938.33±24.13 ms	81.08±1.09%	849.72±20.25 ms	80.53±1.33%
Low Reward Intramodal (LV)	929.56±23.77 ms	80.80±1.29 %	852.98±19.71 ms	80.23±1.48%
High Reward Cross-modal (HA)	934.15±26.25 ms	82.25±1.07%	843.40±20.79 ms	82.25±1.38%
Low Reward Cross-modal (LA)	920.64±26.08 ms	84.48±1.71 %	848.50 ±21.59 ms	84.48±1.36%
Neutral	925.08±24.04 ms	80.68±1.40%	852.67±19.71 ms	80.66±1.60%

3.4.2 Previously reward-associated cues slightly enhanced the speed of visual discrimination during the post-conditioning

We next examined the behavioural effects of rewards from the same (intra-modal) or different (cross-modal) sensory modality on the visual discrimination task. Compared to the pre-conditioning, reaction times decreased for all conditions during the post-conditioning phase indicating that with longer training on the task, participants' speed of perceptual decisions increased (**Table 1** and **Figure 2A**). This speed enhancement was stronger for the high compared to low reward conditions. Accordingly, we found a main effect of reward on the reaction times as higher reward magnitude increased the speed of visual discrimination across sensory modalities ($F(1,32) = 4.46$, $p = 0.04$, $\eta_p^2 = 0.12$). Other main and interaction effects did not reach statistical significance. The effect of reward in individual conditions (cross- and intra-modal conditions) was not significant (both ps>0.1), and although high reward stimuli seemed to lead to faster responses compared to the neutral condition, this effect did not reach statistical significance (F(2,64) = 1.34, *p* = 0.268, η_p^2 = 0.040). Analysis of the accuracies revealed neither a main effect of reward value nor an interaction with the sensory modality (both Fs<1.5 and ps>0.1). Together, these results indicate a weak behavioural advantage for high compared to low reward stimuli in our experiment which was mainly observed for the reaction times.

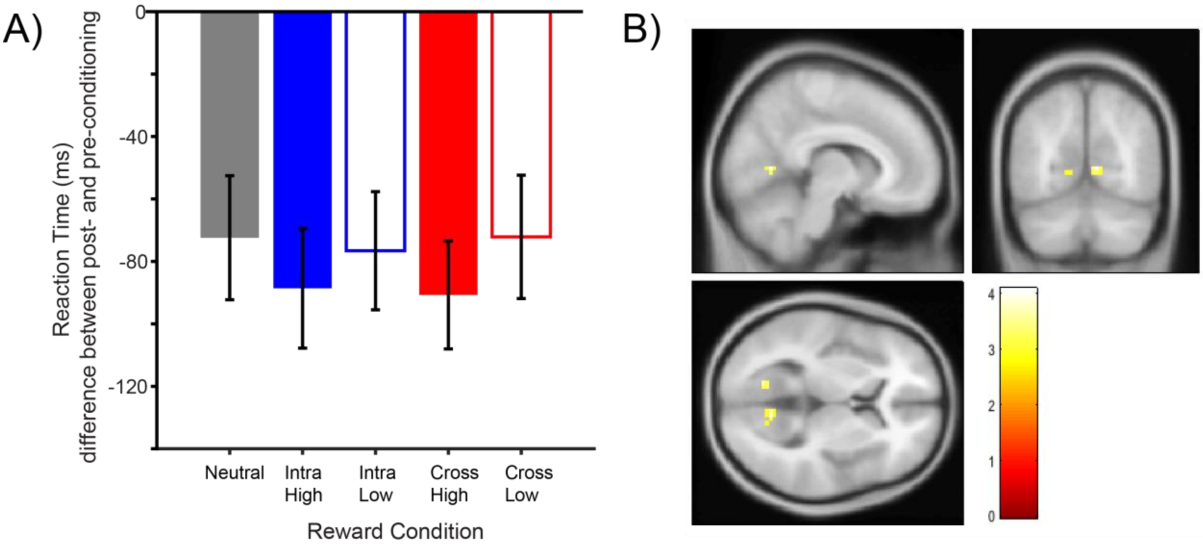

Figure 2. Behavioral and BOLD effects of reward on visual discrimination. A) Baseline corrected reaction times for all conditions. Error bars are s.e.m. **B)** Reward facilitation in early visual areas (masked with V1-V2 anatomical mask from Eickhoff and colleagues (2005)). The activations correspond to regions in area V1-V2 where the classification accuracy of the orientation decoder was higher for high compared to low reward condition during the post-conditioning after correcting for differences in pre-conditioning. Activations are shown at an uncorrected $p < .005$, k = 10, revealing a peak in the right hemisphere located at xyz = [9 -64 5] and in the left hemisphere at xyz = [-12 -67 2].

3.4.3 Reward-driven modulation of target representations in the early visual areas during the post-conditioning

We next examined how the reward value affected the encoding of the target's tilt orientation in the early visual areas. To this end, we examined the results of the whole-brain searchlight *orientation decoder* (for classification of clockwise and counterclockwise orientations) and identified areas within an anatomical mask of area V1-V2 which exhibited a reward-driven increase in the decoding accuracy across sensory modalities in the post- compared to the pre-conditioning.

This contrast revealed a bilateral activation with a peak at xyz = [9 -64 5] on the right and at xyz = [-12 -67 2] on the left visual cortex (**Figure 2B**). Importantly, this activation overlapped with the regions within areas V1-V2 that were activated by the Gabor stimulus in the neutral condition indicating that they corresponded to the target-specific representations within the early visual areas (**Supplementary Figure 2**). This result indicates that higher reward enhanced the neural representation of the visual target already as early as in area V1-V2, in line with previous findings where reward-driven enhancement of the magnitude (Serences, 2008) or the specificity of spatial patterns (Pooresmaeili et al., 2014) of neural responses were observed in the early visual areas. Additionally, to further support this finding, we checked the opposite contrast (classification accuracy in Low Value > High Value) using the same threshold and mask, and did not find any activation.

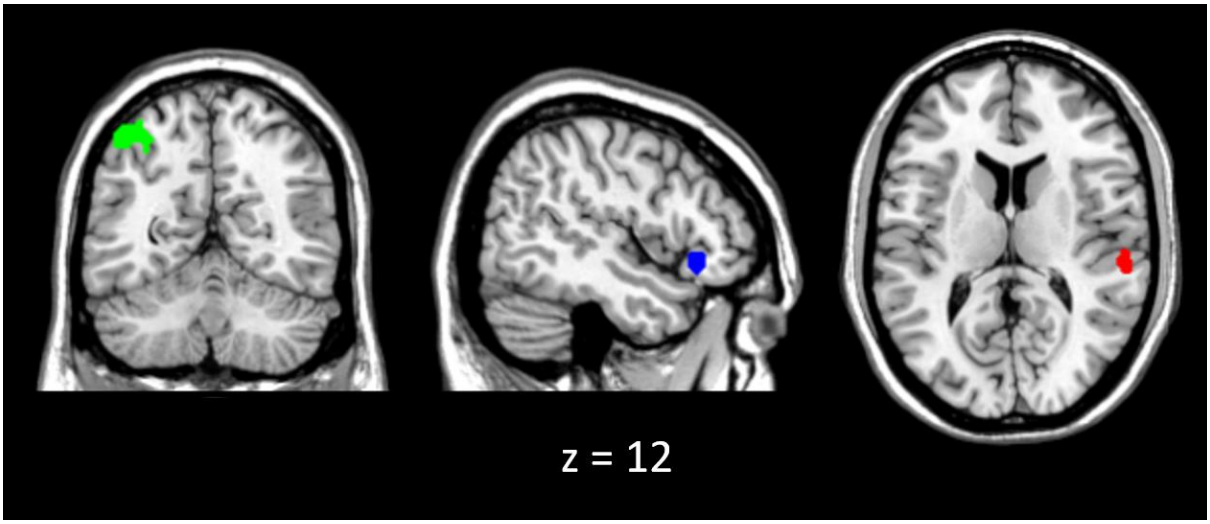

Figure 3. **Regions of interest identified by the *value decoders* and used for the effective connectivity analysis.** *Value decoder1* identified a cluster in the OFC xyz = [51 26 -7] shown in blue, which discriminated high and low value stimuli irrespective of their sensory properties (i.e., location and sensory modality). *Value decoder2*, classified high and low reward stimuli from each location and sensory modality separately and showed clusters in IPS xyz = [-33 -58 53] in green and STS xyz = [57 -28 8] in red, where reward value was reliably decoded across sensory modalities. The activations are shown at uncorrected $p < .005$ with k = 20, and the cursor is located at xyz = [48 -58 12] to illustrate all ROIs.

After establishing that higher reward enhances the reliability of target representations in the early visual areas, we asked *where* in the brain the associated reward value of stimuli is encoded and *how* the reward-related signals are communicated to visual areas. In order to answer these questions, we conducted two types of analyses: 1) An MVPA analysis to identify *where* in the brain the reward value is encoded, and 2) An effective connectivity analysis in which the possible communication patterns between the identified valuation regions and early visual areas were tested (thus answering the question of *how*).

3.4.4 Identification of the brain regions that encode stimulus value during the post-conditioning (*where*)

Towards answering the first question regarding *where* in the brain the stimulus value is encoded after learning of the reward associations, we inspected the results of our two value decoders. To identify brain areas that are responsive exclusively to the stimulus reward magnitude irrespective of its sensory features (sensory modality and location), we inspected the results of the *value decoder 1* (see Material and Methods). This decoder performed a whole-brain search for regions that contained information about the reward value after value associations were learned (class labels were: high or low reward magnitude, see Material and Methods). The classification accuracy of *value decoder 1* was highest in a cluster in the left orbitofrontal cortex (blue cluster in **Figure 3**, **Table 2,** and **Supplementary Figure 3**), while several other areas related to the reward processing such as ventral striatum, ventromedial prefrontal cortex were also identified by this analysis (**Table 2**). The lateral OFC cluster was further selected for the subsequent effective connectivity analysis.

Next, we asked which brain areas are involved in the encoding of stimulus value specifically for each sensory modality and stimulus location. These areas are instrumental in conveying additional information regarding the specific sensory feature of reward cues across the brain. In order to investigate this question, we examined the results of the *value decoder 2* which decoded the stimulus value separately for each sensory modality (intra- and cross-modal) and stimulus location (left and right, see the Material and Methods). We then inspected the results of this decoder across both sensory modalities as well as differentially contrasting one modality against the other. The strongest reward modulation across sensory modalities was observed in the superior temporal areas (STS, red cluster in **Figure 3** and **Supplementary Figure 3**), an area that is tightly linked with the multisensory processing (Calvert et al., 2001; Stein and Stanford, 2008). Interestingly, we also found that across sensory modalities stimulus value was reliably decoded from regions with a known role in attentional processing such as a large cluster in the anterior intraparietal area (IPS, **Figure 3** and **Supplementary Figure 3**). This area has not only been related to the attentional selection (Corbetta and Shulman, 2002), but also has been shown to be modulated by reward (Platt and Glimcher, 1999; Bendiksby and Platt, 2006; Louie et al., 2011). Moreover, we also observed several areas such as the cuneus, cingulate, temporoparietal area, and also motor cortex which contained reliable representations of stimulus value across modalities (see **Table 2**).

Table 2. Whole-brain activations of value decoders thresholded at uncorrected $p < .005$ and $k = 20$. Regions marked with bold font were selected as ROIs used for the effective connectivity analysis.

Cluster size	MNI coordinates (in mm)			T	*p*	Side	Region
	x	y	z				
Results of *Value Decoder 1*: areas that distinguish between high and low value irrespective of sensory properties							
43	**51**	**26**	**-7**	**6.08**	**0.006**	**R**	**Inferior orbitofrontal**
44	-45	-46	-49	5.27	0.006	L	Cerebelum
80	36	-79	-52	4.69	0.000	R	Cerebelum
37	42	-61	-4	4.39	0.01	R	Inferior temporal
22	3	4	11	4.06	0.038	L	Caudate
23	12	8	41	3.64	0.034	R	Cingulate cortex
22	-42	23	-16	3.55	0.038	L	Inferior orbitofrontal
23	-3	65	-7	3.52	0.034	L	Medial orbitofrontal
Results of *Value Decoder 2*: areas that distinguish between high and low value for each location and sensory modality. After value classification was performed, results were inspected **across sensory modalities.**							
37	**57**	**-28**	**8**	**4.62**	**0.01**	**R**	**Superior temporal**
34	-6	-73	23	4.37	0.012	L	Cuneus
36	9	-37	44	4.35	0.01	R	Cingulate cortex
69	**-33**	**-58**	**53**	**4.03**	**0.001**	**L**	**Inferior parietal**
28	-18	-52	8	4.00	0.021	L	Precuneus
20	-51	44	-1	3.82	0.046	L	Inferior orbitofrontal
39	-12	-25	71	3.80	0.008	L	Motor cortex
24	21	-28	53	3.54	0.031	R	Somatosensory
22	-54	-55	26	3.40	0.037	L	Temporoparietal
23	-57	2	-1	3.28	0.034	L	Temporal pole
Results of *Value Decoder 2*: areas that distinguish between high and low value for each location and sensory modality. After value classification was performed, results were inspected for **intra-modal stimuli.**							
27	-12	-22	71	4.81	0.024	L	Paracentral lobule
20	57	-31	8	4.72	0.047	R	Superior temporal
23	45	-28	53	4.58	0.035	R	Postcentral
36	-36	-61	56	4.49	0.011	L	Superior parietal
32	-24	23	56	4.45	0.015	L	Frontal mid
28	3	50	32	4.12	0.022	R	Frontal sup medial
26	9	-55	-43	3.91	0.026	R	Cerebelum
20	-36	-76	-1	3.68	0.047	L	Occipital mid
21	-9	-82	-28	3.54	0.043	L	Cerebelum
22	-51	-64	-16	3.46	0.039	L	Inferior temporal
Results of *Value Decoder 2*: areas that distinguish between high and low value for each location and sensory modality. After value classification was performed, results were inspected for **cross-modal stimuli.**							

60	-39	-25	5	5.17	0.001	L	Heschl
37	54	-28	5	4.66	0.008	R	Superior temporal
20	48	-1	2	4.56	0.041	R	Insula
30	-6	-73	23	4.49	0.015	L	Cuneus
25	-66	-28	17	4.35	0.024	L	Superior temporal
41	-57	-55	29	4.24	0.006	L	Angular
66	12	-25	38	4.07	0.001	R	Cingulum mid
24	-42	5	-19	3.77	0.027	L	Temporal pole sup
27	-15	-46	-13	3.69	0.02	L	Fusiform
21	-18	-52	8	3.44	0.037	L	Calcarine
Results of *Value Decoder 2*: areas that distinguish between high and low value for each location and sensory modality. After value classification was performed, results were inspected for the interaction of **cross-modal>intra-modal.**							
36	-42	-19	5	3.78	0.009	L	Heschl gyrus
Results of *Value Decoder 2*: areas that distinguish between high and low value for each location and sensory modality. After value classification was performed, results were inspected for the interaction of **intra-modal>cross-modal.**							
No voxel survived							

To test whether there are specific brain areas that contain more information about the stimulus value from one compared to another sensory modality, we contrasted the whole-brain results of the *value decoder 2* for Auditory (Cross-modal) >Visual (intra-modal) and vice versa. The first contrast (i.e. classification accuracy in auditory > classification accuracy in visual), revealed a cluster in the left auditory cortex which corresponded to the primary auditory area (area A1, at $p < 0.005$, k = 20 uncorrected). However, in the intra-modal interaction (i.e. classification accuracy in visual > classification accuracy in auditory), no voxel survived at the same threshold (at $p < 0.005$, k =20 uncorrected, see **Table 2**).

Based on the above results and our a priori hypotheses, we took the IPS and STS clusters as ROIs that might be involved in the long-range communications between the valuation network (i.e., OFC, identified by value decoder 1) and the early visual areas (i.e, EVA, identified by the orientation decoder), as they were discriminative of reward value across sensory modalities. Furthermore, value decoder 2 only identified the primary auditory cortex (area A1) as an area that contained more information about one over the other sensory modality (cross-modal > intra-modal), whereas we did not find any area that selectively encoded the value of intra-modal stimuli. In contrast to the A1, that might play a role in processing the sensory features of the auditory reward-associated cues, the superior temporal areas are known to be involved in higher-order auditory processing and the integration of information across senses (Stein and

Stanford, 2008), where most likely both the visual target and auditory reward-associated cues were processed. In fact, when we inspected the results of value decoder 2 in each individual modality, we observed STS activations for both intra- and cross-modal value (**Table 2**). We therefore reasoned that including STS but not A1 in our effective connectivity analyses would capture the reward-driven effects of both cross-modal and intra-modal stimuli, while reducing the complexity of models by adding multiple areas with overlapping functionalities (i.e., STS and A1).

3.4.5 Effective connectivity analysis revealed *how* reward information is broadcasted across the brain

After identifying the potential brain areas that might mediate the reward-driven modulation of early visual areas, we tested possible models of *how* reward information is broadcasted across the brain using an effective connectivity approach. Based on our hypotheses, three possibilities existed which gave rise to 11 biologically plausible schemes in our model space (**Figure 4A**): **1)** reward signals are communicated indifferently from the reward-related areas to the early visual areas, involving either a long-range direct projection (**fig.4A**, model 1) or mediation through the attention-related or higher sensory-related areas (**fig.4A**, model 2-4), **2)** reward signals are communicated following a modality-specific pathway through attention and/or higher sensory-related areas (**fig.4A**, model 5-10), or **3)** reward signals have a long-lasting effect where the neural plasticity in the early visual areas is altered locally without the necessity of information flow from and to the other brain areas (**fig.4A**, model 11 or *null*, see the Material and Methods). These models thus differed with respect to the nodes/regions and connectivity patterns which underlay the intra-modal and cross-modal information transfer. In all models, high and low reward conditions involved the same nodes and connectivity patterns but could influence the strength of the connectivity between each pair of nodes to a different extent (see Material and Methods). Therefore, we first established which nodes and connectivity patterns best explained the BOLD times series of the intra- and cross-modal conditions in pre- and post-conditioning and thereafter tested whether the strength of connections in the winning model was modulated by reward magnitude after the stimulus-reward associations were learned.

Among the possible models, our results (**Figure 4B**) indicated that model 10 gained the highest evidence in the post-conditioning (p_ex = 0.42) relative to the second best model (model 4, p_ex = 0.2). Meanwhile, model *null* gained the highest evidence in the pre-conditioning (p_ex = 0.99). As expected, learning of the reward associations changed the way that information was communicated across the brain, as reward-related areas were only involved in modulating the early visual areas *after* the stimulus-reward associations had been established. In the winning model 10 in the post-conditioning, intra- and cross-modal information needed to be gated through the regions involved in the attentional selection, as IPS was involved in mediating both communication paths. Additionally, the cross-modal condition engaged the STS, a higher-order sensory area, in order to communicate the reward information across the brain. This is aligned with our hypothesis 2, where intra- and cross-modal effects were mediated through both attention and sensory-dependent areas.

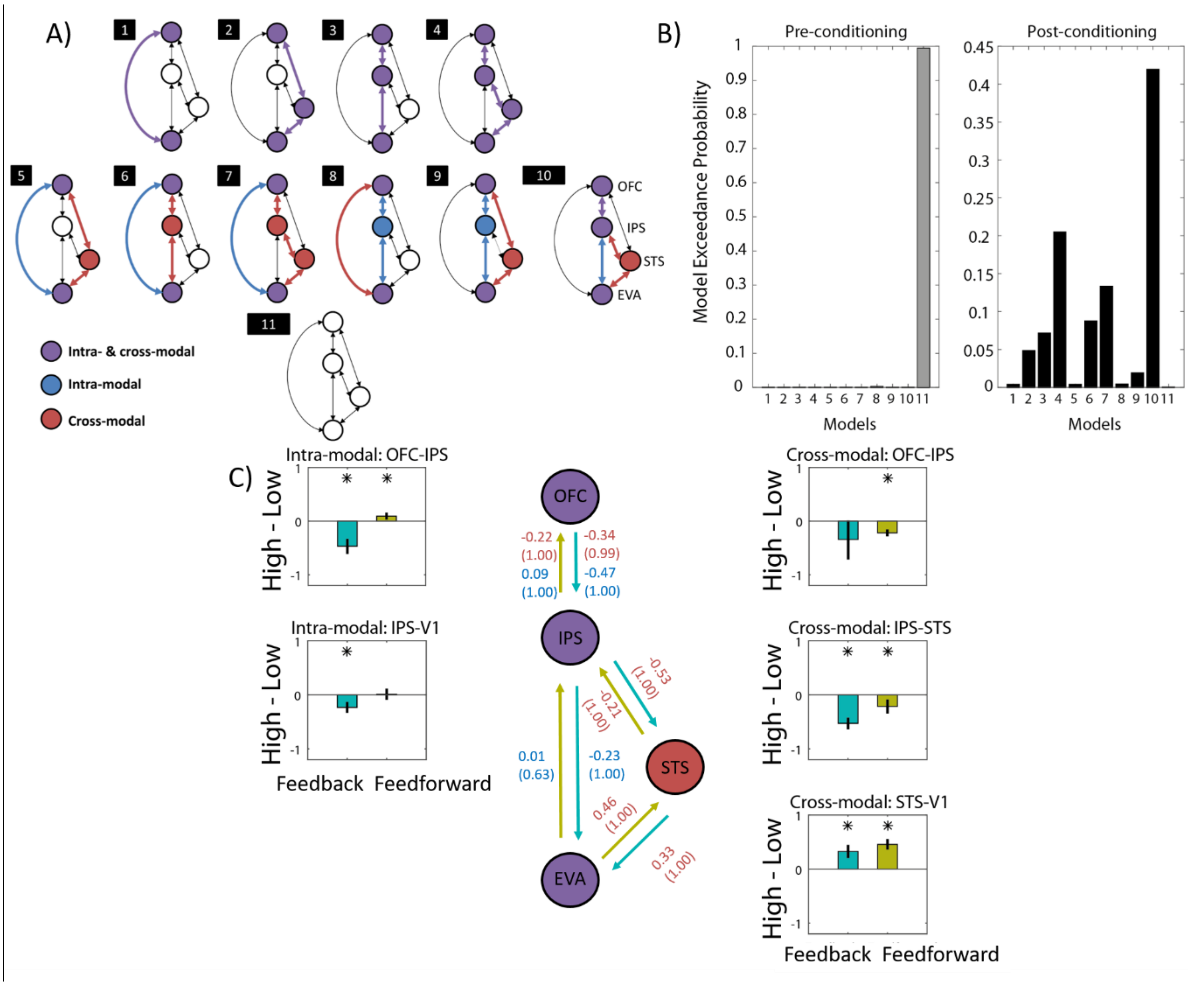

Figure 4. Effective connectivity results. A) Schematic of 11 models that were considered to probe the mode of the bidirectional communication between the reward-related areas and the early visual areas (EVA). **B)** The models were estimated for both pre- (in grey) and post-conditioning (in black) phases. The exceedance probabilities of random effects Bayesian model selection demonstrated that model 11 (null model) wins in pre- and model 10 wins in post-conditioning. **C)** Estimated parameters (in Hz) of the winning model in post-conditioning were used to characterize the reward modulation (i.e. changes in the strength of each connection when comparing high relative to low rewards) corrected for effects before reward associations were learned (i.e. post – pre conditioning). Reward modulations are shown for each connection between two regions and separately for each direction (feedback and feedforward, in teal and dark yellow, respectively). * corresponds to $p < 0.01$ (equivalent to posterior probabilities > 0.99) and corrected for multiple comparison using Bonferroni correction. Errorbars depict 99% confidence intervals of the subtracted distribution (high – low). The middle panel illustrates the schematic of the winning model and depicts the strength of reward modulation for feedforward and feedback connections (teal and dark

yellow arrows, respectively) and their respective posterior probability (in bracket) for the intra-modal (blue) and cross-modal (red) conditions.

In order to infer how reward value modulated the strength of connectivity between every pair of nodes/regions in the winning model, we next conducted a group level analysis on the weights of feedforward and feedback connections. We included both pre- and post-conditioning data of the winning model (model 10 in the post-conditioning) in our design matrix and examined the reward-driven changes in the weights of connections that occurred after the stimulus-reward associations were learned by regressing out the effects in the pre-conditioning (see the Material and Methods). This analysis summarised in **Figure 4C**, revealed widespread effects of reward value on the strength of connections between different regions. Specifically, we found both supra-modal (modality-independent) and modality-dependent reward modulations. The feedback from the valuation area (OFC) to the mediation areas in the IPS in intra-modal and STS in cross-modal condition were regulated similarly (i.e. modality-independent), as in both cases a feedback inhibition was observed (OFC-IPS: -0.47 Hz and -0.34 in intra- and cross-modal, respectively; and IPS-STS in cross-modal: -0.53Hz), likely to prevent the allocation of processing resources to high reward cues that were irrelevant to the target discrimination. However, there was a dissociation in the feedforward communication paths (i.e. modality-dependent), where intra-modal cues relied on the excitatory modulation (IPS-OFC: 0.09 Hz) and cross-modal cues relied on the inhibitory modulation (STS-IPS: -0.21 Hz and IPS-OFC: -0.22 Hz). This dissociation between intra- and cross-modal feedforward connections might indicate that mediation areas (IPS and STS) engage distinct mechanisms to prioritize the processing of sensory features of the high reward stimuli. Specifically, feedforward processing of intra-modal rewards was enhanced due to the need to discriminate the intra-modal reward cues from the visual target as both emanated from the same sensory modality, whereas the feedforward processing of cross-modal reward cues that were distinct from the visual target decreased. Moreover, the dissociation of reward effects was further observed in the communication between the mediation areas and the early visual areas (EVA), where intra-modal cues relied more on the inhibitory and cross-modal cues on the excitatory feedback modulation. Specifically, whereas the feedback communication in the intra-modal condition was suppressed (-0.23 Hz), both feedback (0.33 Hz) and feedforward (0.46 Hz) communication paths were facilitated for cross-modal cues. This distinction might indicate that the way higher reward increases the perceptual discriminability of the target may differ between the intra- and cross-modal conditions, where intra-modal rewards boost the differentiation and cross-modal rewards increase the integration of the reward cues and the target. Accordingly, the top-down inhibitory modulation from the IPS to EVA likely suppressed the processing of the high reward intra-modal cues (i.e. irrelevant information) to improve the representation of the target. In contrast, enhancing the feedforward processing of the visual target in EVA-STS, could potentially enhance the integration of the auditory reward-associated cues and the visual target and subsequently the excitatory feedback from the STS to EVA could boost the representation of the target.

3.5 Discussion

This study aimed to investigate the reward-driven modulation of the early visual processing. We compared intra- and cross-modal previously reward associated cues to probe whether their reward-driven effects depended on the sensory modality of the cues. In our paradigm using a visual discrimination task, previously reward associated task-irrelevant cues slightly improved the speed of perceptual decisions. Moreover, using a multivariate pattern classification approach, we observed that high reward stimuli enhanced the neural representations of the target in the early visual areas. We looked further into the possible neural mechanisms governing this effect by means of an effective connectivity analysis. This analysis revealed that reward-related information is communicated across the brain in both modality-independent and modality-dependent manners. In general, the reward-driven effects of both intra- and cross-modal cues recruited areas involved in the encoding of reward value and attentional selection. However, cross-modal rewards additionally involved the higher-order sensory-related areas such as STS. The feedback communication between these areas was predominantly inhibitory, demonstrating that reward value modulates the prioritization of information processing. Unlike the modality-independent interactions observed between the higher-level areas, the neural communication to and from the early visual areas were differentially modulated by intra- and cross-modal rewards. At this level, intra-modal rewards produced predominantly feedback inhibition whereas cross-modal rewards led to excitatory feedforward and feedback modulations.

Previously reward associated cues have been known to capture attention (Anderson et al., 2011). Consequently, when reward cues are not the target of the task, response times are slowed down as attention needs to be re-oriented from the reward-associated task-irrelevant distractors to the target. In our study, we observed a weak facilitation (i.e. faster reaction times) by the irrelevant high reward cues. A possible reason is the spatial alignment of the reward cues and target in our study that differed from Anderson and colleagues (2011), where in their design, reward cues and target were separated spatially. In contrast, in our design reward cues and the visual target were presented at the same location. Therefore, attention did not need to be re-oriented and the capture of attention created by the irrelevant reward cues could potentially spill over to the target, energizing the responses. Moreover, in contrast to our previous study (Vakhrushev et al., 2021), where perceptual discrimination and visual evoked potentials were either suppressed or enhanced by the intra- and cross-modal rewards, respectively, we did not observe an interaction effect. An aspect that differed with this previous study was the length of training on the task before the reward associations were learned, where in the current study the number of trials in the pre-conditioning phase was doubled so that participants are better accustomed to the reward cues and their relation to the task. This extended training might have allowed that the competition between the target and the task-irrelevant cues especially the ones from the same sensory modality is better resolved. In fact, in a subsequent study (Antono et al., 2022), we showed that after being exposed to the intra- and cross-modal reward cues that were predictive of the delivery of the reward upon correct performance, the visual discrimination was enhanced by previously rewarded cues of both modalities. This finding supports the idea that the duration of training and the history of reward delivery may influence the way that task-irrelevant previously rewarded stimuli affect the perceptual decisions (Jahfari and Theeuwes, 2017; Jahfari et al., 2020). Future studies will be needed to systematically investigate these factors.

In line with the behavioural results, we found that early visual areas within the anatomical boundaries of area V1 – V2 had a better representation of the tilt orientation of the target when the target was presented together with the high reward stimuli. Reward signals have been known to modulate the early sensory areas (*visual*: Bayer et al., 2017; Serences, 2008, *auditory*: Beitel, et al., 2003; Guo, et al., 2019, *somatosensory*: Pleger, et al., 2008). More specifically, it has been known that the early visual areas are sensitive to the reward magnitude (Serences, 2008; Weil et al., 2010; Arsenault et al., 2013) and timing (Shuler & Bear, 2006; Chubykin, et al., 2013). Importantly, the reward-driven modulations in our study were spatially specific and overlapped with the regions within the area V1-V2 that represented the visual target, in line with previous observations (Serences, 2008; Arsenault et al., 2013). In contrast, other studies have provided evidence that reward effects may rely on a combination of stimulus-specific and unspecific modulations, suggesting that reward learning in the visual system may be gated by mechanisms that are distinct from sensory processing (FitzGerald et al., 2013; Schiffer et al., 2014; Poort et al., 2015). Since in our design we did not manipulate the spatial location of stimuli and the delivery of rewards were halted during the test phase, we cannot infer the extent to which the spatial profile of reward-driven effects in our study reflects a general principle as opposed to a particular pattern imposed by our task design. Unravelling the spatial characteristics of reward-driven modulations from different sensory modalities is an important direction for future studies.

What mechanisms underlie the reward-driven enhancement of target representations in the early visual areas? We sought the answer to this question by first mapping the areas where the reward value was represented and thereafter testing different models of how reward information could be communicated between the valuation and early visual areas. Using a multivariate pattern classification approach, the lateral orbitofrontal cortex (OFC) was identified as a region that reliably encoded stimulus value independent of the sensory features of the reward associated stimuli. Previous studies have shown that this area plays a key role in representing the magnitude of rewards, especially when there is uncertainty in the appropriate course of action to be taken such as when previously rewarded responses should be suppressed (Elliott et al., 2000; O'Doherty et al., 2001). Furthermore, IPS and STS were identified by the value decoders which were sensitive to the sensory features of the reward stimuli (i.e., modality and location). IPS has been consistently linked to the processing of the goal-directed information and voluntary orienting towards a spatial location (Corbetta et al., 2000; Corbetta and Shulman, 2002; Serences and Yantis, 2007). Specifically, the coordinates observed in our study is close to the anterior part of the IPS with dense neuroanatomical connectivity with the frontal areas (Greenberg et al., 2012), suggesting that the modulation of IPS may be driven by the top-down signals from the frontal valuation areas. The superior temporal areas such as STS have been classically shown to be involved in the integration of information across sensory modalities (Calvert et al., 2001; Werner and Noppeney, 2010). Moreover, the role of this area in the integration of information has been shown to go beyond the multisensory processing and also include a general role in linking the sensory attributes of stimuli to the cognitive factors such as attention (Shapiro and Hillstrom, 2002), reward (Lim et al., 2013; Pooresmaeili et al., 2014) and affective and social processing (Beauchamp, 2015). Importantly, STS and IPS have been shown to have structural connectivity (Cavada and Goldman-Rakic, 1989) and form a network for attentional (Shapiro and Hillstrom, 2002) and multisensory processing (Werner and Noppeney, 2010), and additionally STS has been shown to communicate the reward-related information to the frontal valuation areas (Lim et al., 2013). Given these findings from the previous studies, the valuation areas identified by our approach constituted a plausible network, shown in **Figure 4,** to represent and communicate the information related to the reward value across the brain.

We next used an effective connectivity analysis to explicitly test how such a putative communication occurs. We tested different mechanisms that either relied on a direct or a mediated communication between the valuation and the early visual areas. This analysis supported a model which assumed the mediation of reward effects through attention and/or higher sensory areas. The communication between the valuation- and attention-related areas are aligned with the notion of attentional gated reward processing (Roelfsema and Van Ooyen, 2005). In line with this model, we found that when there was a need to discriminate the sensory features of reward- and task-related stimuli, as was the case when reward cues were from the same modality, the feedforward communication between the attentional and the valuation network was enhanced relative to when reward-related stimuli were highly distinct from the visual target (i.e. for cross-modal cues). On the other hand, previous studies have also proposed rewards to be a teaching signal for attention (Chelazzi et al., 2013), as the magnitude of reward determines the way that attention should be allocated in space. In line with this proposal, we found a general pattern across the sensory modalities where higher areas sent inhibitory feedback signals to upstream attentional and higher-order sensory areas, potentially in order to suppress the excessive allocation of attention and other processing resources to the task-irrelevant cues. Together, our findings show the fine-tuned mechanisms that underlie the regulation of attention and reward processing across the sensory modalities.

The pattern of connectivity modulations at the lower levels of the network shown in **Figure 4C** revealed further dissociations between the intra- and cross-modal rewards. Specifically, the communication from the IPS back to the early visual areas demonstrated a distinct pattern across intra- and cross-modal conditions. Whereas reward-related information was communicated from IPS directly to the early visual areas and elicited feedback inhibition, cross-modal cues required a mediation through a sensory-dependent area in the superior temporal areas and modulated the early visual areas through excitatory interactions. This pattern is in line with the findings of a previous study (Vakhrushev et al., 2021) where a dissociation between the reward-driven effects of previously rewarded intra- and cross-modal cues was found. Putatively, the feedback inhibition in case of the intra-modal reward cues reflects the down-weighting of the value of the task-irrelevant features of an object (i.e. the colors), which share processing resources with the target. In fact, recent studies have shown that at the level of area V1, processing of orientation and color is more inter-related than previously thought (Garg et al., 2019). This means that by regulating the processing of high reward colors through feedback inhibition, the early visual areas could better dedicate resources to the representation of the stimulus orientation. In contrast, in the cross-modal condition, there is little necessity to suppress the reward cues as they elicit a relatively weaker competition with the target at the level of the early visual areas. In fact, through enhancing the allocation of attention (Eimer and Driver, 2001) or the integration of the auditory tones and visual stimuli (Driver and Noesselt, 2008; Petro et al., 2017), a boost in the processing of cross-modal reward cues could potentially enhance the overall salience of the visual target at the level of early visual areas.

Altogether, the commonalities and dissociations between intra- and cross-modal rewards observed in the effective connectivity results point to two general patterns. Firstly, both reward types engage attentional areas and lead to a predominantly inhibitory feedback connectivity between the valuation and attentional areas. Hence, the regulation of information processing at the level of higher cognition seems to be modality-independent. Secondly, at the lower levels of hierarchy where reward-related information is relayed to the early visual areas, more dissociations between the intra- and cross-modal rewards emerge: not only do the cross-modal rewards additionally engage a higher-order sensory area (STS) but also they elicit an overall enhanced communication to and from the early visual areas, whereas intra-modal rewards evoked an overall inhibition. We interpret the dissociations between the intra- and cross-modal reward effects as a consequence of the differences in the way that they interact with the processing of the target at the level of early visual areas. Future studies will be needed to test whether a systematic relationship exists between the degree of overlap in neural mechanisms of task-relevant and reward-related features of stimuli and the way that perceptual decisions are influenced by the rewards.

Previous theoretical and empirical work has suggested a tight interaction between reward and attention (Roelfsema and Van Ooyen, 2005; Stanisor et al., 2013). In this vein, it has been suggested that attention and reward reinforcement (Seitz and Watanabe, 2009) can work as heuristics which help the visual system to determine the sensory features that are relevant. Similarly, Padmala and Pessoa (2011) discussed that reward information enables a coupling between the attentional and valuation networks. Specifically, comparing the functional connectivity of rewarded and not-rewarded trials (Padmala and Pessoa, 2011; Kinnison et al., 2012) they found that whereas in rewarded trials attentional and valuation mechanisms worked as an integrated system, in not-rewarded trials they worked more independently from each other. Extending these findings, we showed that the coordination of attention and valuation may additionally occur for previously rewarded stimuli and engage higher-order sensory areas such as STS. An important direction for future studies will be to examine whether the mode of interaction between reward-, attention- and sensory-related areas holds under different contexts for instance different attentional loads and contingencies of rewards to performance (Antono et al., 2022). Our hypothesis is that the visual system will engage both attention and reward systems as resources to learn and change its plasticity. However, depending on the availability and the reliability of the resources, it can flexibly rely on one system rather than the other. Furthermore, future studies will be needed to delineate whether the involvement of long-range interactions to and from the sensory areas is a general feature of reward-driven modulation of perception or a specific finding in the setting that we tested. It is conceivable that when rewards are consistently paired with the task-relevant features, they may induce long-lasting changes at the level of early sensory areas that locally enhance the processing of reward-related stimuli, as predicted by computational models (Wilmes and Clopath, 2019). In these cases, a long-term prioritization of reward-related stimuli is advantageous for the system as they could consistently lead to a behavioural gain for the organism. Quantifying the exact relationship between rewards' availability and reliability and the degree to which they promote long-term plasticity in the early sensory areas is an exciting direction for future studies.

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Authors' contributions

JEA and AP conceptualized the project designed the task. JEA conducted the experiments. JEA, SD, RA, and AP analyzed the data. JEA and AP interpreted the results and wrote the first draft of the manuscript. All authors revised the manuscript. AP acquired funding.

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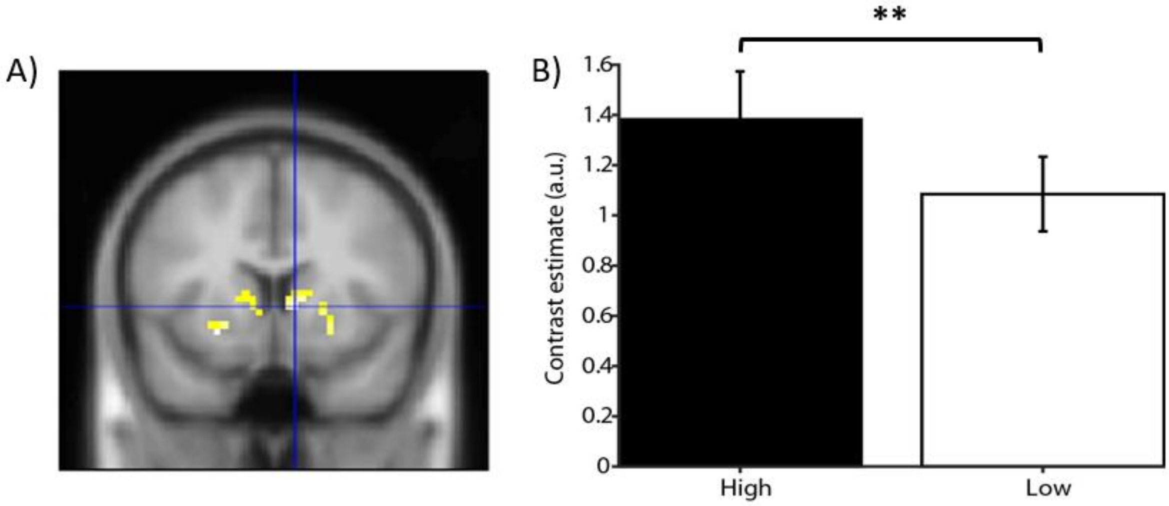
3.7 Supplementary Information

3.7.1 Conditioning phase

To ensure that participants had learned reward-cue associations, we asked a question during and after the experiment. Based on these questionnaires, all participants could correctly identify which cue properties were associated with high compared to low reward magnitudes/ or were aware of the cue-reward associations. We further tested whether during the conditioning phase, reward predicting cues modulated participants' behavior. Participants exhibited near perfect accuracy in localizing both visual and auditory stimuli (mean performance 99.9% and 96%±1%, respectively), with a consistent superiority of vision (F(1,32) = 18.36, $p < .001$, $\eta_p^2 = 0.365$). Similarly, participants' responses were significantly faster in visual compared to auditory trials (F(1,32) = 70.94, $p < .001$, $\eta_p^2 = 0.689$). This result is in line with the superior performance of vision compared to audition in localization tasks. However, we found no significant main effect of reward on either accuracies (F(1,32) = 0.93, $p = 0.34$, $\eta_p^2 = 0.028$) or response times (F(1,32) = 0.29, $p = 0.60$, $\eta_p^2 = 0.009$), neither did we find an interaction between reward and modality on accuracies (F(1,32) = 0.71, $p = 0.405$, $\eta_p^2 = 0.022$) or response times (F(1,32) = 0.20, $p = 0.66$, $\eta_p^2 = 0.006$). This result is likely due to the fact that the task was already done at a near perfect level and performance had already reached a ceiling.



Supplementary Figure 1. Main effect of reward (AH+VH>AL+VL, AH: Auditory High reward, VH: Visual High reward, AL: Auditory low reward and VL: Visual Low reward) during the conditioning phase. A) Contrast between high against low reward conditions, thresholded at $p < .001$ (uncorrected) with k = 10 and masked with an anatomical ROI encompassing the ventral striatum mask (i.e., Putamen, Caudate, and Globus Pallidus). Crosshair is at the peak activation xyz = [9 11 2]. B) Bar graphs depict the contrast estimates of high against low reward conditions. ** corresponds to $p < 0.01$ based on a paired sample *t*-test.

We next examined the reward-driven modulation of BOLD responses during the conditioning phase by inspecting the results of a mass-univariate analysis of fMRI data during this phase. As expected, several brain areas encompassing sensory (e.g. visual cortex) and reward-related areas (such as insula and the ventral striatum) demonstrated a strong modulation by rewards across modalities (i.e. for the contrast AH+VH > AL+VL, see **Supplementary Table S1**). These areas have been consistently shown to be involved in the processing of reward information during associative learning in previous studies (Schultz, 2000; Daniel and Pollmann, 2014), and indicate that participants did learn the association between cues and different reward magnitudes. For illustrative purposes, we examined the main effect of reward in a ROI encompassing the ventral striatum, an area that has been shown to be involved in learning of reward associations in a large body of previous literature (Schultz, 2000; Tremblay et al., 2009; Haber and Knutson, 2010). We found that higher reward magnitude modulated the ventral striatum compared to lower reward magnitude, as shown in **Supplementary Figure 1**. Moreover, we investigated further whether the reward effect had dependencies on the sensory modalities at this stage. To this end, we examined the interaction contrasts corresponding to a stronger reward effect in auditory (AH-AL > VH-AL) or visual (VH-VL > AH-AL) stimuli. We observed that a right lateralized Caudate [15 -22 26] cluster that was modulated stronger by auditory compared to visual cues, whereas no activations were found for the opposite contrast (VH-VL > AH-AL). This result demonstrated that auditory stimuli elicited stronger activations in reward-related areas such as Caudate, suggesting that the sensory modality of rewards could be to some extent dissociated in the reward-related areas. Moreover, this result may also be due to a higher saliency of auditory compared to visual stimuli, as the Caudate has been known to encode saliency of the sensory stimuli (Zink et al., 2006).

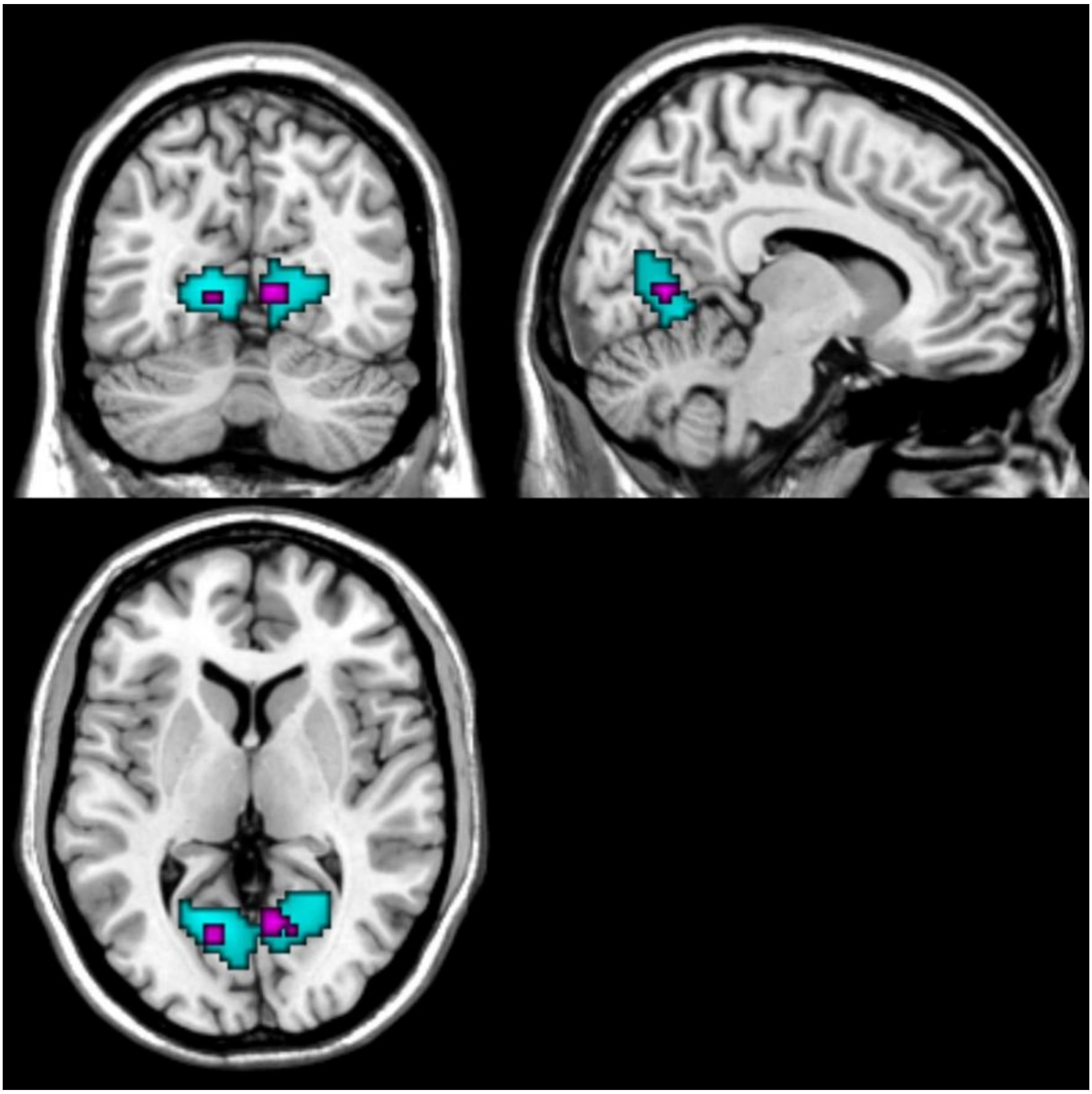
Supplementary Table 1. Whole-brain analysis result during conditioning phase with uncorrected threshold of p < .001 and extent threshold of k = 10.

Cluster size	**MNI coordinates (in mm)**			**T**	***p***	**Side**	**Region**
	x	y	z				
Main effect of reward (VH+AH > VL+AL)							
562	21	-91	-4	7.06	< .001	R	Lingual
813	-27	-94	-1	6.99	< .001	L	Occipital Mid
162	-27	17	-10	5.76	0.004	L	Insula
194	39	17	-7	5.34	0.002	R	Insula
423	9	41	17	4.96	< .001	R	Cingulum Mid
79	-21	-52	-22	4.95	0.031	L	Cerebelum

28	18	-70	62	4.73	0.174	R	Parietal Sup
94	33	-76	35	4.62	0.020	R	Occipital Mid
43	-12	-61	68	4.40	0.098	L	Precuneus
30	45	-61	5	3.79	0.160	R	Temporal Mid
12	-27	-43	50	3.70	0.370	L	Postcentral
11	30	26	8	3.58	0.392	R	Insula
Interaction of reward in cross-modal condition (AH-AL > VH-VL)							
46	15	-22	26	4.56	0.116	R	Caudate
Interaction of reward in cross-modal condition (VH-VL > AH-AL)							
No voxels survived							

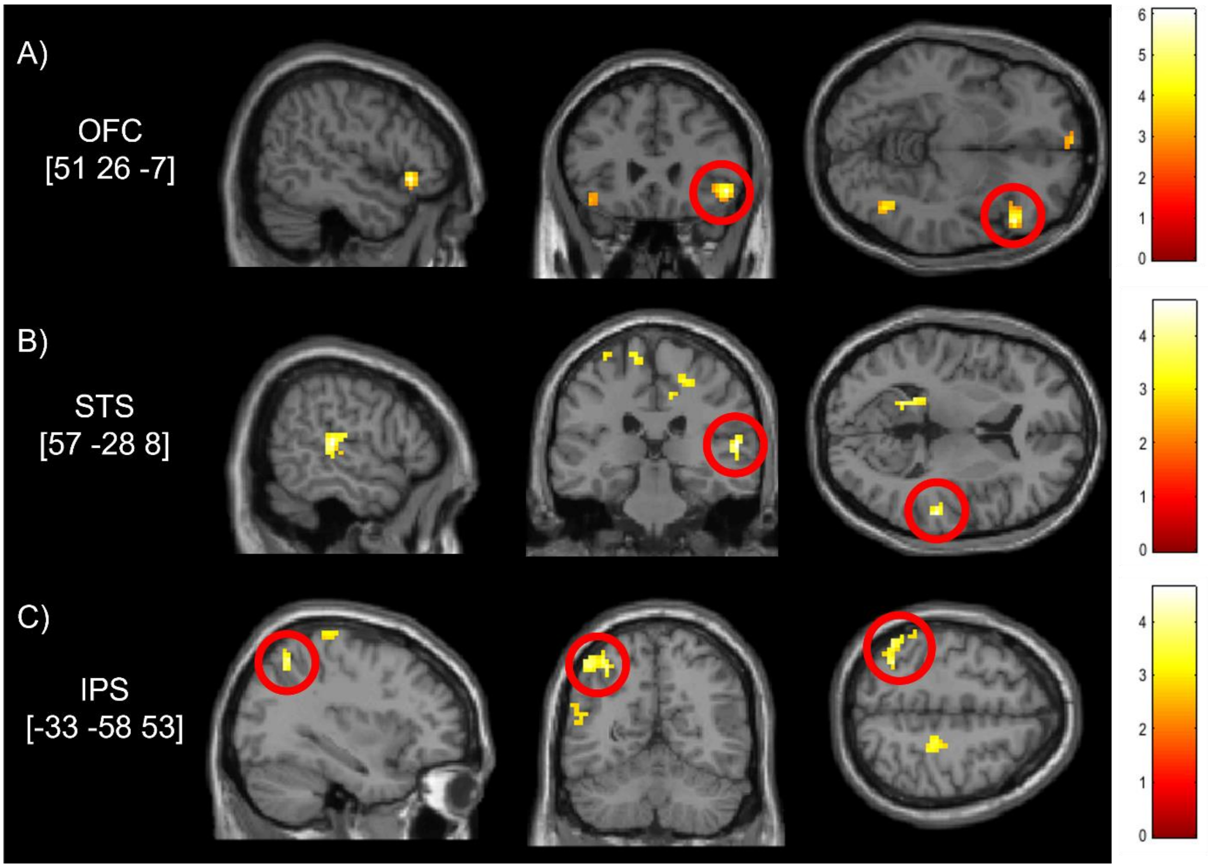
3.7.2 Reward modulation on the early visual areas overlapped with target processing areas

To find a region in the early visual areas that was specifically responsive to the visual target (i.e., was target-specific), we inspected the univariate contrast of Neutral cues > Baseline (corrected at pFWE < 0.05, k = 0, cyan region in **Supplementary Figure 2**). The effect of rewards on the representation of visual target shown in **Figure 2B** of the main text, spatially overlapped with the target-specific regions identified by the above contrast (magenta activations in **Supplementary Figure 2)**. Specifically, reward-driven modulations (right n of voxels = 19; left n of voxels = 14) were small-volume corrected within a mask comprising of target-specific activations (right n of voxels = 14; left n of voxels = 13, *p* uncorrected < 0.005, k = 10, see **figure S2**), indicating that most of the activated voxels correspond to the target-specific regions. Nevertheless, we took the whole cluster within V1-V2 anatomical mask for the effective connectivity analysis.



Supplementary Figure 2. Reward facilitation in the early visual areas (masked with V1-V2 anatomical mask) overlapped with areas responsible for processing the target cue. Cyan color shows the response magnitude of target processing (Neutral vs Baseline) thresholded at *p*FWE < .05 and k = 0. Magenta color shows the rewardd-driven facilitation effect in visual areas thresholded at uncorrected *p* < .005, k = 10. The cursor is at xyz=[9 -64 5].

3.7.3 Whole-brain results of the *value decoders*



Supplementary Figure 3. Whole-brain results of the value-decoders depicting sagittal, coronal, and the axial view for: A) lateral orbitofrontal areas xyz = [51 26 -7] in the right hemisphere from *value decoder 1*. B) The left anterior intraparietal areas xyz = [-33 -58 53] and C) The right superior temporal areas xyz = [57 -28 8] detected by the *value decoder 2* across sensory modalities. These ROIs were taken further to the effective connectivity analysis. All images were thresholded at uncorrected $p < .005$, $k = 20$. The cursor is at the peak activities of each corresponding ROI coordinates written in brackets.

Regions of interests (ROI) extracted from the whole-brain results of the *value decoder*$_1$ and *value decoder*$_2$ (see Materials and Methods), where the right lateral orbitofrontal areas had the strongest modulation in the *value decoder1* (see **figure S3**). Other areas such as the Caudate, Cerebelum, and the left lateral orbitofrontal areas were also modulated by reward (see **Table 1**). Moreover, *value decoder2* showed the right superior temporal areas had the strongest reward modulation. Interestingly, areas that have been linked to attentional processing in the anterior intraparietal areas (Corbetta and Shulman, 2002) also demonstrated as the largest areas modulated by reward. The time-series of these areas were extracted for effective connectivity between the reward-related areas in the lateral orbitofrontal cortex and the early visual areas.

Chapter 4: Modulation of perception by visual, auditory, and audiovisual reward predicting cues

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Chapter 4

As summarized in the previous chapters, we have shown so far how reward affects behavior under two modes of contingencies, where some aspects of reward effects were stronger when the cues were still predictive of the reward delivery upon correct performance. Furthermore, we also observed that even when the reward delivery was halted (i.e. extinction), value-driven modulation of perception by previously rewarded stimuli persisted. Our neuroimaging results revealed that previously rewarded stimuli from the visual (intra-modal) or auditory (cross-modal) modalities exert their effects on the early visual areas through distinct neural pathways. Specifically, we showed that reward-related information was communicated between the frontal valuation and the early visual areas either through the attentional network or additionally also involved the Superior Temporal (ST) Cortex when rewards were cross-modal. Our environment often contains multisensory objects, where an integrative process binds the stimuli from the different sensory modalities together to produce a coherent percept of an object, a phenomena known as multisensory integration (MSI). It has been shown that ST plays a crucial role in this process. Therefore, it is possible that reward has a direct influence on the multisensory integration. In light of this knowledge, in this chapter we explicitly test this possibility and ask whether multisensory reward cues are regulated by similar or different principles compared to the unimodal reward cues.

4.1 Abstract

Rewards influence information processing in the primary sensory areas specialized to process stimuli from a specific sensory modality. In real life situations, we receive sensory inputs not only from one single modality, but stimuli are often multisensory. It is however not known whether the reward-driven modulation of perception follows the same principles when reward is cued through a single or multiple sensory modalities. We previously showed that task-irrelevant reward cues modulate perception both intra- as well as cross-modally, likely through a putative enhancement in the integration of the stimulus parts into a coherent object. In this study, we explicitly test this possibility by assessing whether reward enhances the integration of unisensory components of a multisensory object in accordance with the *supra-additive* principle of multisensory integration. Towards this aim, we designed a simple detection task using reward predicting cues that were either unisensory (auditory or visual, both above the detection threshold) or multisensory (audiovisual). We conducted two experiments, behavioral (experiment 1) and simultaneous behavioral and neuroimaging testing (experiment 2). We expected that reward speeds up reaction times in response to all stimulus configurations, and that additionally the reward effects in multisensory cues fulfill the *supra-additive* principle of multisensory integration. We observed that reward decreased response times in both experiments with the strongest effect found for the multisensory stimuli in experiment 1. However, this behavioral effect did not fulfill the *supra-additive* principle. Neuroimaging results demonstrated sensory supra-additivity at the classical areas involved in multisensory integration such as the Superior Temporal areas (STs), while reward modulation was found in the midbrain and fronto-parietal areas, reflecting the typical areas that receive dopaminergic projections. However, reward did not enhance the *supra-additivity* in the STs compared to a no reward condition. Instead, we observed that some of the reward-related areas showed a *sub-additive* modulation by rewards and areas exhibiting a weaker *supra-additive* response to audiovisual stimuli, namely the fusiform gyrus, were modulated by rewards of audiovisual stimuli as measured by a conjunction analysis. Overall, our results indicate that reward does not enhance the multisensory integration through a *supra-additive* rule. These findings inspire a model where reward and sensory integration processes are regulated by two independent mechanisms, where sensory information is integrated at an early stage in a *supra-additive* manner, while reward modulates perception at a later stage *sub-additively*.

Moreover, an associative area in the Fusiform gyrus exhibits a convergence of both reward and multisensory integration signals, indicating that it may be a *hub* to integrate different types of signals including rewards to disambiguate the information from different sensory modalities.

Keywords: reward, multisensory integration, sensory perception, fMRI

4.2 Introduction

When we are enjoying our environment, for instance in a park, we experience a multitude of rich sensory inputs, such as birds chirping, people chatting while walking their dog, the wind blowing, and so on. Although the stimuli we encounter are coming from different senses (e.g. we see the bird on the tree and we hear the bird chirps), we perceive them as a unity. In other words, the brain integrates multiple sensory signals into a single coherent percept.

This phenomena is called multisensory integration and has been extensively studied in the past (Calvert, Hansen, Iversen, & Brammer, 2001; Soto-Faraco, Kingstone, Calvert, Spence, & Stein, 2004; M. T. Wallace, Meredith, & Stein, 1993; Mark T. Wallace & Stein, 1997), originating from the evidence in the neurophysiological study by Meredith & Stein, (1986), where the neural activity in the Superior Colliculus (SC) of anesthetized cats in response stimuli from either auditory, visual, or audiovisual was measured. When the cat received audiovisual stimuli, the neurons in the SC showed a response that exceeded the sum of the responses to the unimodal stimuli. At the neural level, multisensory integration is defined operationally as a statistically significant difference between the number of impulses evoked by a multisensory cue and those evoked by the most effective of the unisensory cues (Stein & Stanford, 2008). This exceeded response is the hallmark of multisensory integration and is argued to underlie the mechanism by which the brain suppresses the noise evoked by each stimulus alone, thereby disambiguating the percept of a multisensory object (Diederich, 1995; Diederich & Colonius, 2004; Stein & Stanford, 2008). Computationally, multisensory integration is a phenomenon whereby a response to multisensory stimuli exceeds the pooled responses to the unisensory cues, referred as a *supra-additive* response, whereas when the multisensory response shows equal or less response than the pooled response to unisensory cues, it is referred as an *additive* or *sub-additive* response (Colonius & Diederich, 2017; Stein, Stanford, Ramachandran, Jr, & Rowland, 2009). The *supra-additivity* rule has been observed in both neural (Stein, Meredith, & Wallace, 1993; M. T. Wallace et al., 1993) and behavioral responses to multisensory stimuli (Diederich & Colonius, 2004). Critically, in order for multisensory integration to occur, two (or more) sources of stimuli have to coincide in time and in space, i.e., they should occur simultaneously and be located at the same spatial location (Otto, Dassy, & Mamassian, 2013; Stein & Stanford, 2008). Moreover, the more ambiguous/noisy the stimuli are, the better the cues will be integrated (i.e. higher neural response for multisensory cues), a phenomena called the inverse effectiveness (Diederich & Colonius, 2004; Otto et al., 2013; Stein & Stanford, 2008).

Although multisensory integration effect is quite robust, its underlying mechanism has been disputed. Some argue that multisensory integration occurs automatically, as it can happen without the involvement of cognitive factors such as attention or awareness (Romei, Murray, Merabet, & Thut, 2007), while other researchers have provided evidence for an involvement of cognitive factor such as attention (Talsma & Woldorff, 2005) and awareness (Delong & Noppeney, 2021; Lunghi, Verde, & Alais, 2017). At a neurophysiological level, the automaticity of multisensory integration effects has been supported by showing that these effects arise at the level of subcortical or primary sensory areas, as the studies using anesthetized cats have shown (M. T. Wallace et al., 1993). However, multisensory integration response has also been observed in other areas such as in the intraparietal, superior temporal, and frontal cortex (Calvert et al., 2001; Lewis & Van Essen, 2000; Linden, Grunewald, & Andersen, 1999; Schroeder & Foxe, 2002; Stein & Stanford, 2008). These areas are known to process multisensory cues, as they respond to more than one sensory input but are also involved in higher cognitive functions. This indicates that there is an interplay between cortical and subcortical areas regulating multisensory integration that engages different sites, depending on the context. This raises a question as to whether multisensory integration is indeed an automatic process or does it depend on higher cognition?

Previous studies have investigated the role of attention, as a form of top-down/cognitive factor, in multisensory integration. An event related potential (ERP) study found a larger amplitude in the frontal positivity for the attended multisensory cues compared to the unattended ones (Talsma & Woldorff, 2005). Similarly, Senkowski, Talsma, Herrmann, & Woldorff (2005) extended this finding by using gamma band response as a measure and found early (< 90ms) attentional modulation of multisensory integration. These studies showed that attention plays a role in the multisensory integration at an early stage of cortical signal processing. Furthermore, Degerman and colleagues (2007) showed that the underlying neural basis of attentional effects on multisensory integration is similar to the unimodal cues, where it involves areas in the frontal, temporal, parietal, and occipital cortex. Additionally, attended multisensory features produced a stronger response in the superior temporal areas, compared to the attended single feature of a multisensory cue. Moreover, Ferrari and Noppeney (2021) extended this finding using a combination of Bayesian modelling in psychophysics and neuroimaging evidence and proposed that attention guides multisensory perception by two distinct mechanisms: the pre-stimulus attention enhances the precision of the attended sensory inputs, while post-stimulus attention binds features into a coherent percept depending on whether the features need to be integrated or not. The common findings across all these studies is that higher cognitive factors such as attention play a critical role in the multisensory processes, and that rather than being automatic, multisensory integration results from an interplay between higher cognition and early sensory processing.

However, previous studies are largely limited to the attentional processes. Both attention and reward are cognitive factors that shape our behavior and guide our decision (Pessoa & Engelmann, 2010). Unlike attention, the role of reward in multisensory processing has not been much explored. Hence, there is little known about how generalizable the interaction between the higher cognition, such as reward, and the multisensory processes are. Recent studies have investigated the interaction of higher cognition and multisensory processes using reward, questioning the automaticity of multisensory integration as earlier studies in attention have done. For instance, Bruns, Maiworm, and Röder (2014) found that reward expectancy alters the audiovisual spatial integration processes. In their study, they observed that higher magnitude of monetary reward reduced the cross-modal binding between audio and visual cues in the *ventriloquism* effect (i.e. rewarded cues exerted smaller ventriloquism effect), as reward made the auditory cues more spatially separable. Their findings highlight that reward influences that multisensory processes that are thought to be automatic, where possibly the interaction between reward and multisensory processing is enabled through a mediation via cognitive control mechanisms. Furthermore, Bean, Stein, and Rowland (2021) also examined this question by investigating the role of reward associations in multisensory integration. They showed that irrespective of the complexity of the cues, animals approached multisensory objects more reliably than the unisensory objects. However, when the value associated to one of the unisensory components of a multisensory object did not match the other, this gain for multisensory cues was lost. Their study hence shows that reward is an important factor for an organism to bind sensory cues to each other. Specifically, when there is a congruent association between the cues, it is more likely that integration will occur. Similarly, a study by Cheng, Saglam, André, and Pooresmaeili, (2020) observing the reward-driven modulation of saccadic trajectories in human found that the congruency of reward value across unisensory cues determines the combined salience of multimodal stimuli. Moreover, Hoofs, Grahek, Boehler, and Krebs, (2022) investigated the interaction between reward and attention to alter multisensory perception. In their study, they found that multisensory rewarded cues had a qualitatively different modulation than orienting (i.e. attention) processes, where multisensory reward processes were not simply expressed as the sum of the unisensory responses. Instead, in an orienting task, they showed that visual cues had a stronger attentional capture than auditory cues which occurred very early, indicating an automatic attentional process. However, when reward was expected, this attentional capture by visual cues was reduced in that the simultaneous presence of auditory cues helped performance by employing a more strategic orienting to the cued location.

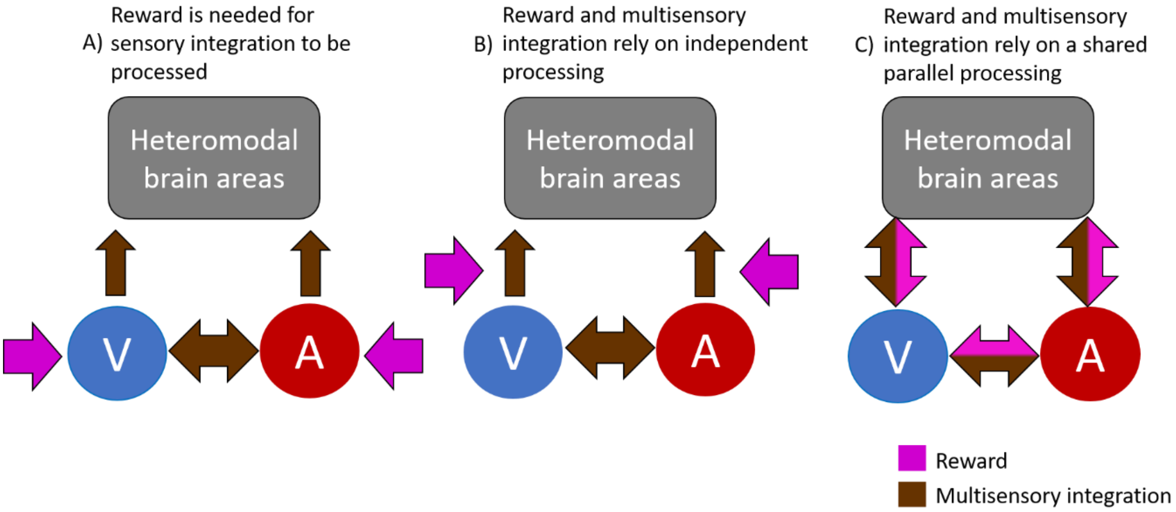

Figure 1. Schematic of the possible interactions between reward and audiovisual integration adapted from Koelewijn et al. (2010). In A), reward signal is needed in order for sensory cues to be integrated. Here, reward effect on multisensory integration is supra-additive. In contrast, B) proposes that reward and multisensory processes are two independent mechanisms, where multisensory integration occurs automatically, and then reward might modulate the effect further. This is expressed as sub-additive or additive reward effect in multisensory compared to unisensory stimuli. Alternatively, C) proposes that reward and multisensory integration are processed at multiple stages simultaneously. Since reward and multisensory integration occur at the same stage of processing, this model also predicts a supra-additive reward modulation for multisensory stimuli (but this supra-additivity could be observed at the level of heteromodal brain areas and not necessarily at the level of primary sensory areas).

Previous studies above have shown that reward plays a role in multisensory integration (Bruns et al., 2014), where either the prior association of reward (Bean et al., 2021; Cheng et al., 2020) or reward probabilities (Hoofs et al., 2022) is critical for the integration process. However, it is not clear whether other properties of reward, such as the magnitude of predicted rewards also plays a role in the integration process. More generally, it is not known how and at what stage of processing reward and multisensory integration interact with each other. As areas that are responsive to the magnitude of reward such as the ventral striatum, have also shown multisensory integrative response (Reig & Silberberg, 2014; Stevenson, Kim, & James, 2009), one possibility is that reward-related areas are also responsible for the integration of multisensory cues when they are predictive of rewards. Another possibility is that reward signals have to be projected to the sensory association areas (e.g. STS) or even the primary sensory areas in order to be affect the multisensory integration. In this context, we have previously shown that unimodal reward-associated cues involved both modality-independent reward- and attention- related areas as well as modality-dependent sensory association areas such as the STS. In this study, we ask whether when the reward is signaled from multiple sensory modalities, its effect would engage yet another distinct processing pathway compared to unimodal rewards or whether it would concurrently engage areas that are involved in the processing of unimodal rewards.

As attention has been more extensively investigated, there has been a systematic proposal of how attention and multisensory processes interact. Koelewijn, Bronkhorst, and Theeuwes (2010) proposed three different frameworks based on audiovisual attention studies. We adapted this framework to effects of reward, assuming that reward effects on multisensory mechanisms will follow a similar pattern as attentional effects. The *early integration* model (**Figure 1A**) proposes that multisensory integration would not occur without the reward information or in other words reward gates the multisensory integration. Here, we expect that reward modulates the responses of unimodal cues at a very early stage and since multisensory integration combines the already modulated responses to rewards, reward effects in multisensory stimuli are *supra-additive*. The *late integration* proposes that reward and multisensory integration are two independent mechanisms (**Figure 1B**). Here, we expect that sensory integration will occur first, producing a *supra-additive* response. Then, reward effect may enhance the response further. Note that in this framework, reward effect may not be *supra-additive,* but rather *additive* or *sub-additive,* as reward effect occurs at a later stage. The last model is the *parallel processing* scheme, suggesting that multisensory integration takes place at multiple stages (**Figure 1C**). Depending on the resources available, multisensory integration may occur at an early or late stage. Here, we expect that reward and multisensory integration share similar processing in the brain, where both of them may occur simultaneously in either sensory cortices or associative cortices. Similar to model A, model C also posits that both reward and multisensory processes occur at the same stage, hence leading to *supra-additive* reward effects.

In order to test the role of the reward in the multisensory integration, we designed a behavioral paradigm employing a detection task, where participants were asked to respond upon detection of unimodal or multimodal cues. In order to manipulate the reward magnitude, one feature of the cues, such as color or sound pitches, predicted reward where upon correct detection a reward was obtained, whereas another feature was paired with no reward. We recorded the behavioral responses -reaction times (*experiment 1 & 2*)-, and the behavioral and functional MRI (fMRI) responses simultaneously (*experiment 2*).

We expected that the reward effect will follow a different mechanism in multisensory compared to unisensory cues. Behaviorally, this distinction can be manifested as an interaction between the effect of reward and sensory modality on response times, where specifically the reward effect in multisensory cues significantly differs from the reward effect in the unisensory cues.

Moreover, as our previous study (Chapter 3) showed that reward modulation is observed already at the level of early sensory areas, we expected that reward and multisensory processes also occur at the early stages of information processing. Hence, the underlying neural mechanism that might support this interaction is either the *early integration* or *parallel processing*. The common feature of these two mechanisms is that the reward signal is integrated at the same stage (or even earlier) as sensory cues are processed, hence producing a supra-additive reward-driven modulation of behavioral and neural responses.

Our results showed that although reward conferred a gain on performance across all unimodal and multimodal cues, its effect did not follow a supra-additive principle, as the enhancement gained from multimodal rewarded cues was similar to the one observed for unimodal rewards. Similarly, examination of the fMRI responses showed that reward effect in multimodal stimuli did not follow a supra-additive principle. However, we found evidence supporting *the late integration* model.

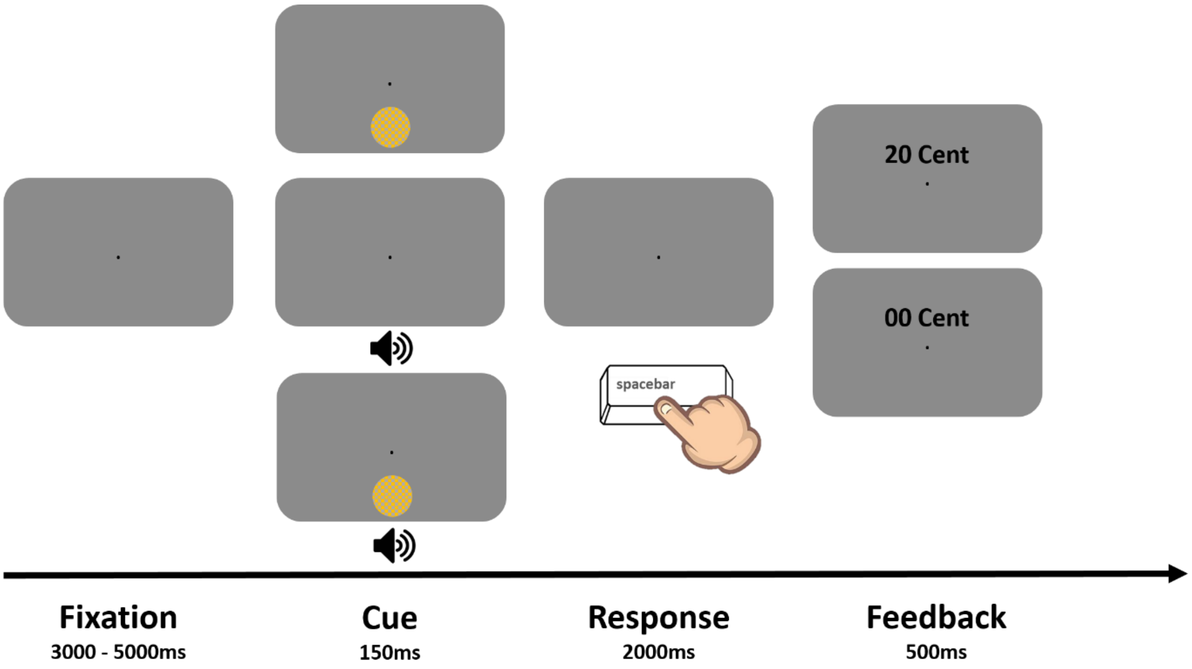

Figure 2. Behavioral paradigm of the simple detection task. Demonstration of the timeline of a trial, where upon fixation (3000, 4000, 5000 ms) either a visual, auditory, or audiovisual cue was briefly presented (150ms) in the periphery. Participants were asked to respond as fast as possible within 2000 ms response window by pressing a button. When detection was accurate, a feedback was displayed showing the reward receipt depending on the sensory features of the cue (e.g. blue color and high pitch tone predicted reward). If they missed a cue, ’00 Cent’ was displayed. Reward associations of the cues were counterbalanced across participants. Furthermore, in order to remove any perceptual bias to cues that is unrelated to the reward assignments, we reversed the reward associations after halfway of the experiment.

4.3 Materials and Methods

4.3.1 Participants

We collected data in two experiments, where in the first experiment only behavioural and eye tracking data were collected, and in the second experiment fMRI data was acquired. The target sample size for both experiments was set to by N = 20 before data collection started and was based on power calculation with a beta = 0.8 for the main effect of reward on auditory and visual modalities in 33 participants observed in a previous study (Chapter 3).

22 subjects participated in the *behavioral* experiment exclusively and 25 subjects participated in both *neuroimaging* including *behavioral* experiment. They were invited via an online recruiting system (http://www.probanden.eni-g.de/orsee/public/). All participants had normal or corrected-to-normal vision, had no history of neurophysiological or psychiatric disorders according to a self-report, and were naïve to the hypothesis of the project.

In the *behavioral* experiment, the total sample comprised 21 participants (14 male and 17 female, age 18 to 45 years; mean 25.54 years old ±5.36 years SD). 18 participants were right-handed and 3 participants were left-handed according to a self-report. 1 participant had to be removed from further analysis, as the participant’s accuracy in detecting the visual stimulus was below our inclusion criterion (accuracies < 70%). For two other participants, parts of the eye tracking data were not saved due to technical problem, nevertheless their data was analyzed to inspect the behavioral effects.

In the *neuroimaging* experiment, the total sample comprised 22 subjects (6 male and 16 female, age 18 to 45 years; mean 25.04 years old ±4.61 years SD). 20 participants were right-handed, while 2 participants were left-handed according to a self-report. Three participants were removed from our original sample (N = 25): one participant was outside of our age inclusion criteria (age > 45 years), one participant detected visual stimuli at ca. 45% accuracies, and for one participant data collection was not completed due to technical problems at the scanner.

Before the experiment started and after all procedures were explained, participants gave their oral and written consent. The study was approved by the local ethics committee of the “Universitätsmedizin Göttingen” (UMG), under the proposal number 15/7/15.

4.3.2 Stimulus presentation and eye tracking apparatus

Behavioral experiment

Throughout the experiment, visual stimuli were displayed on a calibrated ViewPixx ASUS monitor subtending to 1080x1920 pixels, and a refresh rate of 120 Hz placed at a distance of 60 cm to the participants. For tracking the eye position an EyeLink 1000 Plus system with a desktop mount (SR Research) was used to track the right eye. The EyeLink camera was controlled by the corresponding EyeLink toolbox in MATLAB (Cornelissen, et al., 2002). Before each block, the eye tracking system was calibrated using a 9-point standard EyeLink calibration procedure.

The visual stimulus was a circle with a radius of 1.1° filled with a checkerboard pattern presented at 12° distance from the center fixation point. The colors of the checkerboard were orange and blue, RGB values are [255, 74, 44] and [0, 182, 155]. For auditory cues, two pure tone pitches (350 Hz or 1050 Hz) were presented at 70 dB. The tones were delivered through an over-ear headphone. In order to achieve the co-localization of auditory stimuli, we implemented a head-related transfer function based on a recorded database (Algazi et al., 2001) to localize the sound to be perceived as 12° distance relative to the center by taking into account dimensions of participant's head measurement (i.e. width, height, depth, and circumference).

Neuroimaging experiment

Throughout the experiment, visual stimuli were displayed on an MR-compatible projection screen using a calibrated ProPixx projector (VPixx Technologies, Saint-Bruno, QC, Canada) at a resolution of 1920x1080 pixels, and a refresh rate of 120 Hz. The screen was placed at the end of the scanner bore at a distance of 88 cm from the participants' eyes. The full display size on the screen was 43 cm x 24 cm, i.e. the visible range from the central fixation spot was +/-13.6° horizontally and +/-7.7° vertically. For tracking the gaze position a ViewPoint eye-tracker system mounted on the mirror on top of the MR head coil was used (ViewPoint Eye Tracker, Arrington Research). Before the two scanning session, the eye-tracking system was calibrated using a 9-point standard ViewPoint calibration procedure.

The visual stimulus was a circle with a radius of 1.1° filled with a checkerboard pattern presented at 12° distance from the fixation point. In order to keep the same distance and ensure the visibility of the cues are captured within the screen display, we presented the fixation at 5.5°

upwards relative from the center of the screen. The colors were isoluminant orange and blue, RGB values [255, 74, 44] and [0, 182, 155]. For auditory cues, two pure tone pitches (350 Hz or 1050 Hz) were presented at 90 dB. The tones were delivered through MR compatible earphones (Sensimetric S15, Sensimetrics Corporation, Gloucester, MA) with an eartip (Comply™ Foam Canal Tips) to maintain acoustic seal and reduce environmental noise.

4.3.3 Procedure

The experiment consisted of a practice session (6 trials) for the simple detection task and two phases. In the first phase, one color and one pitch (e.g. color1, pitch1) were paired with reward. In the second phase, the reward association was switched, in that the color and the pitch that was predicting reward did not predict reward anymore in the second phase, but the other color and pitch (e.g. color2, pitch2) now predicted reward. This cue-reward association reversal was completed in order to counterbalance participants' sensory bias due to the physical properties of the stimulus. The reward magnitude of the reward predicting cues was drawn from a Poisson distribution (mean = 25 Cents). Throughout the experiment participants had to respond upon detection of either a visual (90 trials), auditory (90 trials), or audiovisual (90 trials) stimulus. We also inserted empty trials (40 trials) to extend the inter-trial intervals randomly to reduce predictability of the onsets of stimulus. Following a response, participants received a feedback display: if participants had correctly detected the stimulus the feedback display showed their obtained reward (e.g. '20 Cent' for rewarded and '00 Cent' for not rewarded), and if they had missed the stimulus, no reward ('00 Cent') was shown. Importantly, we associated the same amount of reward across all cues, ensuring that the reward effect that we expect in the multisensory cues will not be due to a different magnitude of reward associated between unisensory and multisensory cues. The timing of events was identical across all phases. As soon as participants fixated (within 1° of the fixation point) a trial started. After a jittered fixation period of 3000-5000 ms (with a 1000 ms step), a target stimulus appeared (either a colored checkerboard for visual condition, a pure tone for auditory condition, or both checkerboard and the tone presented simultaneously for audiovisual condition). The target stimulus disappeared after 150 ms and participants had to press a button using their dominant hand to confirm detection within 2000 ms following the onset of the target. Finally, a feedback display was presented for 500 ms showing participants' reward, as described above.

In order to determine whether participants learned the reward-cue association, they were asked to indicate which cue from each modality gave them more money. This question was completed in multiple parts following the first 30th, 60th, 90th trials and at the end of each phase (i.e. after

290 trials). Additionally, we also repeated the question in the questionnaire after the experiment was completed. All participants had learned reward associations based on their online results (in which at least one correct answer to the question was set as our criterion) and the questionnaire.

4.3.4 fMRI data preprocessing for univariate analysis

Imaging data was processed using Statistical Parametric Mapping software (version SPM12: v7487; https://www.fil.ion.ucl.ac.uk/spm/). Preprocessing pipeline consisted of realignment of the slices to the mean image and unwarping the images according to the voxel displacement mapped image, slice time correction for multiband interleaved sequence, coregistration of the functional images to the structural scans, segmentation of brain structure according to the tissue probability maps, spatial normalization to the native space, and a spatial smoothing with a kernel size of 8 mm.

4.3.5 Analysis of the behavioral data

The behavioral data obtained from all parts of the experiment was analyzed using custom-written scripts in MATLAB (version R2015a). We analyzed accuracies, reaction times (mean reaction time on a trial in which participants responded). We excluded the first 30 trials as participants needed time to learn the reward and cue association. Furthermore, we removed trials in which participants had reaction time shorter than 100 ms or larger than 2000 ms, or did not respond. This resulted in average 0.53% trials (±1.29 SD) for *experiment 1* and 0.36% trials (±1.41 SD) for *experiment 2* removed. For each response variable, we calculated the mean across all trials of each condition per subject during the pre- and post-reversal phases separately. Afterwards, the response variables (i.e. reaction times) was entered to a 2x3x2 repeated measures ANOVA (rm-ANOVA), with the reward (rewarded or not), sensory modalities of the cue (visual, auditory, or audiovisual), and phase (pre-reversal and post-reversal) as within-subjects factors. Then, we employed a Bonferroni corrected multiple comparison (using *multcompare* function in MATLAB) for the *post-hoc* test.

To quantify the performance gain of multimodal cues in relation to the unimodal gain, we measured the multisensory response enhancement (MRE). The MRE provides information on how much faster responses in the AV are relative to the fastest condition in the A or V, expressed as a percentage. When the values are positive, it indicates enhancement, while negative values demonstrate interference (Van der Stoep, Van der Stigchel, Van Engelen, Biesbroek, & Nijboer, 2019). Afterwards, we compared the MRE from reward predicting and not-reward predicting cues using a paired sample *t-test*.

$$MRE = \frac{\min(mean\ RT_A,\ \ mean\ RT_V) - mean\ RT_{AV}}{\min(mean\ RT_A,\ \ mean\ RT_V)} x\ 100\%$$

4.3.6 Analysis of the fMRI data: Univariate analysis

For the univariate approach, we designed a General Linear Model (GLM) with regressors defined based on the reward magnitude factor (R-rewarded or NR-not rewarded) and sensory modality factor (V-visual, A-auditory, AV-audiovisual) which resulted in 6 regressors of interest as stick function. Moreover, we also modelled 8 nuisance regressors such as 6 movement parameters, events of no interest (e.g. instructions), and the phases of the task (pre- and post-reversal for each participant). For the univariate analysis, we entered preprocessed images to the General Linear Model (GLM). Following the estimation of each regressor in the GLM, we then defined a contrast of each 6 regressors of interest against baseline to be entered in the factorial design for group-level analysis.

In the factorial design, we defined a 2 by 3 repeated measures ANOVA with reward factor (rewarded or not rewarded) and sensory modality factor (audio, visual, and audiovisual) as within-subject factors and the participants were entered as the random factor. Then, T-contrasts were defined for the main effect of reward, main effect of sensory modality, and the interaction term. In the interaction term, we looked into the contrast of reward effect in each sensory modality against another configuration of sensory modality (e.g. Ar – Anr > Vr – Vnr; AVr – Avnr > Ar – Anr) in every possible combination (for a complete list of the contrasts, refer to **Table 1**). Moreover, we also explored reward effect in multisensory processes using an additional conjunction contrast between areas modulated by reward effect and *supra-additive* multisensory integration (main effect of reward ∩ multisensory integration). Important to note, as the areas revealed by this conjunction responded to both *supra-additive* multisensory integration and reward effect, the neural response of these areas cannot be attributed to only one of the components (see Noppeney, 2012). Moreover, we also looked into the interaction contrast where reward effect audiovisual cues were stronger than the sum of reward effect in the unimodal cues (i.e. AVr - AVnr > ((Ar – Anr) + (Vr – Vnr))), as *supra-additive* reward effect, and also the vice versa reflecting the *sub-additive* reward effect. Overall, we thresholded the results with uncorrected $p < 0.001$ with extent threshold (k) of 10. The complete results of the whole-brain univariate analysis are shown in **Table 1**.

4.4 Results

4.4.1 Behavioral results: reward effect in multisensory cues was not stronger than unisensory cues.

Experiment 1

We investigated reward effects when cued from unimodal (auditory and visual) or multimodal (audiovisual) stimuli. Participants detection accuracies were at a near perfect level (*audiovisual*: 99.61%, ±s.e.m 0.27; *auditory*: 99.66%, ±s.e.m 0.21; *visual*: 96.63%, ±s.e.m 0.91) and we focused our analysis on response times. A 2x3x2 repeated measures ANOVA on reaction times demonstrated a significant main effect of modality (F(2,40) = 71.38, $p < 0.001$, $\eta_p^2 = 0.78$, see **Figure 3A**), where multimodal stimuli (mean = 367 ms, ±s.e.m = 15 ms) had the fastest response in comparison to both auditory (mean = 413 ms, ±s.e.m = 17 ms) and visual (mean = 457 ms, ±s.e.m = 13 ms) cues (all *ps* < 0.001). Moreover, reward predicting cues significantly sped up the response as observed in the reward effect across all sensory modalities (F(1,20) = 19.34, $p < 0.001$, $\eta_p^2 = 0.49$, see **Figure 3B**) with the strongest reward effect observed in the post-reversal phase for multimodal cues ($p = 0.03$, Cohen’s d = 0.51), followed by a trend in the post-reversal phase for unimodal visual cues ($p = 0.09$, Cohen’s d = 0.38). These findings are partially aligned with our hypothesis, as the reward effect was strongest in the multisensory stimuli. However, the strong reward effect in multimodal stimuli did not reach a level to produce a statistically significant interaction effect between reward and modality factors (F(2,40) = 0.21, $p = 0.76$, $\eta_p^2 = 0.01$), ruling out the hypothesis that reward effect would show different modulation when signalled from multisensory compared to unisensory cues. Moreover, as reward and cue associations were reversed, we observed a slower response time in the post- compared to pre-reversal phase (F(1,20) = 4.7, $p = 0.04$, $\eta_p^2 = 0.19$), where the reaction time in the pre-reversal phase (mean = 406 ms, ±s.e.m = 14 ms) was faster than the post-reversal phase (mean = 418 ms, ±s.e.m = 16 ms), as expected as participants had to unlearn the previous associations and re-orient to the new reward and cue association. The rest of the effects were not significant (all *p*s > 0.1).

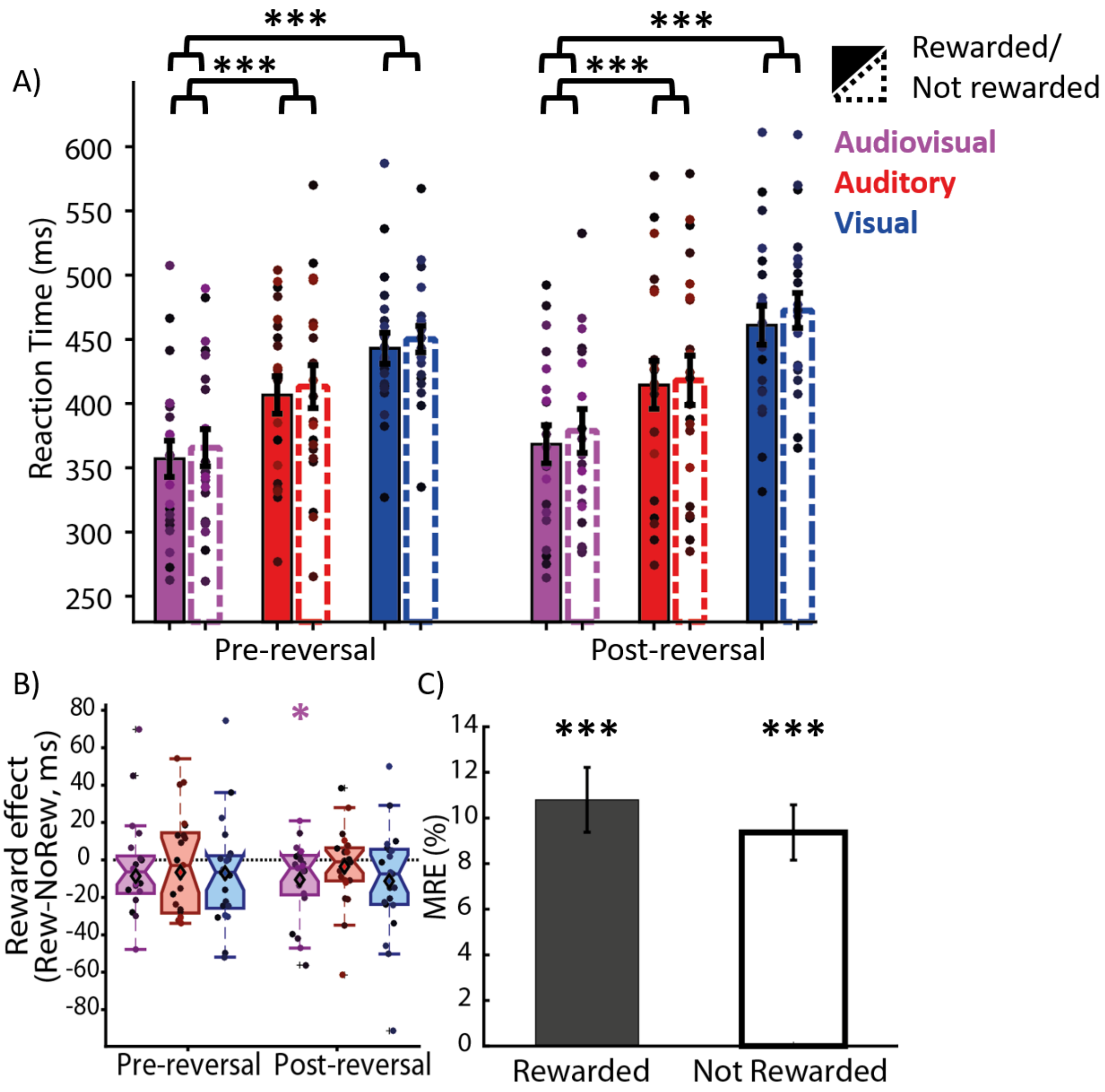

Figure 3. Experiment 1: Reward modulation of multisensory and unisensory cues. A) Bars depict the average response times for each condition at each phase. Colored circles correspond to the data of the individual subjects. Significance stars correspond to the effect of sensory modality. **B)** Reward effect in each sensory modality (auditory, visual, and audiovisual) across phases. **C)** Multisensory response enhancement (in %) between rewarded and not-rewarded conditions. * p < .05, *** p < .001.

However, to quantify how much gain a multimodal stimulus had over unimodal stimuli, we calculated the MRE for both rewarded and not rewarded stimuli (**Figure 3C**). We observed that multimodal cues enhanced the performance gain (rewarded: *p* < .001, Cohen's d = 1.65; not-rewarded: *p* < .001, Cohen's d = 1.68), pointing out that multisensory integration occurred. However, paired sampled *t*-test between rewarded and not-rewarded MREs did not reach significance (*p* = 0.28, Cohen's d = 0.24), indicating that reward did not have a *supra-additive* effect.

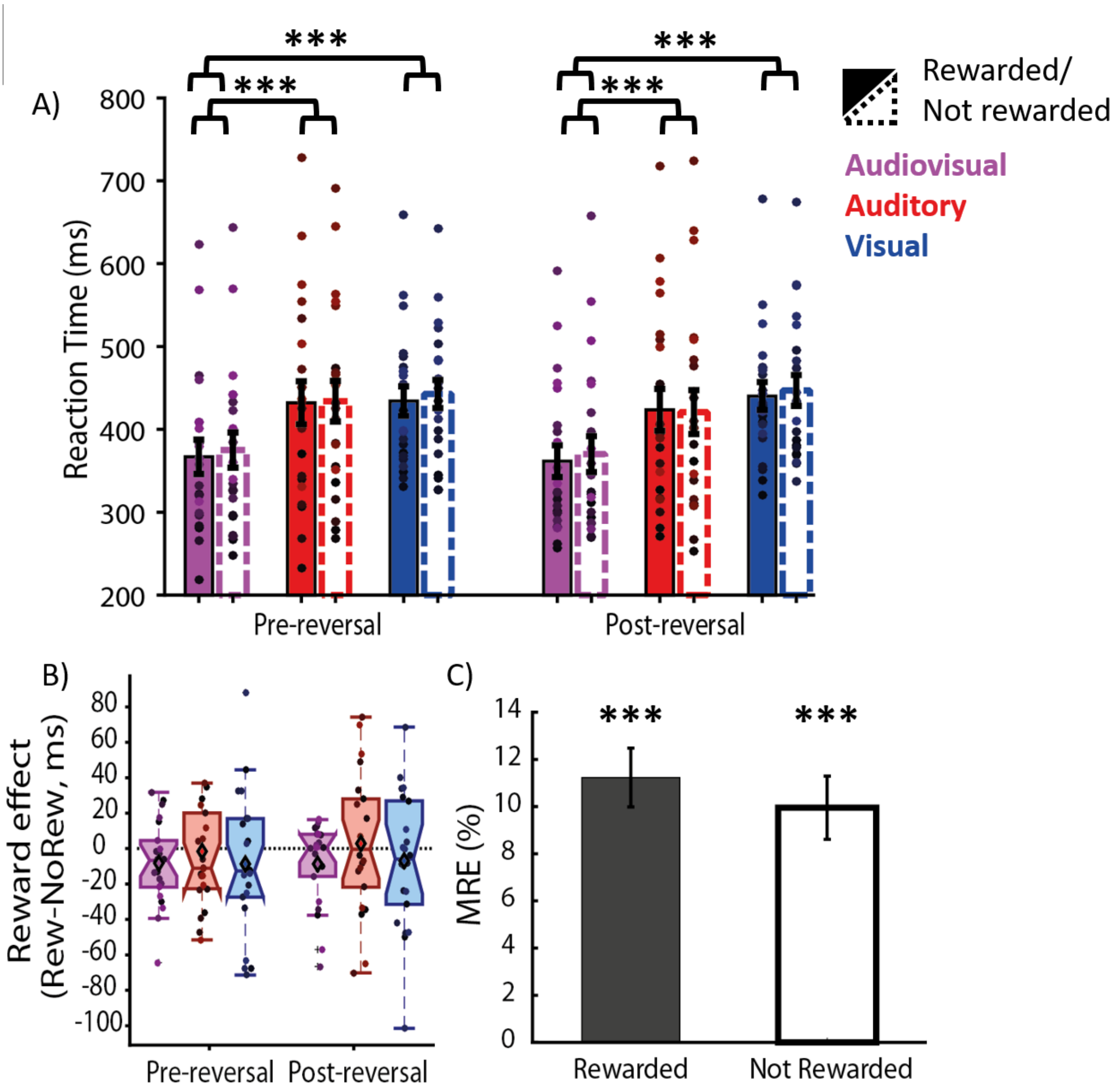

Figure 4. Experiment 2: Reward modulation of multisensory and unisensory cues. A) Bars depict the average response times for each condition at each phase. Colored circles correspond to the data of the individual subjects. Significance stars correspond to the effect of sensory modality. **B)** Reward effect in each sensory modality (auditory, visual, and audiovisual) across phases. **C)** Multisensory response enhancement (in %) between rewarded and not-rewarded conditions. * $p < .05$, *** $p < .001$.

Experiment 2

Similarly as experiment 1, we confirmed that participants' detection accuracies were at a near perfect level (*audiovisual*: 99.89%, ±s.e.m 0.1; *auditory*: 99.59%, ±s.e.m 0.21; *visual*: 94%, ±s.e.m 1.26) and we focused our analysis on response times. We observed a main effect of modality ($F(2,42) = 45.27$, $p < 0.001$, $\eta_p^2 = 0.68$, see **Figure 4A**), in which multimodal stimuli (mean = 368 ms, ±s.e.m = 21 ms) had the fastest responses in comparison to auditory (mean = 428 ms, ±s.e.m = 26 ms) or visual (mean = 441 ms, ±s.e.m = 18 ms) cues (all *p*s < 0.001). Also, rewarded cues made responses across all cues faster as observed in the main effect of reward ($F(1,21) = 4.7$, $p = 0.04$, $\eta_p^2 = 0.18$, see **Figure 4B**). However, we did not observe any significant reward effect in the *post-hoc* tests examining individual modalities. There was also no interaction effect between reward and modality (F(2,42) = 2.36, $p = 0.11$, $\eta_p^2 = 0.1$), indicating that reward in multisensory cues had a similar effect as in unisensory cues. The rest of the effects were not significant (all *p*s > 0.1).

Then, we investigated further the MRE, where here we also observed that even though multimodal cues enhanced the performance gain (rewarded: $p < .001$, Cohen's d = 1.92; not-rewarded: $p < .001$, Cohen's d = 1.58, see **Figure 4C**), reward did not make any significant difference ($p = 0.18$, paired t-test, Cohen's d = 0.29). In general, although the strength of reward effect in experiment 2 was weaker than experiment 1, our behavioural results inside the scanner replicated the observations outside the scanner in terms of the reward effect and the fastest response observed in the multisensory cues. Collectively, the results from both experiments showed that reward effect in multisensory cues are similar to unisensory cues.

4.4.2 fMRI results: whole-brain

Examining a contrast capturing the main effect of reward across sensory modalities, we observed reward modulations in the areas typically involved in the reward processing such as the striatum and frontal areas (**Figure 5A**). Moreover, we found the same areas for unimodal auditory and visual reward effects as shown in **Table 1**. We also tested the contrast of reward effect in each unimodal condition against the other (i.e. Ar – Anr > Vr – Vnr and vice versa) to ensure that the response profile in the unimodal conditions were similar. The reward and unimodal condition interaction contrasts did not reveal any modulation surviving the threshold, indicating that the reward effect is largely similar across sensory modalities. Furthermore, we also tested the interaction contrast of whether the reward effect in the multisensory cues was larger than the reward effect in each of the unisensory cues (i.e. AVr – AVnr > Vr – Vnr and AVr – AVnr > Ar – Anr, and vice versa for each contrast). In these interaction contrasts, we did not see any activation (**Table 1**), indicating that the reward effect was not larger in multisensory compared to the unisensory cues. As reward modulation might be expressed as an inhibition, we also looked into the reverse contrast across all conditions (Anr + Vnr + AVnr > Ar + Vr + AVr), where medial prefrontal areas, precuneus, and the temporo-parietal areas were recruited (see **Table S1**). The suppression of these areas by reward might indicate activities of some brain regions needed to be suppressed to enable reward-seeking behavior, as a previous study in mice observed that the modulation of the medial prefrontal cortex inhibited reward-seeking behavior (Ferenczi et al., 2016).

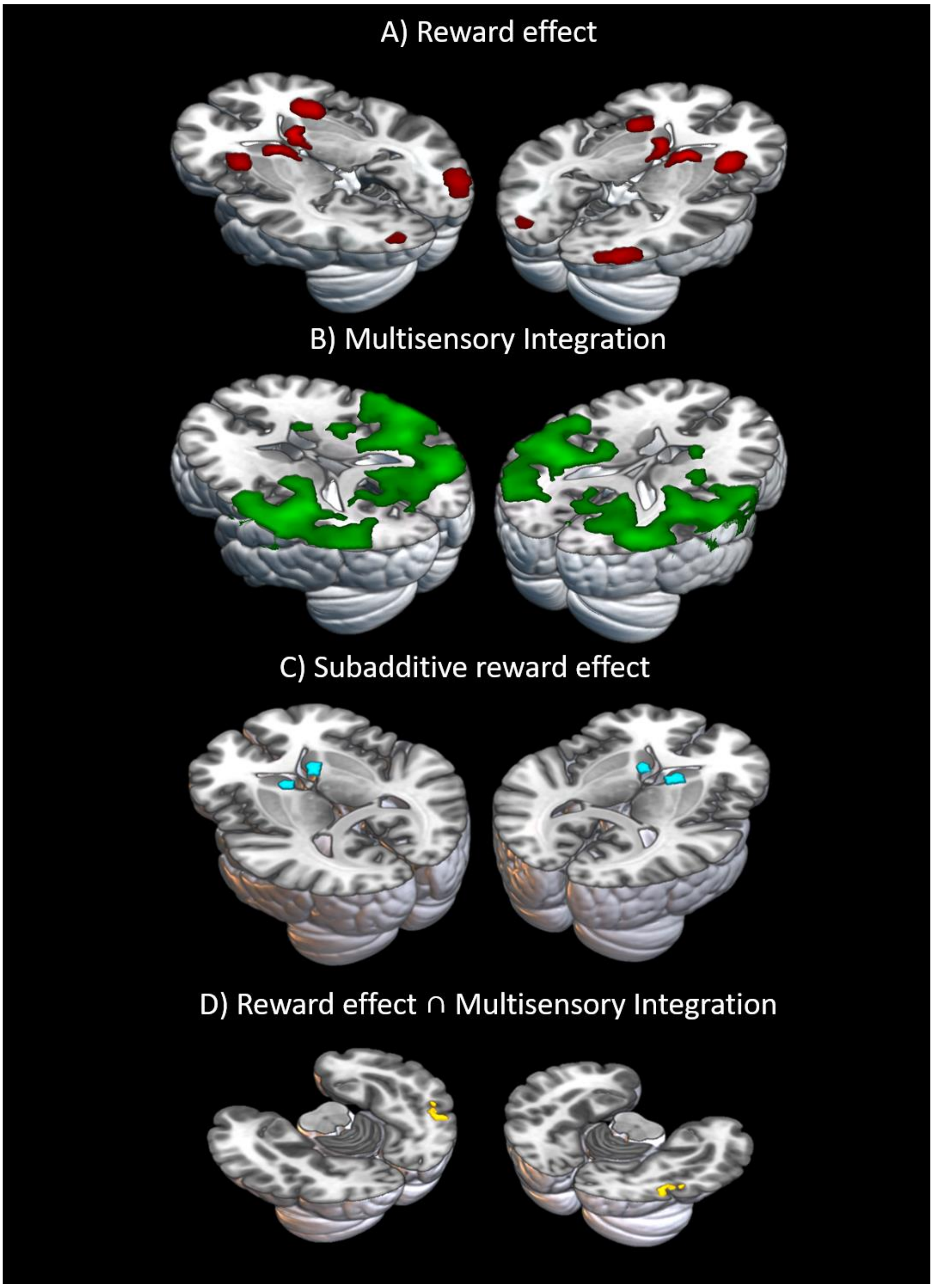

Figure 5. Experiment 2: whole-brain results A) main effect of reward across sensory cues (in red), **B)** areas showing supra-additive responses to multisensory stimuli irrespective of the reward (in green), **C)** sub-additive reward effect, where the sum of reward effects in auditory and visual cues was higher than the reward effect in multisensory cues (in blue), **D)** and the results of a conjunction contrast between reward effect and sensory supra-additive responses to multisensory stimuli (in yellow). Note that we found no activities in the contrast capturing the supra-additive reward effects. All images were displayed at uncorrected $p < .001$ with extent threshold 10.

4.4.3 fMRI results: multisensory integration effect, supra-additivity of responses to audio-visual stimuli and its modulation by reward

We next examined the areas that show supra-additive responses to multisensory stimuli (**Figure 5B**). To do this we tested the multisensory integration contrast (AV > A + V, across reward conditions). Here, we observed the strongest activations in the Superior temporal areas, as has been reported in previous studies (Beauchamp, 2005; Calvert et al., 2001). Other areas such as the fusiform gyrus and the precuneus were also showed supra-additive integration characteristics (**Table 1**). The observation in precuneus is in line with previous findings indicating that this area is involved in the multisensory processing (Renier et al., 2009) and fusiform areas have been also shown to be involved in binding of face and voice stimuli (De Gelder & Bertelson, 2003). Interestingly, the right caudate, an area strongly linked to the reward processing (Schultz, 2000), was also involved in integrating the multisensory cues showing a supra-additive effect, as has been also observed by previous studies (Nagy, Eördegh, Paróczy, Márkus, & Benedek, 2006; Reig & Silberberg, 2014; Stevenson et al., 2009). This might be an indication that reward processing might occur at the same stage as multisensory integration following a supra-additive principle. However, the sensory supra-additivity in Caudate was observed at locations that were distinct from regions that exhibited reward modulation (see **Figure S1**). Furthermore, to examine whether there are also areas responsible for a sub-additive integration, we looked into the sub-additive multisensory integration contrast (AV < A + V). However, we found no activation, indicating that the processing of the compound of the auditory and visual signals in the multisensory cues produces an effect that cannot be explained by the linear summation of the unisensory cues.

4.4.4 fMRI results: examining the supra-additivity of reward effects in multisensory cues

The sensory integration contrast above showed that the multisensory cues had a different response compared to the unisensory cues. We hypothesized that the reward effects in multisensory cues would be different from the reward effects in unisensory cues. Therefore, to test this hypothesis, we looked into the *supra-additive* reward effect contrast (AVr – Avnr > ((Ar – Anr) + (Vr – Vnr)), **Table 1**). However, this contrast did not reveal any activation. In fact, areas with the maximum supra-additive response (i.e., STS: peak at xyz=[63 -19 8]) were not modulated by reward, as we looked specifically into the reward effect in the superior temporal areas (p = 0.47, Cohen’s d = 0.15, **Figure S2**). This finding could indicate that reward effect might enhance multisensory integration in a *sub-additive* manner, as has been observed before (Werner & Noppeney, 2010, 2011). Indeed, in the *sub-additive* contrast of the reward effect (AVr – Avnr < ((Ar – Anr) + (Vr – Vnr)), bilateral Caudates were modulated (right: [9 11 2]; left: [-9 11 5], **figure 5C**). This *sub-additivity* of reward effect might indicate that reward effect does not depend on the configuration of the stimulus. However, note that both our unimodal and multimodal cues were associated with the same magnitude of reward. In that case, contrasting the sum of reward effect in unimodal cues against reward effect in multimodal cues might reflect the processing of reward magnitude and not necessarily a specific interaction between the reward coding and multisensory integration.

Our evidence so far has been hinting towards independent mechanisms for the processing of reward and multisensory information, where sensory cues were integrated in a *supra-additive* manner in the sensory association areas, while reward information was processed as an additive factor (i.e. similar across uni- and multisensory cues) in the striatum. However, we asked further how the two processes converge; whether there is a region that acts as a hub to undertake both processes? In order to investigate this, we employed a conjunction analysis between the reward effect and multisensory integration contrast (i.e. main effect of reward ∩ AV>A+V). The conjunction revealed activations in the Fusiform gyrus [42 -58 -19] and the premotor cortex [-54 -1 38] (see **Figure 5D** and **Table 1**). Furthermore, bilateral activations were observed in the Fusiform gyrus at a more lenient threshold (at xyz = [42 -58 -19] as well as xyz = [-39 -61 -7], at *p* uncorrected < 0.005, k = 20). This result hence indicates that the Fusiform areas were modulated by both reward and sensory integration, indicating they might act as a hub where both reward and multisensory processing converge.

Table 1. Whole-brain activations of univariate results thresholded at uncorrected $p < .001$ and k = 10. Significance (*p*) showed at cluster-level. Activations marked in bold survived corrections for multiple comparisons at *p*FWE < 0.05.

Cluster size	**MNI coordinates (in mm)**			**T**	***p***	**Side**	**Region**
	x	y	z				
Reward effect across sensory modalities ($AV_{rew}+A_{rew}+V_{rew} > AV_{not\ rew}+A_{not\ rew}+V_{not\ rew}$)							
822	**48**	**11**	**23**	**6.64**	**< 0.001**	**R**	**Inferior frontal operculum**
75	**9**	**11**	**-1**	**6.38**	**0.059**	**R**	**Caudate**
631	**54**	**-34**	**53**	**6.20**	**< 0.001**	**R**	**Inferior parietal**
61	**-9**	**11**	**-1**	**6.07**	**0.085**	**L**	**Caudate**
295	**-42**	**-37**	**41**	**5.99**	**0.001**	**L**	**Inferior parietal**

292	**42**	**-79**	**-7**	**5.69**	**0.001**	**R**	**Inferior occipital**
43	6	-1	29	5.33	0.142	R	Cingulum
81	9	26	44	5.10	0.051	R	Frontal superior medial
187	**-48**	**-52**	**-13**	**5.03**	**0.006**	**L**	**Inferior temporal**
78	-30	17	2	5.01	0.055	L	Insula
143	-42	5	23	4.83	0.013	L	Frontal inferior operculum
25	-24	-70	-49	4.11	0.257	L	Cerebelum
17	9	38	14	3.92	0.350	R	Anterior cingulum
16	21	44	-16	3.89	0.365	R	Frontal superior orbital
32	3	-25	26	3.69	0.202	R	Cingulum
15	-27	-91	-4	3.45	0.381	L	Middle occipital
Audiovisual reward effect ($AV_{rew} > AV_{not\ rew}$)							
53	48	-43	59	3.93	0.106	R	Superior parietal
43	33	-91	-1	3.79	0.142	R	Middle occipital
18	51	38	26	3.62	0.336	R	Frontal inferior triangularis
12	48	11	23	3.50	0.435	R	Frontal inferior operculum
Visual reward effect ($V_{rew} > V_{not\ rew}$)							
70	**-9**	**11**	**2**	**6.15**	**0.067**	**L**	**Caudate**
595	**48**	**38**	**17**	**5.41**	**< 0.001**	**R**	**Middle frontal**
454	**45**	**-34**	**44**	**5.12**	**< 0.001**	**R**	**Supramarginal**
41	9	11	2	4.93	0.151	R	Caudate
105	33	20	-1	4.52	0.029	R	Insula
97	9	26	44	4.46	0.035	R	Frontal superior medial
131	51	-46	-16	4.44	0.017	R	Inferior temporal
47	-42	-37	41	4.43	0.126	L	Inferior parietal
113	-45	-55	-13	4.39	0.024	L	Inferior temporal
38	-30	17	2	4.34	0.166	L	Insula
36	-42	5	23	3.82	0.177	L	Frontal inferior operculum
30	-24	-64	44	3.74	0.216	L	Superior parietal

11	6	-1	29	3.70	0.456	R	Middle cingulum
Auditory reward effect ($A_{rew} > A_{not\ rew}$)							
39	9	11	2	4.55	0.161	R	Caudate
81	45	11	23	4.24	0.051	R	Inferior frontal triangularis
88	45	38	11	4.06	0.043	R	Inferior frontal triangularis
38	57	-28	53	4.01	0.166	R	Inferior parietal
26	33	17	-4	3.75	0.248	R	Insula
15	-60	-7	41	3.73	0.381	L	Postcentral
12	42	-79	-10	3.67	0.435	R	Inferior occipital
22	-45	-37	41	3.64	0.287	L	Inferior parietal
18	-42	5	29	3.59	0.336	L	Precentral
11	3	-31	29	3.38	0.456	R	Middle cingulum
Supra-additive multisensory integration (AV > A + V)							
6561	**63**	**-19**	**8**	**7.54**	**< 0.001**	**R**	**Superior temporal**
162	21	-85	-43	4.93	0.009	R	Cerebelum
22	15	14	20	4.31	0.287	R	Caudate
79	-18	-88	-40	4.24	0.054	L	Cerebelum
48	-30	-43	-16	4.11	0.123	L	Fusiform
240	-30	26	47	3.99	0.002	L	Middle frontal
33	-15	-67	-19	3.93	0.195	L	Cerebelum
16	0	-43	71	3.89	0.365	L/R	Precuneus
13	-12	41	-13	3.89	0.416	L	Frontal medial orbital
45	-18	-31	59	3.85	0.134	L	Postcentral
49	21	29	41	3.65	0.119	R	Superior frontal
41	24	-31	53	3.62	0.151	R	Postcentral
30	-42	-73	-46	3.61	0.216	L	Cerebelum
21	21	-64	-22	3.60	0.298	R	Cerebelum
21	48	-58	-40	3.59	0.298	R	Cerebelum
Sub-additive multisensory integration (AV < A + V)							
No voxel survived							
Interaction: auditory reward effect > visual reward effect ($A_{rew} - A_{not\ rew} > V_{rew} - V_{not\ rew}$)							
No voxel survived							
Interaction: visual reward effect > auditory reward effect ($V_{rew} - V_{not\ rew} > A_{rew} - A_{not\ rew}$)							
No voxel survived							

Interaction: audiovisual reward effect > visual reward effect ($AV_{rew} - AV_{not\ rew} > V_{rew} - V_{not\ rew}$)							
No voxel survived							
Interaction: audiovisual reward effect < visual reward effect ($V_{rew} - V_{not\ rew} > AV_{rew} - AV_{not\ rew}$)							
No voxel survived							
Interaction: audiovisual reward effect > auditory reward effect ($AV_{rew} - AV_{not\ rew} > A_{rew} - A_{not\ rew}$)							
No voxel survived							
Interaction: audiovisual reward effect < auditory reward effect ($A_{rew} - A_{not\ rew} > AV_{rew} - AV_{not\ rew}$)							
No voxel survived							
Interaction: supra-additive reward effect ($AV_{rew} - AV_{not\ rew} > (A_{rew} - A_{not\ rew}) + (V_{rew} - V_{not\ rew})$)							
No voxel survived							
Interaction: sub-additive reward effect ($AV_{rew} - AV_{not\ rew} < (A_{rew} - A_{not\ rew}) + (V_{rew} - V_{not\ rew})$)							
25	9	11	2	4.08	0.257	R	Caudate
20	-9	11	5	3.95	0.310	L	Caudate
15	51	5	26	3.53	0.381	R	Inferior frontal operculum
28	42	38	17	3.49	0.231	R	Middle frontal
12	9	38	14	3.48	0.435	R	Anterior cingulum
33	3	38	44	3.45	0.195	R	Superior frontal medial
13	-48	-43	-16	3.44	0.416	L	Inferior temporal
Conjunction: main effect of reward ∩ supra-additive multisensory integration							
56	42	-58	-19	3.72	0.098	R	Fusiform
14	-54	-1	38	3.53	0.397	L	Precentral

4.5 Discussion

Our study aimed to investigate the effect of reward on the multisensory integration. In comparison to the unisensory reward effects, reward-driven effect on multisensory stimuli have been less explored, and thus it is unclear whether they are following similar principles or are regulated by distinct mechanisms. Previous studies have shown that multisensory cues elicit a distinct response compared to unisensory cues, adhering to a supra-additive principle. Therefore, we expected that if rewards influence the multisensory processes at an early stage in which sensory integration occurs (i.e., models A and C in **Figure 1**), their effect on the multisensory stimuli should also adhere to a supra-additive principle (i.e., be larger than the pooled reward-driven modulation of unisensory stimuli). Our behavioral results showed that although the sensory processing of the multisensory cues was distinct from the unisensory cues (i.e., supra-additivity in the speed of responses), the reward modulation did not show any distinction across the sensory modalities (i.e., a lack of an interaction between reward and sensory modality and supra-additivity). Moreover, our neuroimaging results showed similar effects. Although we found strong reward-driven modulations and supra-additivity in the responses to the multisensory stimuli, no interaction was found between the two. In fact, areas with the strongest supra-additivity for sensory integration, such as the STS, were not modulated by reward. Instead, we found two lines of evidence supporting a late integration model (panel B in **Figure 1**). Firstly, the responses of some of the reward-related areas such as the Caudate to multisensory rewards was smaller than the sum of their responses to unisensory rewards (sub-additivity), indicating that they are primarily sensitive to the reward magnitude and did not differentiate multi- and uni-sensory stimuli. Secondly, using a conjunction contrast, we found an area in the Fusiform gyrus showing both sensory supra-additivity and reward modulation, albeit no supra-additivity of reward effects. Therefore, this area might act as a convergence point between the reward and multisensory processing and contribute to the late integration of the two sources of information.

In the behavioral results, we observed that multisensory integration did occur, as indexed by the Multisensory Response Enhancement (MRE). However, we found no interaction effect between the sensory modalities and reward, indicating that multisensory integration and reward might be regulated independently or at different stages. This result did not resonate with our hypothesis that reward would be integrated as *early* as the sensory cues are. Furthermore, our results are in contrast with the observations from Bean and colleagues (2021), as in their study they observed a robust reward-driven enhancement of multisensory integration as measured by the approach behavior of cats. There are several differences in the paradigm used by the latter study and ours that might lead to this difference. First, the strength of the stimuli employed in the two studies was different. In our study, we employed supra-threshold cues presented at a single peripheral location, as we expected that irrespective of the strength of the stimuli, reward will enhance the multisensory integration. In contrast, the paradigm used in Bean and colleagues (2021), used low intensity unisensory cues presented at several randomized peripheral locations. Since according to the *inverse effectiveness* rule, multisensory integration is stronger for weaker unisensory stimuli, it is possible that reward only affects multisensory integration when unisensory stimuli are weak. In such settings, increasing the gain of the multisensory integration by rewards can have crucial behavioral advantages. Second, in our study, we did not manipulate the congruency of the reward in each of the unisensory stimuli, as both components of the bimodal cues predicted the same reward (i.e. either both visual and auditory cues were rewarded or unrewarded). In contrast, the studies from Bean and colleagues

(2021) and Cheng and colleagues (2020) highlight the importance of the manipulation of the congruency between rewards of the unisensory cues. In their studies, reward congruency helped the brain to discern which unisensory stimuli had congruent rewards and hence were more likely to belong to the same object, similar to how spatial and temporal overlap promote the multisensory integration. In fact, as our paradigm did not manipulate the congruency of rewards in unisensory stimuli, there might have been no necessity for the organism to sort out whether the two unisensory cues in an audiovisual stimulus derive from the same source or not. However, we also note that using the reward congruency allows an additional contribution of semantic factors, i.e. the numeric or categorical value of rewards, to the observed effects. As we were primarily interested in the sensory and physical factors that drive the multisensory integration, we decided not to vary the reward congruency. However, future studies will be needed to determine the extent to which this factor plays a role in the reward-driven changes of multisensory integration.

Examination of the BOLD activities revealed a similar pattern to our behavioral results. Firstly, there were areas recruited in the multisensory integration process exhibiting a supra-additive response to the audiovisual stimuli, especially in the Superior Temporal areas (STS). STS has been consistently reported to converge and integrate signals from multiple sensory modalities (Beauchamp, 2005; Calvert et al., 2001; Degerman et al., 2007; Ferrari & Noppeney, 2021b). Secondly, we observed that reward enhanced the BOLD responses in the classical reward-related areas such as the caudate and the frontal areas. However, our index of supra-additivity of the reward effect did not show any activations. Together, these findings rule out our hypothesis that reward affects the multisensory integration in an early stage and through a supra-additive change in neuronal responses.

Further examination of the BOLD responses revealed several interesting findings. As we compared the reward effect of each sensory modality configuration using interaction contrasts, there was no difference in the reward effect depending on the sensory modality configuration. Indeed, the same coordinates in caudates showing significant activations for the main effect of reward, also revealed a *sub-additive* reward modulation for audiovisual stimuli, indicating that the reward modulation in this area is primarily sensitive to the magnitude of the reward (which was the same for all conditions) and does not differentiate multisensory cues from the unisensory stimuli. Together, these findings suggest that in the setting we employed the brain’s reward network is largely invariant to the sensory modality. Another interesting observation was that in the distinct regions of the caudates, an area primarily known for its role in reward processing, there were regions that also played a role in sensory integration (see **Figure S1**). Specifically, the right caudate showed a *supra-additive* response to multisensory stimuli compared to unisensory stimuli (across reward conditions). This is in line with previous studies, showing the existence of both unisensory and multisensory neurons found in the Caudate (Nagy et al., 2006; Nagy, Paróczy, Norita, & Benedek, 2005). Moreover, the Caudate has also been reported to be involved in the integration of sensory information in mice (Reig & Silberberg, 2014) and also humans (Stevenson et al., 2009). Hence, the Caudate has been known to respond to multisensory cues, as one of its critical function is to coordinate movement (Nagy et al., 2006). In our study, the peak of the Caudate that were modulated by reward effect and *sub-additive* reward effect in multisensory stimuli are similar, but the peak that was modulated by *supra-additive* sensory integration was distinct. Therefore, we conclude that the areas that receive sensory information in the Caudate do not overlap with the areas that respond to rewards.

Up to this point, our evidence pointed that reward and sensory integration are two independent mechanisms where sensory information would be integrated in a *supra-additive* manner at an early stage, while at a later stage reward can modulate the neuronal responses *sub-additively* (**model B** in Figure 1). Then, how do the two mechanisms interact with each other? To test this question, we looked into a conjunction contrast between reward effect across all sensory modalities and the *supra-additive* multisensory sensory integration. Interestingly, the conjunction revealed an area in the Fusiform Gyrus (**Figure 5D**). The coordinates of the activations in the Fusiform Gyrus found in our study overlap with areas in the Fusiform Gyrus that have been shown to be responsible for the integration of face and voice stimuli into a coherent speech perception (De Gelder & Bertelson, 2003; Rüsseler, Ye, Gerth, Szycik, & Münte, 2018) and integration of face and haptic stimuli (Kitada, Johnsrude, Kochiyama, & Lederman, 2009). In fact, it has been suggested that Fusiform Gyrus may be a convergence point across multimodal cues (Stevenson et al., 2009). In relation to reward processing, Padmala and Pessoa (2011) showed that the Fusiform Gyrus mediated the motivational cues to reduce a conflict-related processing of a target. Extending this view, Rothkirch, Schmack, Deserno, Darmohray, & Sterzer (2014) argued in their study that the Fusiform gyrus is an area where reward and attention compete for sensory processing resources. Based on our results and previous studies, we speculate the role of the Fusiform gyrus in our paradigm to act as a *hub* where sensory and reward signals converge. As fusiform gyrus did not exhibit the strongest supra-additive response to the multisensory stimuli, this might indicate that reward assists multisensory integration only when the sensory integration is weak. Another possibility is that the *supra-additive* sensory integration found in the Fusiform gyrus might occur earlier than the modulation by reward, which would be interesting to investigate using a method that has a better time resolution such as electroencephalography (EEG) or magnetoencephalography (MEG).

Moreover, we also observed areas in the premotor cortex that were modulated by both reward and multisensory integration as indexed by the conjunction contrast. Premotor cortex is an area that is critical for goal-directed behavior (Gremel & Costa, 2013) and its responses can be modulated by rewards (Peterson & Seger, 2013; Roesch & Olson, 2003). Furthermore, premotor cortex has previously been reported to be involved in multisensory integration, as it has efferent connections from multisensory areas such as the superior colliculus (Meredith, Nemitz, & Stein, 1987). The modulation of the premotor cortex revealed by the conjunction contrast may reflect that the motor preparation signals are enhanced by multimodal stimuli and this effect is further boosted by reward. Our conjunction analysis revealed both Fusiform and the premotor cortex that can be mapped to afferent and efferent communications to the brain areas that implement the final motor response. Thus, as both areas were detected using the same conjunction analysis, the Fusiform areas might process both sensory and reward information that is further signaled to the premotor areas to optimize goal-directed behavior (i.e. “how fast should I press the button?”) depending on the reward at stake.

Collectively, our behavioral and neural findings contradicted our hypothesis that reward would enhance multisensory integration according to a *supra-additive* principle. Instead, the evidence we found indicates that reward enhances multisensory integration at a late stage and *sub-additively*. Following this hypothesis, we considered possible mechanisms of the interaction between reward and multisensory integration as shown in **Figure 1**. These mechanisms either map to an *early integration scheme*, where reward is integrated as early as the sensory information is (either at the primary sensory areas or in the heteromodal areas, hence **model A and C** in Figure 1), thus this would mean that the reward effect would be *supra-additive*. In contrast, *late integration* proposed that reward information is integrated after sensory integration occurs, thus the reward effect may have a *sub-additive* pattern (**model B** in Figure 1). Lastly, the *parallel processing scheme* (**model C** in Figure 1) suggests that reward and sensory systems share similar mechanisms and can be integrated at both early and late stages (see also Koelewijn et al., 2010). Based on the evidence provided by the univariate analysis of the fMRI data, we ruled out *early integration* and *parallel processing* mechanisms, as they both predict a *supra-additive* reward modulation for multisensory stimuli. Furthermore, we observed distinct regions that exhibited strong modulations either by reward (frontal and midbrain areas) or by multisensory information (occipital and temporal regions). Thus, we showed that reward and sensory integration are two independent mechanisms, where sensory cues are integrated automatically, and then reward may enhance the integration further in a *sub-additive* manner. This indicates that reward interacts with multisensory integration at a later stage, supporting the *late integration* framework (**panel B** in Figure 1), at least in the context of the task we used in this study. Our findings are in line with early studies on the role of attention in multisensory integration, as observed in Vroomen, Bertelson, & De Gelder, (2001), where they demonstrated that cross-modal interactions such as the one observed in visual Ventriloquism effect do not depend on visual spatial attention. Furthermore, an ERP study by Santangelo, Van Der Lubbe, Olivetti Belardinelli, and Postma (2008) also revealed that although multisensory cues showed a supra-additive effect, this pattern did not extend to the cueing effect, since the cueing effect in the multisensory cues did not differ from that of unimodal cues. So can we conclude that reward, akin to some aspects of attentional processing, may not have a strong effect on multisensory integration, which largely occurs automatically?

Before the above claim about a lack of interaction between reward and multisensory processing or the existence of a late integration mechanism can be made, there are some alternative possibilities that need to be considered. In our paradigm, we marked the rewarded and not rewarded cues by presenting on the display either some amount of money (e.g. ’20 Cent’) or none (i.e., ’00 Cent’), respectively. However, if participants missed a cue, the same feedback display as not rewarded conditions (’00 Cent’) was shown. Although in our experiments, cues were rarely missed (**Figure S1.A**), this setting was suboptimal as the feedback for accuracy and rewards were identical. Potentially, this might disrupt the association of the cues with the reward magnitude. Moreover, as mentioned in relation to the differences between our design and that of Bean and colleagues (Bean et al., 2021), using weak unisensory stimuli may enhance the multisensory integration and potentially also its modulation by rewards, according to the *inverse effectiveness* (but also see **Figure S1.C**). In future studies, this possibility can be investigated by presenting stimuli at or below the detection threshold for each participant. Furthermore, another consideration is the mode of reward administration. In our paradigm, we manipulated the magnitude of rewards. However, reward expectancy constitutes of both magnitude and probabilities of obtaining the reward (Schultz, 2006; Yacubian et al., 2007). For instance, future studies could investigate whether enhancing the uncertainty in the reward predictability, for instance by varying the reward probability, can have an impact on its role in multisensory integration.

To conclude, our study is the first to provide evidence for a late integration model of reward and multisensory processing. We confirmed previous findings that the information from two modalities are integrated *supra-additively.* Additionally, we showed that at this stage, reward does not influence multisensory integration. Instead, we provided evidence that reward modulation occurs at a later stage and in a *sub-additive* manner. Importantly, we found that association areas in the Fusiform gyrus show both multisensory supra-additivity and reward modulation and may hence play a role in the late integration of the two types of information.

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Authors' contributions

JEA and AP conceptualized the project designed the task. JEA conducted the experiments. JEA and AP analyzed the data. JEA and AP interpreted the results and wrote the first draft of the manuscript. All authors revised the manuscript. AP acquired funding.

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4.7 Supplementary Information

4.7.1 Caudate BOLD response to *supra-additive* sensory integration and reward predicting cues

To investigate further whether the areas of the Caudate responding to the *supra-additive* sensory integration overlap with the areas that were modulated by reward, we extracted and overlaid the two functional ROIs (see **Figure S1**). The areas in the Caudate showing the reward modulation (xyz = [9 11 -1]) and *supra-additive* sensory integration (xyz = [15 14 20]) did not overlap, suggesting that areas in the Caudate had different functionality. In fact, reward modulation was observed in ventral caudate in line with previous observations (Nakamura et al., 2012), whereas integration of multimodal sensory inputs was observed in dorsal Caudate (Haber, 2011).

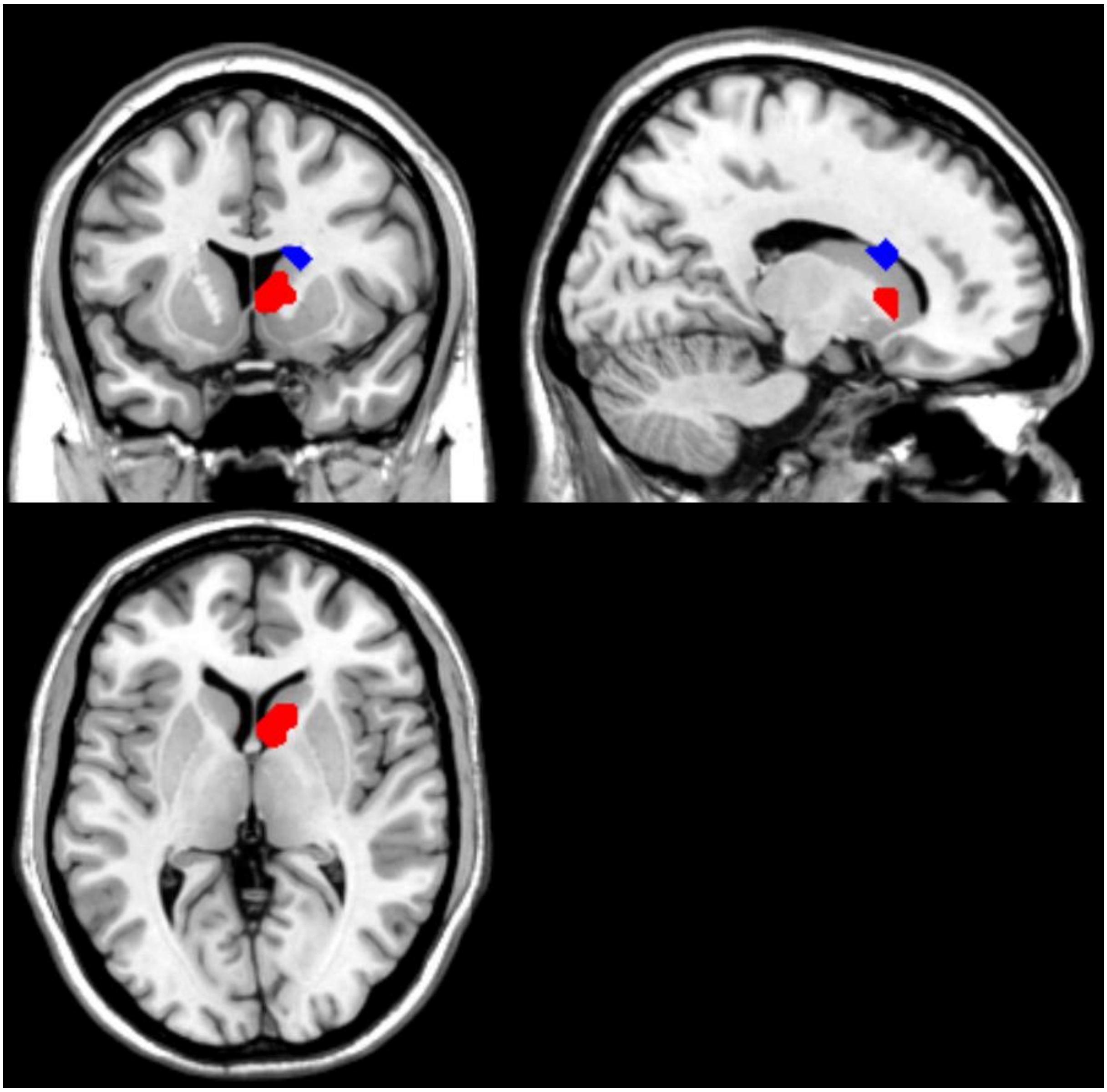

Figure S1. Overlays of the Caudate activities in reward modulation across sensory modalities (in red), where the peak is at xyz = [9 11 -1] and *supra-additive* sensory integration (in blue), where the peak is at xyz = [15 14 20]. ROIs were obtained from images thresholded at uncorrected $p < 0.001$ with extent threshold 10. Cursor is at xyz = [15 11 4].

4.7.2 Reward effects on the strongest areas in the supra-additive sensory integration

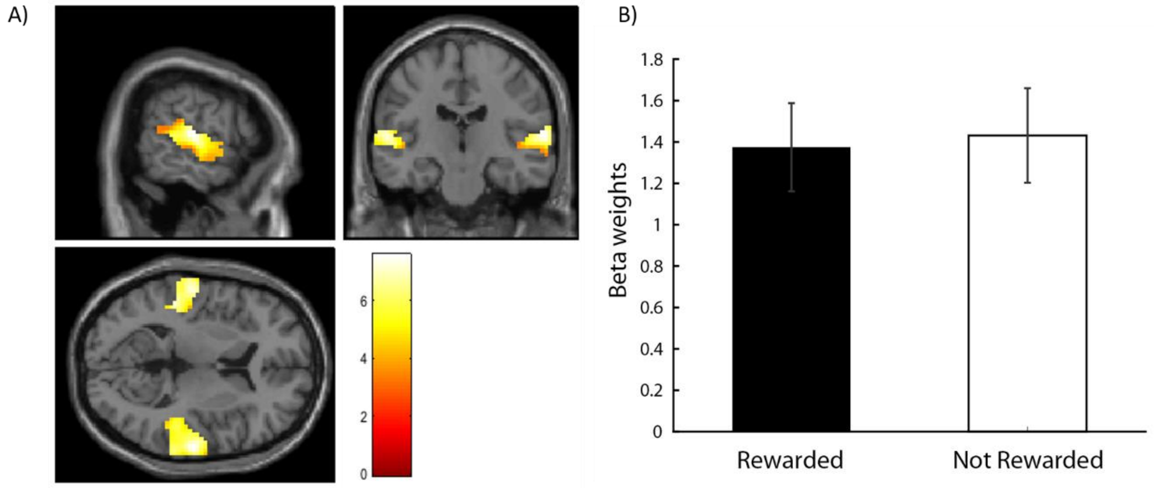

Figure S2. A) Regions of interest (ROI) of superior temporal areas extracted from the supra-additive sensory integration contrast (thresholded at uncorrected $p < 0.001$, k = 10) and masked with an anatomical superior temporal areas from the AAL atlas. Cursor is located at the global maximum xyz=[63 -19 8]. B) Functional ROI analysis examining reward effects on the beta weights of the superior temporal ROI.

We examined reward effects using paired sample *t*-test of the functional region of interest (fROI) analysis in the strongest areas showing *supra-additive* sensory integration in the superior temporal (peak at xyz=[63 -19 8], **Figure S2A**). However, reward did not modulate the activities in the superior temporal areas as demonstrated by the paired sample *t*-test ($p = 0.47$, Cohen’s d = 0.15, **Figure S2B**).

4.7.3 Identification of brain areas that showed a reverse reward modulation

Since reward can either enhance or suppress neural responses, we examined the reverse reward contrasts, i.e. High Reward < Low Reward, for all comparisons that are reported in the main text. This analysis predominantly revealed areas in the frontal and fronto-occipital areas as shown in **Table S1**.

Table S1. Whole-brain activations of univariate results thresholded at uncorrected $p < .001$ and k = 10 for the inversed reward-effect (Rewarded<not Rewarded). Significance (*p*) are reported for cluster-level.

Cluster size	MNI coordinates (in mm)			T	*p*	Side	Region
	x	y	z				
Inversed main effect of reward (AVnot rew+Anot rew+Vnot rew > AVrew+Arew+Vrew)							
107	-30	35	44	4.48	0.028	L	Middle frontal
215	-45	-58	23	4.16	0.003	L	Angular

77	-3	-58	23	3.84	0.056	L	Precuneus
26	-63	-10	-22	3.63	0.248	L	Middle temporal
13	27	35	41	3.58	0.416	R	Middle frontal
Inversed reward effect in audiovisual (AVnot rew > AVrew)							
194	-27	35	41	4.33	0.005	L	Middle frontal
50	-48	-55	29	3.61	0.116	L	Angular
16	27	32	44	3.51	0.365	R	Middle frontal
14	-60	-13	-22	3.45	0.397	L	Middle temporal
Inversed reward effect in visual (Vnot rew > Vrew)							
28	-3	-55	23	3.46	0.231	L	Precuneus
17	-42	-61	26	3.43	0.35	L	Angular
Inversed reward effect in auditory (Anot rew > Arew)							
No voxels survived							

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Chapter 5: General Discussion

5.1 Summary of the results

The aim of this thesis was to characterize the principles of reward-driven modulation of neural correlates of perception when reward was cued under different contexts. Specifically, the project aimed to compare reward-driven modulation of visual perceptual decision-making when reward is signaled from visual (intra-modal) or auditory (cross-modal) modalities (*Objective 1*), the interaction of intra- and cross-modal rewards with the performance-contingent delivery of reward (*Objective 2*), and whether the modulation can be combined across sensory modalities when reward was cued from multiple sensory modalities (*Objective 3*). Towards these aims, three studies were conducted: in the *first study*, reward-associated cues were signaled from intra- and cross-modal and tested under different reward contingencies. Using behavioral and pupillometry, we found that although both performance-contingent rewards and previously rewarded cues both improved the accuracy of visual perception, some aspects of performance were more strongly affected by the former. Specifically, performance-contingent rewards not only improved the accuracy but also the speed of perceptual decisions and led to larger pupil dilation when high and low reward cues were compared. However, the behavioral and pupillary response showed that reward effect did not depend on the sensory modality of the cues. In other words, performance-contingent reward cues seemed to mobilize cognitive resources, such as the pupil-linked arousal and speed-accuracy control mechanisms, more efficiently compared to cues that signaled past rewards. These findings hence indicate a degree of dependency of reward-driven modulations on the contingencies of reward to performance.

In the *second study*, we investigated the underlying neural mechanisms of the effect of previously reward-associated intra- and cross-modal cues on visual perception using behavioral and neuroimaging techniques. Similarly, as in the first study, reward-driven modulation of visual perceptual decision-making did not depend on the sensory modality of the cues, as demonstrated by a faster response and improved perceptual discriminability in the early visual areas when the cues were associated with higher reward magnitude. Interestingly, reward engaged both attention and sensory association areas and followed both supra-modal (i.e. similar pattern for intra- and cross-modal reward cues) and sensory-dependent (i.e., distinct patterns for intra- and cross-modal reward cues) pathways. Specifically, we found that there was a supra-modal pathway between the valuation (i.e. lateral orbitofrontal cortex) and attention-related areas (i.e. intraparietal areas), but reward was inhibited when signaled from cross-modal cues and enhanced when signaled from intra-modal cues. Moreover, attentional areas communicated directly to the early visual areas when signaled from the intra-modal cues, whereas in contrast, reward information in cross-modal cues needed to be mediated through the sensory-association areas in the superior temporal cortex. Along with the sensory-dependent pathway, the sign of the modulation also showed further distinctions between intra- and cross-modal reward modulations, where intra-modal cues were inhibited, while cross-modal cues were facilitated. Altogether, these results provided evidence that the neural mechanism of reward-driven modulation of early visual areas engaged both supra-modal (sensory-independent) and sensory-dependent communication modes.

Furthermore, in the *third study*, we compared the reward effects when cued from multiple sensory modalities (multisensory) or one single sensory modality (unisensory) to investigate whether reward-driven modulations depend on the configuration of the sensory modalities. In this study, we employed performance-contingent reward and signaled the reward from unisensory (visual or auditory) and multisensory (audiovisual) cues inspecting the effects by behavioral and neuroimaging techniques. We observed that reward modulation was regulated independently of the configuration of the sensory modalities, as there was no distinction between uni- and multisensory reward effects on both behavioral and neural response magnitudes. However, the sensory configuration had different effects, where multisensory cues elicited the fastest response that exceeded the combination of the response of the unisensory cues (i.e. supra-additive) and engaged areas such as the superior temporal areas, which has been known to integrate sensory cues from different modalities. This result indicated a different stage of information processing: where sensory information was integrated automatically in a supra-additive manner and at a later stage, reward enhanced the integrated percept further in a sub-additive manner (i.e. the magnitude of multisensory reward effect did not exceed the sum of unisensory reward effect).

Altogether, our results provided evidence of distinct reward mechanisms depending on how and from which sensory modality reward was cued from. Hence, reward and sensory processing systems are tightly linked, where depending on the context, the two systems may or may not interact with each other to regulate information to optimize adaptive behavior. In the following section, we will discuss the results of the three studies from a broader perspective.

5.2 Context-independent reward-driven modulation of perception

Overall, our studies provided evidence that at a behavioral level, reward-driven modulation did not depend on where the reward was signaled from, as reward effects facilitated accuracies (*study 1*), response time (*study 1-3*), and pupil dilation (*study 1*) similarly for visual and auditory (referred as intra- and cross-modal for *study 1* and *2*) reward-associated cues. Moreover, the modulation also did not depend on the configuration of the sensory modality of the cues, as reward effects from the uni- and multisensory cues elicited similar magnitude on response time (*study 3*). Previous literature has shown that reward value facilitates response time (Kang et al., 2015), irrespective of the sensory modality of the cues (Kang et al., 2018). This evidence also suggests that reward enhanced arousal, as participants were instructed to be as accurate as possible instead of being fast across the studies. Despite the goal to be accurate, our results demonstrated a faster response across sensory modalities of the cues and their configuration. In a review by Aston-Jones and Cohen (2005), the arousal system is regulated by a tight coupling between the locus-coeruleus and norepinephrine (LC-NE), where the system involves the evaluation of costs and benefits associated with the task performance and the trade-off between exploiting task-related sources of reward and exploring other possible rewards. Moreover, the modulation of the LC-NE system can also be observed in pupillary dilation, as the neurons in locus-coeruleus also regulate pupil dilation (Aston-Jones and Cohen, 2005). Aligned with our evidence in the first study, we also observed that reward modulates pupillary dilation, as reward-predicting cues (i.e. performance-contingent) elicited larger pupil dilation compared to when reward deliveries were halted (i.e. previously rewarded). This might be explained by assuming that performance-contingent reward exerted more cognitive control induced by reward, as LC system is tightly linked with cognitive effort. Moreover, it has been demonstrated that dopaminergic projections to the mesolimbic and nigrostriatal areas coincide with arousal, showing that dopamine neurons response might reflect the salience and arousal value (Horvitz, 2000). Previous studies have also observed pupillary dilation by anticipation of reward (Schneider et al., 2018) and that the dilation indexes incentive-related changes in cognitive control dynamics prior to and independent from overt responding (Chiew and Braver, 2013). Furthermore, the reward effects in the pupillary response have also been reported in the eye movement, as performance-contingent reward elicited faster eye movement toward a target compared to a random reward (Manohar et al., 2017). Hence, reward effects might have a tight interaction with the arousal system, as reward energizes our behavior and physiological responses to meet environmental demands. Therefore, disentangling reward effects and arousal will be of interest for future studies.

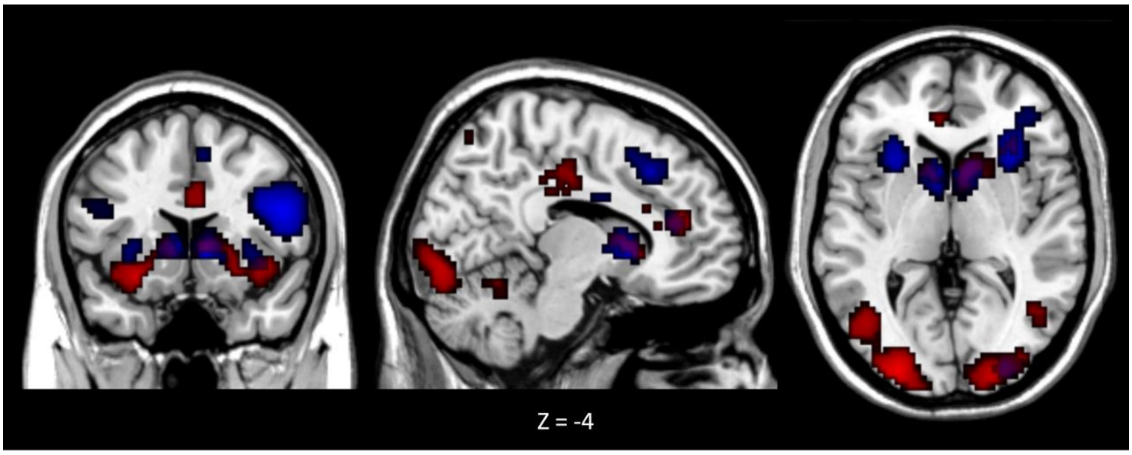

Figure 1 Overlays of reward modulation as reward was contingent on the performance, such as during the conditioning phase in the *second study* (in red) and reward modulation across sensory configuration in the *third study* (in blue). Purple color corresponds to common areas modulated by reward in both studies. Both images were thresholded at uncorrected $p < 0.001$ with the extent threshold of 10. The cursor is located at xyz = [10 14 -4].

Furthermore, our fMRI results also demonstrated that as reward was continuously delivered in a performance-contingent manner, the sensory modality of the cues did not matter, as shown during the reward association (i.e. training phase) in *study 2* and throughout the experiment in *study 3*, where reward-predicting cues were employed. Interestingly, areas such as the Caudate, Insula, and the anterior Cingulate cortex responded to visual and auditory reward cues similarly in both studies, as indexed by the BOLD response magnitude (see **Figure 1**). These areas were modulated when the visual and auditory cues were predictive of reward and the reward was delivered upon correct responses, which are aligned with areas receiving dopaminergic projections (Schultz, 2000), demonstrating that these areas responded to reward prediction error. Moreover, using a multivariate approach, we also observed that the lateral orbitofrontal areas were showing higher accuracies classifying high compared to low reward magnitude when reward deliveries were halted. According to the previous notion, reward value can be represented independently of the features of the stimuli or the type of reward, also known as the “common currency” as inspired by the economic theories (Sugrue et al., 2005; Izuma et al., 2008; Padoa-Schioppa, 2011; Levy and Glimcher, 2012). Our evidence showing the modality-independent modulation of reward in the striatum and lateral orbitofrontal cortex is also aligned as previous studies reported that orbito-striatal areas play a pivotal role in representing the common currency of reward (Montague and Berns, 2002; Levy and Glimcher, 2012; Sescousse et al., 2013).

Moreover, we also observed neurons in the early visual areas responded similarly to the reward-associated cues signaled from the visual (intra-modal) or auditory modality (cross-modal). Our findings are aligned with the previous literature, which already demonstrated a modulation of reward in the early sensory areas (*visual*: Shuler and Bear, 2006; Serences, 2008; *auditory*: Beitel et al., 2003; Guo et al., 2019; *tactile*: Pleger et al., 2008). Extending these findings, it has also been known that reward modulation of early sensory areas can be communicated from cross-modal cues (Leo and Noppeney, 2014; Pooresmaeili et al., 2014). However, it is not known whether reward effects on early sensory areas depend on the source of the modalities of reward cueing. Our studies compared the intra- and cross-modal reward effects in the early visual areas systematically (*study 2*), where we observed that the magnitude of reward effects did not depend on the sensory modality of the cues, as both intra- and cross-modal facilitated the representation of the cues similarly in the early visual areas.

Altogether, we found that reward-driven modulation facilitated behavior and early visual areas, irrespective of the sensory modality of the cues, observed in a faster response time and increased accuracies of perceptual discriminability in the early visual areas. However, a study demonstrated that previously reward-associated cues captured attention (Anderson et al., 2011, 2014), where responses were slowed when the cues were associated with higher compared to lower reward magnitude and the BOLD response in the visual areas such as the extrastriate cortex was increased. This difference might be resulted from the paradigm employed, where in theirs, reward and target cues were located at a different spatial location, while in our paradigm, both reward and target cues were presented at the same spatial location. Hence, as the spatial location was constrained to the same area, neural populations that responded to the cues might overlap with the target cue in the early visual areas, leading to a facilitation by reward. Although, further investigations are required to systematically test the relationship between reward and different features of the stimuli (such as their location and relationship to the target) in affecting the responses of early visual areas.

Furthermore, we asked whether reward-driven modulations depended on the configuration of the sensory modality of the cues. Previous literature has shown that other higher cognitive functions, such as attention, depended on whether the cues were signaled from single or multiple sensory modalities (for a review, see Koelewijn et al., 2010). However, reward dependency on the sensory modality configuration has been underexplored to date. In *study 3*, we compared reward-driven modulation on behavior and neural response magnitude when cued from uni- or multisensory modalities. There are different possibilities of how the interaction between reward and sensory integration processing may occur that can be categorized as whether reward and multisensory integration occur at the same stage and hence reward is processed in a *supra-additive* principle (i.e. the response of the multisensory cues exceeded the sum of responses of the unisensory cues), a hallmark of multisensory integration phenomena (Stein et al., 1993; Stein and Stanford, 2008), or they are two independent mechanisms that may affect each other at different stages of processing. Our evidence pointed out that the two systems are regulated independently, as indexed by the response time and the neural correlates. Specifically, we observed that reward effects accelerated the response similarly across sensory configurations and *supra-additive* sensory integration was evident in the multisensory cues, but there was no interaction between reward and sensory integration. Similarly, the neural correlates demonstrated that reward modulation was observed pre-dominantly in the midbrain, while multisensory integration was modulating the superior temporal areas, typical areas that have been linked to the processing of multimodal cues (Calvert et al., 2001). Interestingly, areas in the Caudate responded to both reward and sensory integration. However, the areas regulating the two processes were not overlapping, indicating different functionalities exist within the Caudate structure. Hence, our evidence demonstrated that reward is immune to the *supra-additive* integration processes, indicating that reward is regulated independently from sensory integration. Specifically, the results are aligned with the second proposal, where the two systems are independent as they occurred at different stages of processing. However, in the paradigm employed to test reward interaction with multisensory processes, we held the uncertainty for reward and sensory information at a constant level. It is interesting for future studies to test whether the two systems might develop a dependency when the ambiguity of the reward and/or sensory information is increased.

5.3 Context-dependent reward-driven modulation of perception

Our studies also demonstrated a dissociation of reward-driven modulation of visual perceptual decision-making in different contexts of reward cueing. First, as reward was contingent on the performance, response times were faster and pupillary dilation was larger in contrast to the context when reward deliveries were halted (*study 1*). Second, the underlying neural mechanism revealed a dissociable pathway depending on the sensory modality of the cues.

The stronger modulation of reward in performance contingent reward is aligned with the previous literature that demonstrated when reward was associated with a task-relevant feature, reward enhances perception by engaging attentional and motivational networks in the brain to modulate the target sensory perceptual areas (Chelazzi et al., 2013; Pessoa, 2015). Therefore, the contingency of reward to performance enables reward to access higher cognitive resources (Pessoa, 2009, 2015) and behaviorally can be observed as the reward modulation of pupillary dilation and energized behavior (i.e. faster response time). Moreover, as a preliminary observation in **Figure 1**, the strongest areas in the striatum were recruited during the conditioning phase in the *second study* and the reward effects across sensory configuration in the *third study*. This observation is aligned with the previous study demonstrating that the striatum received a dopaminergic projection (Schultz, 2000) and is related to the integration of motivational and goal-directed behavior (Delgado, 2007).

In contrast, when reward deliveries were halted, previous studies showed divergent reward modulation: when reward cues were irrelevant to the task at hand, reward-driven modulation captured attention away from the target and impaired performance (Anderson et al., 2011; Anderson and Yantis, 2012; Qin et al., 2020; Watson et al., 2020) or reward effect on the target persisted, engaging a mechanism that continues to facilitate performance (Leo and Noppeney, 2014; Pooresmaeili et al., 2014; De Tommaso et al., 2017). Therefore, what underlies the divergent observations in the previously rewarded cues? There are two possibilities: the first one is based on the previous studies employing cross-modal previously reward-associated cues (Leo and Noppeney, 2014; Pooresmaeili et al., 2014). In these studies, by signaling reward from another sensory modality, reward might engage a dissociated mechanism that is not overlapping with the attentional mechanism required for processing the target, hence utilizing independent resources as used by the target cues. The second factor is the spatial relationship between the reward and target cues. For instance, as reward and the target cues were located or trained at the same spatial location, previously reward-associated cues facilitated perceptual decision-making (De Tommaso, 2017; Pooresmaeili et al., 2014). In contrast, as the reward and target cues were separated spatially, previously-rewarded cues captured the attention and impaired performance (Anderson et al., 2011; Theeuwes and Belopolsky, 2012). Thus, the spatial position determined whether reward-driven modulation may facilitate or impair the performance of the target cues.

Supporting the claim of existing dissociation between performance-contingent and previously rewarded cues, previous studies examining the neural correlation underlying the previously rewarded cues demonstrated that reward relies on other neural mechanisms, without the involvement of the striatum (Kim and Anderson, 2019). Instead, as observed from our *second study*, reward-driven modulation relies on another neural mechanism involving the frontal-parietal areas, such as the lateral orbitofrontal and anterior intraparietal areas, and sensory association areas in the superior temporal. Furthermore, previous studies comparing the neural underpinnings of reward-driven modulation on task relevance also demonstrated that there is a dissociation between the task-relevant and task-irrelevant reward association, where for instance the nucleus accumbens was engaged in a task-relevant association, while task-irrelevant reward association rather involved the medial frontal areas in the pre-supplementary motor areas (Krebs et al., 2011).

Moreover, not only the distinction between reward modulation in the context of reward contingency relies on the switch of neural mechanisms mentioned above, but also reward-driven effects became dependent on which sensory modality the reward was signaled from. In our *second study*, we examined the underlying neural mechanism of the intra- and cross-modal previously rewarded cues using effective connectivity. Our effective connectivity results revealed a dissociated pathway for the intra- and cross-modal cues, where intra-modal cues were mediated through attention-related areas in the anterior intraparietal, and cross-modal cues were mediated through both attention-related and sensory association areas in the superior temporal. Our findings are aligned with a previous study observing modulation by cross-modal reward-associated cues in the superior temporal sulcus, indexed by an increase in the BOLD response magnitude for high compared to low reward conditions (Pooresmaeili et al., 2014). Extending the findings from the previous study (Pooresmaeili et al., 2014), we observed further a dissociation in how the direction of reward modulation depended on the sensory modality of the. Specifically, the results can be divided into two observations. First, as the intra-modal cues relied on an excitatory modulation from attention-related to reward-related areas (i.e. feedforward), cross-modal cues relied on inhibitory modulation. The excitation in the intra-modal cues might reflect an enhancement of the reward-driven saliency, where higher reward associated percept had more gain and thus were represented in the higher valuation area more effectively (Hickey and Peelen, 2017). In contrast, the inhibition in the cross-modal cues between the attention- and reward-related areas might reflect the suppression of the irrelevant sensory features in the auditory to enhance the visual target. Second, the communication between the early visual areas and the mediation areas (i.e. IPS for intra-modal, STS for cross-modal cues) also differed. Specifically, as intra-modal cues relied on inhibitory feedback communication, cross-modal cues relied on excitatory feedback and feedforward communication. The inhibition in the intra-modal cues might reflect a down-weighting of the reward cues, hence enabling the target to access the resources in the early visual areas. Meanwhile, there was no necessity for the cross-modal reward information to be suppressed, as the reward cues originated from different sources (i.e. another sensory modality), thus there was no competition of resources between the cue and the target. Our findings are aligned with a previous electrophysiological study, demonstrating competition of the intra-modal reward associated cues that were reflected in the early suppression, as observed in the depression of P1 component in the early visual areas, whereas cross-modal cues were observed to be enhanced at a later stage, as indexed by the N1 component facilitation (Vakhrushev et al., 2021).

In summary, we demonstrated that there are dependencies observed in how reward is regulated under different contexts of reward cueing. The dissociation lies in which resources reward can access, such as when reward was contingent on the performance, reward may mobilize different resources from the higher cognition, resulting in a more effective behavior. Meanwhile, previously rewarded cues engaged other mechanisms that regulate goal-directed behavior, involving areas in the frontal and parietal (Corbetta and Shulman, 2002; Pessoa, 2015). As reward relies on a more specific mechanism, other factors, such as the source of the reward cues signal also play a role, dictating how reward would be communicated to aid goal-directed behavior.

5.4 Conclusions and future directions

This thesis aimed to investigate the principles of reward-driven modulation of the neural correlates of perception in different contexts of reward cueing. Three studies were conducted to compare reward-driven modulation of visual perceptual decision-making when reward was signaled from the visual or auditory modalities under different reward contingencies and sensory configurations using behavioral, pupillometry, and neuroimaging techniques. We characterized the dissociation of reward-driven modulation depending on the contingencies of the reward, where performance contingent reward relies on the multifaceted resources from the higher cognition to modulate perceptual decision, making them immune to another context, such as the sensory modality of the cue. Furthermore, reward did not depend on the configuration of the sensory modality of the cues, as reward effects across sensory configuration were similar, demonstrating that there is a degree of independence between reward and sensory processing. However, as reward was no longer contingent on the task, to maintain the facilitation of the goal-directed behavior, reward engaged other mechanisms involving the frontal-parietal areas in the lateral orbitofrontal and anterior intraparietal. Moreover, reward became dependent on the source of the sensory modality of the cues, as a dissociable pathway was observed in the auditory (i.e. cross-modal) condition recruiting areas in the superior temporal.

Overall, the thesis provides evidence of distinct reward mechanisms depending on how and from which sensory modality reward was cued, highlighting the tight link between reward and sensory systems in modulating the neural correlates of perception. Understanding that reward-driven modulation has adaptive mechanisms depending on the context of reward cueing encompassing different neural substrates from the higher cognition to early stages of information of processing in the sensory cortices enriches our knowledge about the reward circuitry. This knowledge may allow better therapeutic or rehabilitation methods for reward-related or sensory-related impairments in the future. For instance, cross-modal reward association can be an effective tool to help amblyopia by providing reinforcement using reward association to some features of a sensory property to improve the neural plasticity of the weaker eye. This can be done by using visual (intra-modal) cues, auditory (cross-modal), or multisensory cues.

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Appendix

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Value-driven modulation of visual perception by visual and auditory reward cues: The role of performance-contingent delivery of reward

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Perception is modulated by reward value, an effect elicited not only by stimuli that are predictive of performance-contingent delivery of reward (PC) but also by stimuli that were previously rewarded (PR). PC and PR cues may engage different mechanisms relying on goal-driven versus stimulus-driven prioritization of high value stimuli, respectively. However, these two modes of reward modulation have not been systematically compared against each other. This study employed a behavioral paradigm where participants' visual orientation discrimination was tested in the presence of task-irrelevant visual or auditory reward cues. In the first phase (PC), correct performance led to a high or low monetary reward dependent on the identity of visual or auditory cues. In the subsequent phase (PR), visual or auditory cues were not followed by reward delivery anymore. We hypothesized that PC cues have a stronger modulatory effect on visual discrimination and pupil responses compared to PR cues. We found an overall larger task-evoked pupil dilation in PC compared to PR phase. Whereas PC and PR cues both increased the accuracy of visual discrimination, value-driven acceleration of reaction times (RTs) and pupillary responses only occurred for PC cues. The modulation of pupil size by high reward PC cues was strongly correlated with the modulation of a combined measure of speed and accuracy. These results indicate that although value-driven modulation of perception can occur even when reward delivery is halted, stronger goal-driven control elicited by PC reward cues additionally results in a more efficient balance between accuracy and speed of perceptual choices.

KEYWORDS

visual perception, reward, pupil response, sensory modality, psychophysics

Introduction

Stimuli associated with rewards have a strong influence on our behavior as they trigger the expectation of desirable outcomes, thereby driving agents to optimize their goal-directed actions (Schultz, 2015) and value-based choices (Delgado, 2007; Wallis, 2007; Schultz, 2015). Accordingly, brain areas underlying action planning and value-based decisions are strongly modulated by rewards. Moreover, reward effects even extend to the earliest stages of information processing in the brain as reward associations of stimuli influence their representation in the primary sensory areas (Shuler and Bear, 2006; Serences, 2008). Understanding the underlying mechanisms of value-driven modulation of perception is important since it allows a better understanding of how experience-related and contextual factors in general influence sensory perception (Pessoa and Engelmann, 2010; Seriès and Seitz, 2013).

Reward effects on perception are typically investigated using paradigms where correct detection or discrimination in a perceptual task (Engelmann and Pessoa, 2007) or efficient orienting responses in a motor task (Milstein and Dorris, 2007) lead to higher magnitude or probability of rewards. In such scenarios, prioritization of reward cues, through engaging mechanisms such as selective attention or preparation of oculomotor responses, aligns with the goal-driven mechanisms that help agents to maximize their obtained rewards (Chelazzi et al., 2013; Failing and Theeuwes, 2018). Using such tasks, value-driven modulations have been observed at the early stages of sensory processing in the brain. For instance, Weil et al. (2010) provided evidence that rewarding feedbacks improved behavioral performance in a visual discrimination task and also increased the activity in the human primary visual cortex during the discrimination phase following a reward feedback. Another study by Pleger et al. (2008) also demonstrated that reward facilitated somatosensory judgments. There, high reward cues improved tactile performance and enhanced the hemodynamic response in the primary somatosensory cortex, indicating that reward signals can influence early sensory areas when a decision is based on the sensory features of stimuli. Thus, reward signals, during the delivery of reward or during the presentation of reward-predicting cues, can be propagated not only within the classical reward-related regions, but also to sensory areas, especially when the reward delivery is contingent on the accuracy of sensory judgments [i.e., performance-contingent (PC)]. One criticism to these designs is that value-driven effects cannot be distinguished from attentional (Maunsell, 2004) or cognitive control mechanisms (Botvinick and Braver, 2015) that are involved in processing of the task-relevant feature of a task. Accordingly, such paradigms do not allow a differentiation between value-driven effects due to voluntary, goal-driven mechanisms from effects due to stimulus-driven and involuntary mechanisms.

Another line of research has shown that value-driven modulation of perception also occurs when reward cues are not the relevant feature of the task or when reward delivery and hence the motivation to strategically optimize performance has been removed. For instance, the delivery of reward in response to a saccadic target in some trials can affect the oculomotor performance in subsequent unrewarded trials when a non-target stimulus contains a similar feature as the rewarded target in the past (Hickey and van Zoest, 2012). It has also been shown that reward effects outlast the delivery of reward so that previously rewarded (PR) features automatically affect participants' performance (Yantis et al., 2012; De Tommaso et al., 2017). The latter experiments typically employ a two-phase paradigm (De Tommaso and Turatto, 2021), where in the first training or conditioning phase participants learn the association of stimulus features with certain amount or probability of reward, and in the subsequent test phase PR cues are presented without the actual delivery of reward (i.e., during extinction). Although during the test phase reward associated cues are not reinforced anymore, it has consistently been shown that they can still involuntarily capture participants' attention, a phenomenon called value-driven attentional capture (VDAC) (Anderson et al., 2011), and thereby influence perceptual judgments across a variety of tasks (Anderson et al., 2011; Yantis et al., 2012; Camara et al., 2013; Failing and Theeuwes, 2015; Bucker and Theeuwes, 2017; Tankelevitch et al., 2020). The typical finding of these studies is that when PR stimuli are the same as the target of a task they facilitate performance (accuracy or RT) but importantly when they are irrelevant to the task or assigned to distractors, they can impair performance (Anderson et al., 2014; Asutay and Västfjäll, 2016; Gong et al., 2017; Bucker and Theeuwes, 2018; Qin et al., 2020; Watson et al., 2020), a so-called value-driven distraction (Rusz et al., 2020). Such effects likely arise as a result of the enhanced representation of distractors in visual cortex (Itthipuripat et al., 2019), which limit the processing resources that are available to the target.

Interestingly, it is not always the case that task-irrelevant reward cues capture attention away from the target and suppress performance. For instance, Pooresmaeili et al. (2014) utilized one sensory modality (audition) to signal the reward value while keeping the target of the task in another modality (vision). Using this design, it was shown that task-irrelevant auditory cues that were previously associated with high reward enhanced the visual sensitivity compared to low reward cues. A follow-up study (Vakhrushev et al., 2021) used a similar design and compared task-irrelevant reward cues from the same (vision) or different (audition) sensory modality in terms of their effect on perceptual decisions made about a visual target. In this study, it was found that PR auditory and visual cues had distinct effects on behavioral and electrophysiological correlates of visual perception, suggesting that reward-driven modulations may have dependencies on the sensory modality of task-irrelevant stimuli.

Overall, across different paradigms employed to investigate the effects of reward on sensory perception, PC rewards have been often found to be associated with the facilitation of sensory processing, whereas divergent effects were observed for cues previously associated with rewards based on whether the target or the task-irrelevant distractors contained a rewarded feature. Another factor that also seems to weigh in is where the reward information was signaled from, with different effects for rewards cued intra-modally or cross-modally. However, a systematic investigation of these factors where the same perceptual judgment is tested under different modes of reward delivery and cuing has been missing. Therefore, in the current study, we designed a paradigm that tested the effect of three factors on visual perception: reward magnitude, sensory modalities of reward cues, and the contingency of reward delivery on task performance. Specifically, a similar design as two previous studies from our lab (Pooresmaeili et al., 2014; Vakhrushev et al., 2021) was used where auditory or visual cues were first associated with either high or low monetary reward during a training phase (referred to as conditioning). During the test phase, auditory and visual cues were presented at the same time as the target of a visual discrimination task but did not carry any information about the task at hand (i.e., orientation discrimination). Importantly, participants either obtained rewards upon correct responses or did not receive any reward feedback in any condition. In the first case, participants' rewards depended on the identity of auditory or visual stimuli and these cues were *PC* predictors of rewards, whereas in the second case auditory and visual stimuli were *previously associated with rewards* (PR) and did not predict the delivery of reward anymore. We hypothesized the two modes of reward cuing are linked to distinct processes: goal-driven (voluntary) and stimulus-driven (involuntary) attention. In result, when the cues were PC, the voluntary control would dominate and therefore the cues would benefit performance. However, when the cues were associated with rewards in the past and did not lead to reward feedbacks during the test phase, they would only involve the involuntary capture of attention and lead to weaker reward-driven modulations, which may differ between the intra- and cross-modal rewards. Pupil responses can be used as a sensitive readout of changes in the motivational state due to salient events (Chiew and Braver, 2013; Schneider et al., 2018; Pietrock et al., 2019), even when such events are not consciously detected (Bijleveld et al., 2009). Pupil responses have also been recently linked to the level of cognitive effort exerted in a task (van der Wel and van Steenbergen, 2018). We therefore hypothesized that PC reward cues are associated with higher goal-directed cognitive effort in prospect of higher rewards, hence producing a stronger value-driven modulation of pupillary responses compared to cues that were previously associated with rewards.

Our results demonstrate that reward associated cues enhance the accuracy of visual discrimination irrespective of the sensory modality and whether the reward delivery was continued (PC) or halted (PR). Additionally, PC reward cues energized behavior, as indexed by reaction times (RTs) and pupil responses, an effect that was absent in PR cues.

Materials and methods

Participants

In total, 43 subjects participated in the experiment to fulfill a target sample size of $N = 36$ based on a previous study (Vakhrushev et al., 2021). They were invited *via* an online recruiting system.[1] All participants were naïve to the hypothesis of the project, had no history of neurophysiological or psychiatric disorders according to a self-report, had normal or corrected-to-normal vision, and performed the key presses during the task with their dominant hands (five left handed). Eight participants were removed from the final sample, as due to technical problems the experiment had to be terminated before the complete dataset was collected ($N = 4$), the psychometric method used to estimate the orientation discrimination thresholds did not converge on a reliable value ($N = 2$, based on our previous work the QUEST method needed to converge on a stimulus orientation $< 2°$ and performance during the baseline phase needed to be $<90\%$), the participant did not learn the reward associations ($N = 1$) or had a strong bias for one of the colors or sounds prior to learning the reward associations ($N = 1$, estimated as a bias toward high reward colors or sounds $>$ 2.5 SD of the group mean). Thus, the final sample comprised data from 35 participants (18 female; age: 18–45, 27 ± 5 SD years).

Participants were informed that after the experiment they would obtain a reward comprising a fixed hourly rate (~8 Euros per hours) plus an added bonus that depended on their performance. To calculate the total reward, the fixed hourly rate was added to the money participants obtained during the experiment and a fraction of the total amount (4%) was handed over to the participants in cash.

Before the experiment started and after all procedures were explained, participants gave their oral and written consent. The study was approved by the local ethics committee of the "Universitätsmedizin Göttingen" (UMG), under the proposal number 15/7/15.

Stimulus presentation and apparatus

The behavioral paradigms used during the reward associative learning (conditioning) and test phase were

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[1] http://www.probanden.eni-g.de/orsee/public/

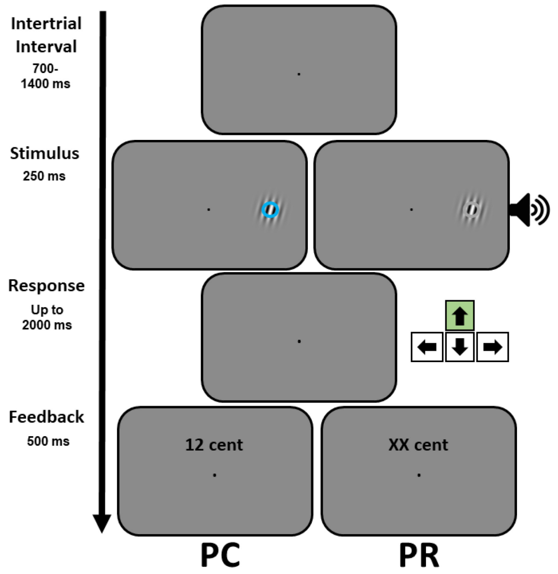

FIGURE 1
Behavioral paradigm employed during the test phase. An example trial of the visual discrimination task, illustrating the Gabor target and the task-irrelevant visual **(left)** or auditory **(right)** stimuli, is shown. Participants reported the orientation of the Gabor target by pressing either the up or down arrow keys (the correct response for the example trial is illustrated symbolically by the arrow in the green box). Prior to the test phase, participants learned to associate different visual (blue or orange circles) or auditory (high or low pitch tones) stimuli, counter-balanced across participants, with different reward magnitudes during a conditioning phase (see **Supplementary Figure 1**). The test phase comprised two parts with different reward contingencies (PC and PR). In case of a correct response, during the performance-contingent reward (PC) phase, the monetary reward associated with a specific stimulus was displayed (for instance 12 cent). In a subsequent phase, previously reward-associated (PR) stimuli were not predictive of reward delivery, but to keep the layout of the feedback display similar across the two phases the letters XX were shown for all conditions.

identical to a previous study (Vakhrushev et al., 2021). The paradigm employed during the conditioning was a spatial localization task (see **Supplementary Figure 1** and the Section "Experimental procedure") where participants reported the side (left or right) from which visual or auditory stimuli were presented. During the test phase, a visual orientation discrimination task was used in which the tilt direction of a Gabor patch (a Gaussian-windowed sinusoidal grating with SD = 0.33°, a spatial frequency of 3 cycles per degree, subtending 2° diameter, displayed at 9° eccentricity to the left or right side of the fixation point) had to be reported (**Figure 1**). The tilt orientation of the Gabor patch was set to each participant's perceptual threshold estimated after the initial training. To determine this threshold, we employed a QUEST algorithm (Watson and Pelli, 1983) to estimate the Gabor tilt orientation for which participants' performance was at 70%. In each trial, a task-irrelevant semi-transparent ring (alpha 50%, 0.44° in diameter) was superimposed on the Gabor patch. The color of the rings (orange or blue for visual conditions, or gray for auditory and neutral conditions) was adjusted individually for each participant in such a way that they were perceptually isoluminant. Perceptual thresholds for the visual discrimination task were determined when Gabors were superimposed with a gray circle. For auditory cues, two pure tones with different frequencies (350 or 1,050 Hz) were presented at 70 dB simultaneously with the Gabor patch and at the same side.

The timing of events was identical across the experiment (see **Figure 1** and **Supplementary Figure 1**). As soon as participants fixated (within 1° of the fixation point) a trial started. After an additional fixation period of 700–1400 ms, a target stimulus appeared (either a colored circle or a tone during conditioning or a Gabor patch together with a colored circle or a tone during the test phase). The target stimulus disappeared after 250 ms and participants had to indicate its side (conditioning) or the orientation of the Gabor patch (during the test phase) within 2,000 ms from the onset of the target. Finally, a feedback display was presented for 500 ms. The feedback display contained the reward magnitude that participants received (in numbers) during conditioning and PC phase (see the Section "Experimental procedure"). To keep the visual layout of the feedback display similar across PC and PR phases, in the latter phase "xx cent" was shown for all conditions.

Throughout the experiment, visual stimuli were displayed on a calibrated ViewPixx monitor (refresh rate = 120 Hz, resolution 1,080 × 1,920 pixels, and placed at a viewing distance of 60 cm). The auditory tones were delivered through an over-ear headphone (HAD 280 audiometry headphones, Sennheiser).

Experimental procedure

The experiment consisted of a practice session (32 trials) for the orientation discrimination task and three phases. In the first phase, referred to as the *baseline phase* (160 trials), participants were required to report the tilt direction of a Gabor patch relative to the horizontal meridian by pressing a keyboard button (either the down or up arrow keyboard button for clockwise and counter-clockwise directions, respectively; see **Figure 1**). They were additionally instructed to ignore the simultaneously presented visual or auditory cues that accompanied the Gabor. Afterward, participants completed a *conditioning* task to learn the reward associations of auditory and visual cues (see **Supplementary Figure 1**). In this task, participants decided whether a colored circle or an auditory tone was perceived to be on the left or right side by pressing the corresponding arrow key buttons. Upon correct response, participants saw the magnitude of the reward that was paired with a certain cue and thereby learned whether a visual or auditory stimulus was associated with high (mean = 25 Cents) or low (mean = 2 Cents, drawn from a Poisson distribution) monetary reward. In the third phase, referred as the *test phase*, participants performed the same orientation discrimination task as in the baseline phase, but in the presence of task-irrelevant visual or auditory cues that had been associated with different amounts of reward during conditioning. As the main task was a visual discrimination task, task-irrelevant visual and auditory stimuli will be referred to as intra- and cross-modal, respectively. Additionally, the test phase was split into two parts: in the first part (320 trials, the phase with *performance-contingent reward cues*, *PC*), upon correct response, similar reward feedbacks as in the conditioning phase were presented, i.e., reward depended on the identity of cues and was either high or low. In the second part (320 trials, referred to as the phase with *previously associated reward cues*, *PR*), the delivery of rewards was halted. Here, participants were instructed similarly to the PC phase with the exception that they were informed about a different feedback display shown after each trial. Specifically, they were told that in the PR phase the differential reward deliveries would be halted and instead after each trial they would see a feedback in the form of "xx cent" indicating a constant amount of reward that would be added to their total earning in case they responded correctly.

In order to determine whether participants learned the reward-cue association, they were asked to indicate which cue from each modality presented to them sequentially had been associated with more money. This question was completed in multiple parts following the conditioning, PC, and PR phases. Additionally, we also repeated the question in the questionnaire after the experiment was completed. If a participant did not provide any correct response across all experimental phases (*conditioning*, PC and PR), then the participant was removed from further analysis ($N = 1$).

Pupillometry

An EyeLink 1000 Plus system with a desktop mount (SR Research) was used to track the right eye. The EyeLink camera was controlled by the corresponding toolbox in MATLAB (Cornelissen et al., 2002). Before each block, the eye tracking system was calibrated using a nine-point standard EyeLink calibration procedure.

Pupil responses were acquired at a sampling frequency of 1,000 Hz. The pupil data of each trial was extracted from 100 ms prior to the target onset until the end of the trial (i.e., the end of the feedback display). Trials in which more than 50% of data was lost were removed from further analysis. For the missing data due to blinks, a linear interpolation was applied, where the missing data was interpolated based on the samples within a window of 10 ms before and after the blink. The data was then low-pass filtered (fourth order Butterworth with a cut-off frequency of 2 Hz), normalized to z-score (across all samples recorded for each participant) and subsequently corrected for baseline (i.e., 100 ms). For the statistical analysis, the average stimulus-evoked response in a window from the target onset until the end of each trial (the end of the feedback display as shown in **Figure 1**) was examined. Note that a trial's timing depended on how fast the participant responded. Therefore, to examine the relation between the pupil size and the behavioral measures, pupil responses were estimated from the data of the first 500 ms interval after the target onset. This was done to ensure that for all participants and all experimental conditions the same number of pupil samples were considered.

Data analysis

The data obtained from all parts of the experiment was analyzed using custom-written scripts in MATLAB (version R2015a). We analyzed accuracies, reaction times (RT: median reaction time across correct and incorrect trials), inverse efficiency scores (IE) (median RT of correct trials divided by the accuracy) d-prime (d') and pupil size. We removed trials in which any of the following conditions were met: lack of stable fixation during the presentation of the target (i.e., the distance of eye gaze from the fixation point exceeded 0.9°), no response, RTs exceeding the 2.5 SD of each phase, or loss of more than 50% of pupil data. This resulted in 2.98% (±1.20 SD), 2.62% (±2.25 SD), 3.01% (±1.04 SD), and 3.64% (±2.97 SD) trials removed from baseline, conditioning, PC and PR phases, respectively. For each response variable, we calculated the average across all trials of each condition per subject during the baseline and test phases separately. D-prime was measured based on the probability of hits and false-alarms, as $d' = Z(PHit)–Z(PFA)$, where one of the tilt directions was arbitrarily treated as "target-present" as in formal Signal Detection Theory analysis of discrimination tasks (Macmillan and Creelman, 1991). Extreme values of PHit or PFA were slightly up- or down-adjusted (i.e., a probability equal to 0 or 1 was adjusted by adding or subtracting $\frac{1}{2\times N}$, where N is the number of trials, respectively). Afterward, the difference in response variables (accuracies, reaction times, d' and pupil size) between baseline and test phase was entered to a 2 × 2 × 2 repeated measures ANOVA, with the reward contingency (performance-contingent: PC and previously associated: PR), reward magnitude (high and low), and sensory modality (visual or auditory, i.e., intra- and cross-modal, respectively) as within-subjects factors. Significant effects in RM ANOVA were followed up by *post-hoc* tests (*multcompare* in MATLAB with *Bonferroni* correction). To test whether the value-driven modulation of pupil size is predictive of the modulation of the behavioral measures a robust regression method (*robustfit* with default settings in MATLAB) was employed.

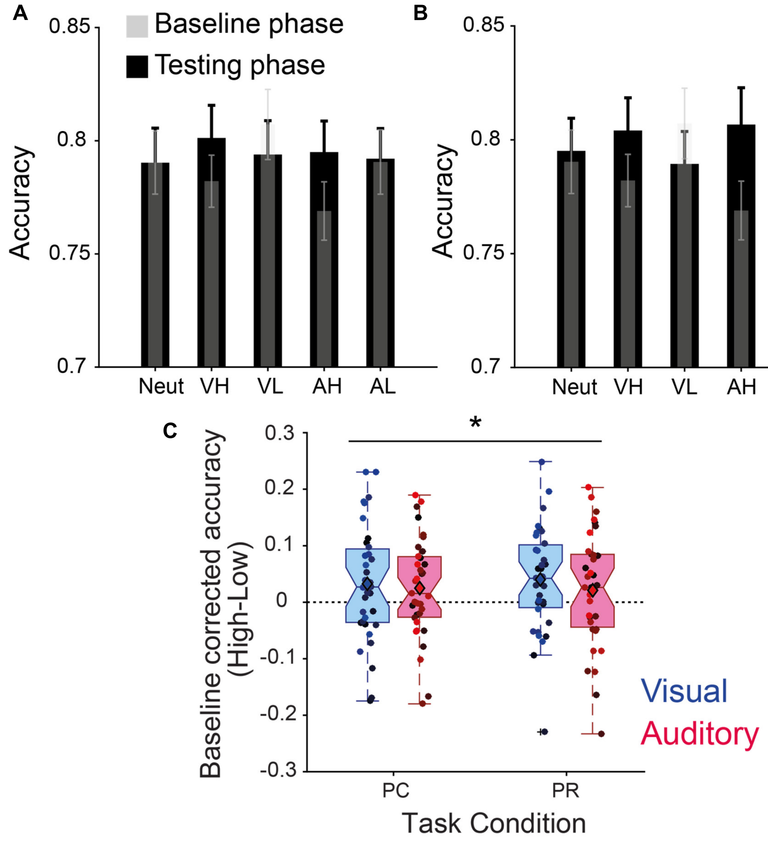

FIGURE 2
Value-driven modulation of discrimination accuracy. **(A)** Accuracies of the baseline and performance-contingent reward (PC) phase. **(B)** Same as panel **(A)** for the previously associated rewards (PR) phase. The transparent gray shades represent the baseline performance before learning the reward associations, overlaid on the test phase performance in black for each condition (neut, neutral; VH, visual high-; VL, visual low-; AH, auditory high-; and AL, auditory low-reward). **(C)** Baseline -corrected reward effect (high–low) for intra-modal (visual) and cross-modal (auditory) reward cues during the two phases. Error bars in panels **(A,B)** represent s.e.m., circles with different color shades in panel **(C)** correspond to the data of individual participants, and * stands for the main effect of reward at $p < 0.05$.

Results

The main objective of this study was to examine whether visual discrimination is influenced by co-occurring visual and auditory stimuli which did not carry any information about the dimension over which the discrimination was performed (i.e., the orientation of a Gabor stimulus, see **Figure 1**) but were either predictive of the reward delivery upon correct performance (i.e., performance-contingent: PC phase) or were previously associated with the reward delivery (i.e., previously rewarded: PR phase). Participants first learned the reward associations of visual and auditory stimuli during a conditioning phase by performing a localization task (see the **Supplementary Text** and **Supplementary Figure 1**). We found a weak effect of reward on the behavioral performance and pupil responses (see the **Supplementary Text** and **Supplementary Figure 2**) during the conditioning phase. Nevertheless, the conditioning task was successful in establishing the associations between stimuli and rewards, as according to the debriefings performed after this phase, all participants had learned the reward associations of tones and colors correctly. Therefore, we next examined the behavioral and pupillometric responses during the visual discrimination task, testing whether the learned reward associations affected the visual perception during the PC and PR phases compared to the baseline (i.e., done prior to the conditioning).

Effect of performance-contingent and previously associated reward cues on the accuracy of visual discrimination

Overall, during the initial baseline phase where the cues were not associated with any reward magnitude, participants performed on average across all conditions with 78.78% accuracy (±0.94 s.e.m) (**Figures 2A, B**), while in the PC phase, mean accuracy increased to 79.44% (±1.23 s.e.m) and in the last phase with PR cues increased to 80.06% (±1.32 s.e.m). This indicated that with time, participants became more proficient in the task. However, the improvement of accuracy across time (Baseline, PC and PR) did not reach statistical significance [$F(2,34) = 1.04$, $p = 0.35$, $\eta_p^2 = 0.03$].

In the test phase, a repeated measures 2 × 2 × 2 ANOVA conducted on the baseline corrected accuracy rates showed a significant main effect of reward magnitude across PC and PR phases (**Figure 2C**): $F(1,34) = 7.37$, $p = 0.01$, $\eta_p^2 = 0.18$. All other main and interaction effects were non-significant (all $ps > 0.1$). *Post-hoc* tests revealed a significant increase in accuracies by high- compared to low-reward visual cues in PR ($p = 0.016$, Cohen's d = 0.430), a trend in PC ($p = 0.068$, Cohen's d = 0.319) and non-significant effects in auditory conditions (PC: $p = 0.108$, Cohen's d = 0.279; and PR: $p = 0.235$, Cohen's d = 0.204). We obtained similar results when d-prime (d′) scores instead of accuracies were used [$F(1,34) = 6.75$, $p = 0.01$, $\eta_p^2 = 0.17$], indicating that the improvement in participants' performance was not driven by an enhanced false-alarm rate.

The main effect of reward is in line with our hypothesis predicting that high-reward cues improve the perceptual discriminability. Contrary to our predictions, we did not find a significant interaction effect with reward contingency or sensory modality, although the effect sizes were larger for intra-modal (visual) cues.

Effect of performance-contingent and previously associated reward cues on the speed of visual discrimination

The analysis of RTs across all conditions demonstrated that participants became overall faster as they proceeded through the experiment (**Figures 3A, B**), an effect that reached statistical significance when tested with an ANOVA with phase (Baseline, PC and PR) as the independent factor [$F(2,34) = 21.39$, $p < 10^{-7}$, $\eta_p^2 = 0.39$]. Participants' RTs in both PC (M = 770.83 ms, s.e.m = 18.24 ms) and PR phases (M = 782.41 ms, s.e.m = 18.93 ms) were significantly faster than the baseline phase (M = 843.01 ms, s.e.m = 21.33 ms, both $ps < 10^{-4}$).

A repeated measures 2 × 2 × 2 ANOVA on the baseline corrected RTs revealed a significant interaction between reward magnitude and task contingency [$F(1,34) = 4.61$, $p = 0.039$, $\eta_p^2 = 0.12$, **Figure 3C**]. This effect demonstrates that when cues associated with higher value were predictive of the reward delivery, participants reacted faster than when reward delivery was halted. Specifically, *post-hoc* tests revealed that this effect was more pronounced for PC, high-reward visual cues ($p = 0.048$, Cohen's d = 0.33) than other conditions (visual/PR: $p = 0.47$, Cohen's d = 0.123; auditory/PR: $p = 0.30$, Cohen's d = 0.178; auditory/PC: $p = 0.80$, Cohen's d = 0.043). Although mostly driven by the visual cues, this finding is in line with our hypothesis predicting that PC rewards have a stronger influence on the speed of perceptual decisions.

Effect of performance-contingent and previously associated reward cues on pupil responses

We next examined the pupil responses using a 2 × 2 × 2 repeated measure ANOVA with three factors: reward magnitude (high and low), sensory modality (auditory and visual), and reward contingency (performance-contingent: PC and previously associated: PR). Pupil responses were the baseline corrected average pupil size (z-score) extracted from the target onset until the trial end (**Figure 4**). Across all visual and auditory conditions, task-evoked pupil responses were significantly higher in PC compared to PR phase [$F(1,34) = 61.32$, $p < 10^{-8}$, $\eta_p^2 = 0.643$]. Additionally, a significant interaction effect was observed between the reward magnitude and contingency [$F(1,34) = 7.17$, $p = 0.011$, $\eta_p^2 = 0.174$], as higher rewards increased the pupil size compared to lower rewards only in PC ($p = 0.04$, Cohen's d = 0.354) but not in PR phase ($p = 0.94$, Cohen's d = 0.014). A weaker interaction effect [$F(1,34) = 4.80$, $p = 0.035$, $\eta_p^2 = 0.124$] was also observed between the sensory modality and reward contingency, corresponding to larger pupil responses evoked by cross-modal (auditory) compared to intra-modal (visual) stimuli in PC phase and an opposite effect in PR phase. The effect of sensory modality in each phase did not reach significance (PC: auditory-visual = 0.02 ± 0.02 s.e.m, $p = 0.31$; PR: auditory-visual = −0.01 ± 0.02 $p = 0.34$, $p = 0.34$).

The lack of reward-driven effects in the PR phase could be due to a time-dependent habituation of pupil responses to reward rather than the termination of reward delivery, since the PR phase consistently occurred after the PC phase. However, we ruled out this possibility by examining the pupil responses of the first and second half of each phase (see the **Supplementary Text** and **Supplementary Figure 3**).

We next examined whether the value-driven modulation of pupil responses observed in the PC phase exhibited any correlation with the modulation of our behavioral measures. Since we observed both a modulation of accuracy (**Figure 2**) and RTs (**Figure 3**), we combined these measures into one single parameter, i.e., IE defined as the ratio of RTs of correct trials to accuracy (Vandierendonck, 2021). This parameter provides a measure of how well participants adjust their speed-accuracy trade-off. We found a strong linear relation ($\beta = -0.77$, $t_{33} = -2.59$, $p = 0.01$, **Figure 4E**) between the net effect of reward on pupil size (i.e., pupil size in high reward condition of both modalities minus pupil size in low reward of both modalities) and on IE scores. This effect indicates that a stronger value-driven pupil dilation was predictive of a stronger value-driven acceleration of visual discrimination across participants.

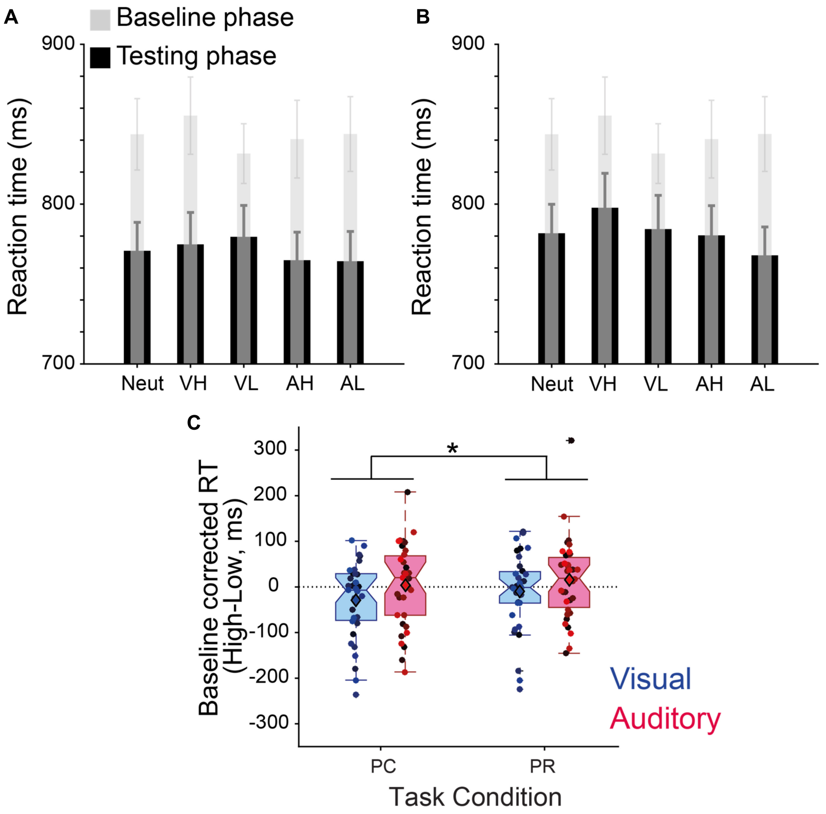

FIGURE 3
Value-driven modulation of discrimination speed. **(A)** Reaction times (RTs) (ms) of the baseline and performance-contingent reward (PC) phase. **(B)** Same as panel **(A)** for the previously associated rewards (PR) phase. The transparent gray shades represent the baseline RTs before learning the reward associations, overlaid on the test phase performance in black for each condition (neut, neutral; VH, visual high-; VL, visual low-; AH, auditory high-; and AL, auditory low-reward). **(C)** Baseline–corrected reward effect (high–low) for intra-modal (visual) and cross-modal (auditory) reward cues during the two phases. Error bars in panels **(A,B)** represent s.e.m., circles with different color shades in panel **(C)** correspond to the data of individual participants, and * stands for the interaction effect between reward and task phase at $p < 0.05$.

This correlation was non-existent in the PR phase ($\beta = 0.13$, $t_{33} = 0.35$, $p = 0.73$, **Figure 4F**).

Discussion

This study aimed to compare PC and previously associated (PR) reward cues from visual or auditory modality in terms of their modulatory effects on visual perception and task-evoked pupil responses. Our results showed that reward associated cues exert a persistent effect, in that once the reward associations are learned, reward cues improved the accuracy of perceptual judgments even when rewards were not delivered anymore (i.e., during the PR phase). PC cues were overall associated with larger task-evoked pupil responses indicating that they invoke more engagement with the task and higher goal-driven control. Furthermore, in contrast to PR, PC cues especially in visual modality, also sped up perceptual choices when a higher reward was expected and this effect was correlated with the value-driven modulation of pupil responses. These results suggest that despite the persistent effects of reward even when reward delivery is halted, some aspects of value-driven effects are specific to PC cues.

Previous research has provided evidence for a value-driven modulation of perception when the task-relevant features of stimuli are associated with high reward (Chelazzi et al., 2013; Pessoa, 2015; Failing and Theeuwes, 2018), an effect that also persists when the reward delivery is halted (De Tommaso et al., 2017). Conversely, it has been shown that the association of task-irrelevant stimuli with rewards inflicts a cost on performance, likely due to capturing attention away from the target and exhausting the cognitive control mechanisms (Sali et al., 2013; Anderson et al., 2014; Rusz et al., 2020; Watson et al., 2020). Although the majority of past research has focused on visual modality, recent studies have also examined the cross-modal effects of rewards (Leo and Noppeney, 2014; Pooresmaeili et al., 2014). Interestingly, the latter studies showed that cross-modal (auditory) stimuli that have been previously associated with higher rewards facilitated visual perception compared to low reward stimuli, despite being irrelevant to the task at hand.

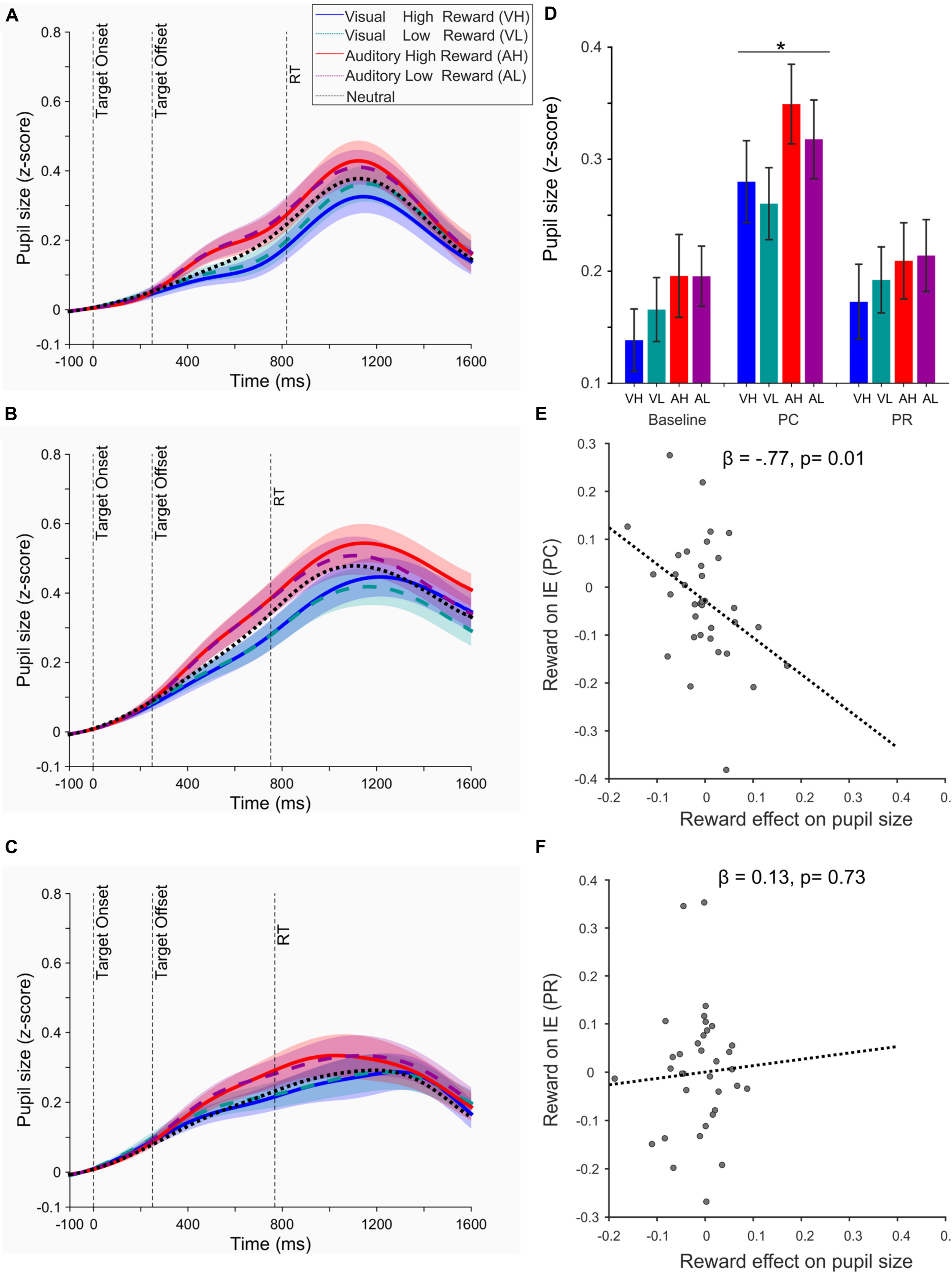

FIGURE 4

(A) Time course of pupil response for each condition during the baseline phase. **(B)** Same as panel **(A)** during the performance-contingent phase (PC). **(C)** Same as panel **(A)** during the previously associated rewards (PR). In panels **(A–C)** the vertical dashed line denoted as RT shows the mean reaction time across all conditions and across all participants. **(D)** Bar plots represent the mean task-evoked pupil size measured from the target onset until the trial end (i.e., the end of feedback phase, see Figure 1) for each condition (VH, visual high-; VL, visual low-; AH, auditory high-; and AL, auditory low-reward). *The effect of reward value was only significant in the PC phase at $p < 0.05$. **(E)** Relation of the value-driven modulation of pupil size (in the first 500 ms after the target onset) and inverse efficiency scores (IE) during the PC phase. **(F)** Same as panel **(E)** during the PR phase. In panels **(E,F)** regression lines are estimated based on a robust regression analysis.

These findings suggest that the value-driven increase in the salience of task-irrelevant stimuli is not necessarily associated with costs on performance. What determines whether rewards boost or impair perception in light of findings of the current study and the past research?

To understand the divergent effects observed across studies and thereby provide a unifying explanation for reward effects on perception, it is important to point to differences in the design and experimental procedures that were employed. There is a critical difference between the current study and previous studies showing that task-irrelevant reward cues captured attention away from the target and were thus associated with a cost on performance (Sali et al., 2013; Anderson et al., 2014; Rusz et al., 2020; Watson et al., 2020). In those previous studies, the majority of which employed a visual search paradigm, the target and the reward associated task-irrelevant stimuli were spatially separated. This separation might be the factor explaining the capture of attention to a different location than the target by reward cues, thereby competing with the task goal. In our study, however, both target and task-irrelevant reward cues were presented at the same spatial location, hence the capture of attention by task-irrelevant high reward cues may have spilled over to the target, increasing its representation and therefore optimizing behavior compared to low reward cues. This is in line with the findings of MacLean and Giesbrecht (2015) showing that when task-irrelevant cues were in the same location as the probed target, cues associated with higher reward magnitude improved visual search performance compared to low reward magnitude. Another related possibility is that higher reward may in fact promote perceptual grouping between the reward-associated cues and the target, as reward has been shown to interact with object-based attention (Shomstein and Johnson, 2013; Stanisor et al., 2013; Zhao et al., 2020). Therefore, in our paradigm high-reward task-irrelevant cues may have enhanced the processing of the target through a combination of space-based and object-based selection mechanisms, especially since during the PC phase these cues were predictive of the reward delivery.

The results of the current study show that PR stimuli can have long-lasting facilitatory effects on perception. However, we note that PR phase in our experiment was only tested after the PC phase, and therefore participants had a long exposure to the reward cues in a setting when they were predictive of the reward delivery when orientation discrimination task was performed correctly (i.e., the PC phase). In contrast, in our previous work (Vakhrushev et al., 2021), we tested the PR phase only after a conditioning phase which employed a different task (i.e., cue localization) than the test phase (i.e., orientation discrimination), and found that reward effects were most prominent for cross-modal cues. Together, the current results and results of our previous study indicate that the effects of reward critically depend on the training mode (Jahfari and Theeuwes, 2017; Failing and Theeuwes, 2018) and the relation between the rewarded stimuli and the task-relevant features.

Although accuracies were enhanced by high reward cues in both PC and PR phase, speed of visual discrimination was only modulated by rewards in the PC phase, especially for intra-modal cues. It is important to note that our task instructions encouraged accuracy over speed, as participants received a reward only for correct responses and independent of RT. Therefore, speeding up choices in PC occurred without an explicit instruction for speedy responses or an impact of doing so on reward magnitudes. However, by increasing the speed of choices during the PC phase for high reward cues, participants could increase their total reward rate, i.e., the amount of reward obtained in a given time for a self-paced task, a factor that has been shown to play an important role in perceptual decision making (Gold and Shadlen, 2002). When reward delivery is halted increasing the reward rate is not at stake anymore and hence in PR we did not find a speed enhancement. The motivation to increase speed in high reward PC trials, however, did not lead to a decrement in accuracy due to speed-accuracy-trade-off, suggesting that the goal-driven control mechanisms invoked by PC cues may increase the overall efficiency of perceptual choices.

Examination of pupil responses provided further evidence that PC reward cues invoke a stronger engagement of goal-driven mechanisms, as demonstrated by two key findings. Firstly, we found a stronger task-evoked pupil dilation in PC across all conditions, suggesting that in this phase participants exerted overall higher cognitive effort compared to the PR phase. Recruiting higher cognitive effort is known to increase the activity of noradrenergic neurons in Locus Coeruleus (LC) and thereby induce pupil dilation (van der Wel and van Steenbergen, 2018). Accordingly, previous studies have shown that large pupils predict the higher cognitive control required before goal-directed eye movements (Mathôt et al., 2015), reflect the higher effort required for task switching (da Silva Castanheira et al., 2021), and are indicative of the degree to which endogenous orientating of spatial attention is invoked by a task (Lasaponara et al., 2019). Importantly, the degree to which humans engage in a cognitively effortful task depends on the inherent relation between costs and benefits that ensue from performing a task (Shenhav et al., 2021) and whether the cost-benefit relations remain predictable over time (Manohar et al., 2017). In our experiment, the continuous and consistent delivery of reward upon correct performance in PC may have allowed a more direct estimation of how much rewards could compensate for the cost of extra cognitive effort, hence encouraging participants to maintain a sustained heightened level of goal-directed attention across all conditions. Secondly, in addition to the overall heightened dilation of pupils in PC phase, we found that only in this phase value-driven modulation of pupil size was significant, and this effect was predictive of the behavioral speed modulation. Modulation of pupil responses by reward value is in line with a number of previous findings (Chiew and Braver, 2013, 2014; Massar et al., 2016; Koelewijn et al., 2018; Pietrock et al., 2019; Walsh et al., 2019) and indicates that when the delivery of reward is contingent on task performance, higher reward incentives could efficiently mobilize the processing resources, and settle an efficient relationship between the speed and accuracy of choices, effects that are also reflected in the task-evoked pupil dilatation and have been reported across motor (Naber and Murphy, 2020), perceptual (Walsh et al., 2019), and cognitive (Kozunova et al., 2022) tasks. On the other hand, the lack of value-driven modulation of pupil responses for PR cues is in line with effects reported in previous studies, where reward-driven modulations of pupil size were only found during the learning of reward associations (Anderson and Yantis, 2012) but were absent during the test phase when reward-associations were implicit (Hammerschmidt et al., 2018). Taken together, these findings suggest that pupillary responses are not modulated by the mere exposure to the associative value of stimuli, but rather depend on the context in which rewards are delivered (Preuschoff et al., 2011; Cash-Padgett et al., 2018).

In the current study, the PR phase consistently occurred after the PC phase. Although our results in the PR phase could be directly compared to the previous studies that used a similar design (Vakhrushev et al., 2021), future studies would benefit from counterbalancing the task order across participants to confirm whether the results in each phase and the differences observed between PC and PR phases could be replicated. In fact, comparing our results to those reported previously (Vakhrushev et al., 2021), suggests that the reward-driven effects in the PR phase, especially for intra-modal cues, could be boosted when preceded by a phase when the delivery of rewards is PC, although this conclusion awaits future replications. In doing so, future studies may also benefit from using a larger sample size, as across experiments the effect sizes that we observed were relatively small. However, we also notice that small effect sizes could be due to the nature of the task we employed, as unlike previous studies, we used reward cues that did not carry information about the target of the visual discrimination task, a scenario when rewards and attentional requirements of the task align and larger reward driven effects are expected. Furthermore, studies on pupillometric correlates of value-driven effects can make use of paradigms in which the timing of events in each trial is tailored to the sluggish nature of pupil responses. Specifically, in our study the trial duration was relatively short (1,450–2,150 ms), which might have been insufficient to isolate the sluggish pupil modulations evoked by some of the conditions. This can be achieved by introducing a delay between the target offset and the appearance of the feedback display (see **Figure 1**) and by prolonging the intertrial intervals (ITI). Another important direction for future studies would be to further investigate which neural mechanisms give rise to the behavioral and pupillary effects that were observed here, through using neuroimaging or electrophysiological methods. This direction is important as it will allow to test whether the stronger involvement of goal-driven control during PC phase occurs through the same mechanisms that underlie attentional and reward-driven selection, namely, an enhanced engagement of fronto-parietal attentional regions (Corbetta and Shulman, 2002; Padmala and Pessoa, 2011) or changing the temporal profile of attentional control (Krebs et al., 2013). Moreover, future neuroimaging studies should investigate how the sensory modality of rewards interacts with the value-driven modulations of perception, as intra-modal and cross-modal reward effects may rely on distinct neural mechanisms (Vakhrushev et al., 2021).

In summary, our findings demonstrate a persistent effect of intra- and cross-modal rewards on visual perception. The stronger goal-driven control invoked by PC rewards and reflected in pupil responses, can additionally enhance the overall efficiency of perceptual choices by increasing the speed without sacrificing the accuracy.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving human participants were reviewed and approved by Local Ethics Committee of the "Universitätsmedizin Göttingen" (UMG), under the proposal number 15/7/15. The patients/participants provided their written informed consent to participate in this study.

Author contributions

JA and AP conceptualized the project, interpreted the results, and wrote the first draft of the manuscript. JA conducted the experiments. AP acquired funding. All authors designed the task, analyzed the data, and revised the manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fnhum.2022.1062168/full#supplementary-material

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