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“Effect of reward contingencies on multiple target visual search”

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Premise

Visual attention enables us to select relevant items for processing (Bundesen & Habekost, 2008; Pashler, 1998). Visual search for single targets is a popular and classical way of modelling this type of attention (Kristiansen, 2006; Nakayama & Martini, 2011; Wolfe, 1998): observers' task is to determine whether the target is present or not (Riesman & Gelada, 1980).

However, for many scenarios, a search that involves a single decision after which the search itself ends may not be very realistic: this is why multiple-target foraging may better tap into the nature of attentional allocation across the visual field (Cain, Val, Clark & Metro, 2012; Gilchrist, North & Hood, 2001; Hills, Kale & Wiener, 2013; Kristiansen, Johannsson & Thornton, 2014; Wolfe, 2013).

In *classical visual search tasks*, observers look for a target item among some distractors; in *hybrid search tasks*, they search for one instance of any of several types of target held in memory; in *foraging search tasks*, perceivers collect multiple instances of a single target type (Wolfe, Aizenman, Boettcher & Cain, 2016). Combining these paradigms, in *hybrid foraging tasks* observers search visual displays for multiple instances of any of several types of target. If the set of possible targets is held in memory, these tasks have both a memory search component and a visual search one. Schneider and Shiffrin (1977) named these *"hybrid searches"*.

In our common daily life, we often have to deal with search tasks in which the number of targets is unknown and potentially large. This kind of search is the same we experience everyday while buying food at the supermarket or collecting clothes to put into the washing machine.

The foraging paradigm is well suited to investigate some of the complications of the real world (Wolfe, 2016): indeed, searching for any of several target types is characteristic of our real world search tasks. Collecting information from internet has been considered as a task of this kind (Pirolli, 2007) and another example is searching memory for specific concepts or words (Hills, Jones & Todd, 2012).

Foraging is an understudied area of visual search that needs to be investigated, mostly for the two following reasons:

- Much is known about visual search for single targets but relatively little about how people “forage” for multiple targets. This kind of search, as underlined above, is closer to our daily life scenarios, since natural tasks typically do not involve a single target but multiple targets of various types;
- There is a lack of studies about this topic: foraging tasks have been extensively studied in animals (Stephens & Krebs, 1986) but way less in human beings, despite their importance for our behaviour.

It has long been known that human beings’ search behaviour is influenced by different mechanisms of control of attention: we can voluntarily pay attention, according to the context-specific goals, or we can involuntarily direct it, guided by the physical conspicuity of perceptual objects.

Recent evidence suggests that pairing target stimuli with reward can modulate the way in which we voluntarily deploy our attention. In this thesis, the explored line of research focuses on the effects of reward, specifically a monetary reward: neutral stimuli are imbued with value via associative learning, through a training phase. This work aims to investigate if these stimuli will be able to capture attention in a subsequent foraging task. This mechanism, known as *value-driven attentional capture*, has never been investigated in a foraging context, but only in a classical visual search one: will it be able to influence the search behaviour when the targets are multiple?

Foraging is a large field of inquiry, within which many questions need to be investigated: when we have to look for visual targets in a set of images and the number of these targets is unknown, how do we perform this search? How do observers maximize target collection? When is time to end a search? Which factors and/or strategies influence the search behaviour?

The first chapter of this work, through the analyses of the literature, aims to describe the answers to these questions, illustrating the characteristics of visual search in general and foraging in particular; the second chapter is dedicated to an examination of the different mechanisms of attentional selection, focusing on the *value-driven attentional capture* and its features; the third chapter reports three experimental studies carried out to look at the effect of a previous reward, obtained during a training phase, on a subsequent foraging task performance; finally, the fourth and last chapter exposes the general conclusions drawn from the results of the above experiments.

CHAPTER 1

“HUMAN FORAGING IN A VISUAL SEARCH CONTEXT”

> *“Each of us literally chooses, by his way of attending to things,*
> *what sort of universe he shall appear to himself to inhabit.”*
> William James

1.1 Introduction

Searching the world around us is an important everyday human behaviour, whether we are seeking a friend's face in the crowd or trying to locate where we parked our car. Indeed, many daily activities imply looking for something. In our lifetime, we make about 5 billion eye movements and move our eyes approximately three times each second (Rayner, 1998). Our visual system is able to dedicate its limited capacity to the right input (Chun & Nakayama, 2010; Kristjánsson & Campana, 2010): we can efficiently decide where to look at, where to attend.

Visual search - the exploratory activities/mechanisms that allow us to find visual objects - has been examined for years through the “visual search paradigm”. In classical visual search tasks, observers look for a target item among some number of distracting items. The two most commonly studied dependent measures are reaction time (RT) and accuracy to detect target(s) or to indicate its absence.
Some tasks are much easier than others, for example, searching for a blue item among yellow distractors: in this case, the number (set size) of yellow items is non-influential. In fact, either blue is present or it is not. The resulting RT x set size slopes have slopes near zero msec/item. These results reflect an underlying *parallel* search: all items can be processed at once to a level sufficient to distinguish targets from non-targets. The blue item “pops out” so that we can immediately notice it.

Now consider a different kind of search, for example we are looking for a S among mirrored Ss: on a target present trial, the target might be the first item visited by attention, the last one or any item in between. On average, attention will need to visit half of the items. On trials in which there is no target (blank trials), attention will have to visit all items to confirm this absence. The cost of adding one additional distractor is twice as great for blank trials and so the resulting slopes of these ones should be twice as great (Horowitz & Wolfe, 1997). This type of search is defined *serial*.

This division between parallel and serial visual searches became important when Anne Treisman presented the Feature Integration Theory (FIT; Treisman & Gelade, 1980). Her proposal was that many *feature* searches were parallel searches and that everything else required serial search. In feature searches, the target is distinguished from distractors by a single basic feature (for example, colour, size or motion). “Everything else” included searches for targets defined by *conjunctions* of features (for example, the target can be defined by colour and size together, and so by the conjunction of both these features). Today, this serial/parallel dichotomy is still useful but not accepted by various models of visual search (Duncan & Humphreys, 1989; Wolfe, 1994; Wolfe, Cave & Franzel, 1989; Humphreys & Muller, 1993; Grossberg, Mingolla & Ross, 1994). For these authors, of course there is a clear and evident difference between searches where targets “pop out” of the display and searches where each additional distractor makes it harder to find what we are looking for, but they prefer to describe these searches as *efficient* in the former example and *inefficient* in the latter, rather than parallel and serial.

Another important dichotomy refers to the pre-attentive processes used to direct attention: *bottom-up* (stimulus-driven) and *top-down* (user-driven). The bottom-up attentional control is driven by factors external to the observer, such as stimulus salience; the user-driven attentional control is driven by factors that are ‘internal’ to the perceiver, such as his/her goals. If a target is sufficiently different from the distractors, efficient search is possible even if the observer does not know the target’s identity in advance. This happens when, for example, stimuli can be distinct in colour, orientation or size. We need pre-attentive processes to alert us to the presence of stimuli that might be worthy of our attention. We also need to voluntarily deploy our attention to stimuli that we have decided to notice: we need top-down, user-driven control of our pre-attentive processes. For example, if we are looking for a specified colour, even in a group of very heterogeneous distractors, it will be possible to efficiently find the target (Duncan, 1989; Wolfe, 1990).

Singleton search is probably the simplest use of pre-attentive information in a visual search task: a single target is presented among homogeneous distractors and differ from those ones by a single basic feature. Pre-attentive processing of the unique item causes attention to be deployed to that item, that will be examined before any distractors: RT is independent of the number of distractors presented. Mostly, in the real world, stimuli we need to search for are not defined by single basic features but by conjunctions of two or more of them. In fact, we will not only look for “red” when we are looking for an apple to eat: our visual search will be based on other features too (for instance, the shape).

1.2 The classical visual-search paradigm and its tasks

The visual-search paradigm provides a controlled and easy to implement experimental situation to study the search process. In our daily lives, we are constantly faced with the problem of spotting items of interest in a complex visual environment. A considerable amount of research has explored how we find such target items in visual displays containing distractor items (e.g., Chelazzi, Miller, Duncan & Desimone, 1993; Duncan & Humphreys, 1989; Eckstein, 1998; Eriksen & Schultz, 1979; Klein, 1988; Neisser, 1964; Palmer, 1990; Treisman & Gelade, 1980; Wolfe, 1994, 1998, 2003; Wolfe, Cave & Franzel, 1989; Woodman & Luck, 1999). This enormous research effort has brought the publication of a very substantial body of research (Eckstein, 2011; Nakayama & Martini, 2011; J. M. Wolfe, 1998, 2010, 2012c; Wolfe & Reynolds, 2008). There are a number of reasons for this focus. First, visual search provides a convenient method to study low-level perceptual processes by using a reaction time measure (Rensink & Enns, 1995; Gilchrist, 1997; Davis & Driver, 1998); a second reason is that visual search provides a constrained experimental paradigm in which to study a more general behaviour (the exploratory activity). Most of this work has concerned search for a single target in displays that either do or do not contain that target. The standard requirement of a visual search task is for observers to detect the presence (or absence) of a target item, presented on a computer monitor, within an array of distractor items. The single target is present or absent, and a search ends when the target is found or the observer quits the search, declaring the target to be absent. This all occurs over the course of a few hundred to a few thousand milliseconds. By manipulating factors such as the number of distractors and the visual similarity between them and the target, researchers have produced different models of human search behaviour (e.g. Duncan & Humphreys, 1989; Treisman & Gelade, 1980).

We now understand a great deal about this type of visual search (Chan & Hayward, 2013; Eckstein, 2011; Wolfe, 2014; Wolfe, Horowitz & Palmer, 2010), knowing that there are a number of well-established properties: first, when search becomes more difficult, search time increases linearly with display size for both target-absent and target-present displays; moreover, the target-present slope is half the target-absent slope (Treisman & Gelade, 1980). We also know that the efficiency of these searches falls on a continuum, as indexed by the slope of the function relating RT to set size (Wolfe, 1998). The relationship of target to distractor items is a powerful determinant of search efficiency (Duncan & Humphreys, 1989). If the target differs from a homogeneous set of distractors on the basis of a basic attribute like motion or colour, search will be really efficient. Indeed, the target will pop-out independent of the number of distractors (Egeth, Jonides & Wall, 1972). If the target and distractors share all their features, differing only in their arrangement, search will be quite inefficient, even if the items are clearly resolvable in peripheral vision (Bergen & Julesz, 1983), perhaps reflecting serial deployment of attention from item to item (Kwak, Dagenbach & Egeth, 1991).

If a basic feature of the target can give partial information, attention will be guided by that information. For example, if the target, when present, is black, and only half the distractors are black, then attention will be guided to black items (Egeth, Virzi & Garbart, 1984), and the efficiency will be double what it would have been without the colour information. Hence, the idea of *guided search* (Wolfe 1994, 2007, 1989) with a limited set of attributes available to guide (Wolfe & Horowitz, 2004). This body of research tells us something about searching for our bike in the parking lot (if it is red, we won’t waste time attending to black bikes) or the bottle opener in the kitchen drawer (this will be inefficient due to a lack of a salient defining feature, and because of crowding effects too; Balas, Nakano & Rosenholtz, 2009).

Undoubtedly, researchers study phenomena in the laboratory in order to understand how they work in the real world, and the single target task has an obvious similarity to a large class of real-world search tasks: where is my mobile? Where is the sugar? Is my name on this list? And so on. But searching for a particular target item (e.g., where did I leave my bag?) is only one example of the set of visual search problems we daily face. In most of the cases, in our environment, we are not trying to find a single item, but a class of items of unknown quantity: these types of search define the foraging behaviour.

Nowadays, much is known about visual search for single targets, but relatively little about how observers ‘‘forage’’ for multiple targets. In the following section, it will be illustrated what it is known so far about this particular search behaviour.

1.3 The “patch-leaving” behaviour

The most investigated topic about foraging is the answer to the following question: “when to quit the search”? Many tasks that we need to perform on a daily basis require surveying an environment for items of interest and facing decisions about how to maximize the number or quality of items that are obtained. The topic of search termination has been studied in human visual searches having zero or one target (Chun & Wolfe, 1996; Cousineau & Shiffrin, 2004; Moran, Zehetleitner, Müller & Usher, 2013; Wolfe, 2012). Quitting times in searches with multiple targets have been studied extensively in the animal foraging literature: it is described as the *patch-leaving problem* (Stephens, Brown & Ydenberg, 2007; Stephens & Krebs, 1986). For example, if a bee is sipping nectar from flowers on a plant, when should it leave for the next flowering plant? Like for animals, human foraging can involve acquisition of resources, like food: if I am picking apples from a tree, at what point do I quit searching the current tree and move onto the next? The principles of foraging can also extend to our mental life: how long should we ‘fish’ for a word in the pool of our long-term memory?

Moreover, new foraging tasks are created by civilization: how long would we stay on one webpage before moving to another? These kind of questions address an understudied area of visual search and explore the interactions between decision making and visual cognition. Decision-making in visual search tasks has been explored by studying the foraging behaviour in animals (Charnov, 1976; Hayden, Pearson & Platt, 2011; McNamara, 1982; Mellgren, 1982; Stephens & Krebs, 1986; Wajnberg, Fauvergue & Pons, 2000; Ydenberg, 1984) and by studying human behaviour in laboratory foraging tasks (Cain, Vul, Clark & Mitroff, 2012; Wolfe, 2013; Hutchinson, Wilke & Todd, 2008; Pirolli, 2007).

Search termination becomes important if the observer does not know how many targets might be present, as in many real-world search tasks. Let us take the following one as an example: a radiologist might be looking for all signs of cancer. In search tasks like these, of course we are very interested in the discovery of targets, but search termination rules are important too.

There is very substantial animal literature on foraging, much of it centered on the question of whether or not animals are ‘‘optimal’’ foragers (Pyke, Pulliam & Charnov, 1977; Stephens & Krebs, 1986). The whole idea of ‘‘optimal’’ foraging is problematic (see Witness, Pierce and Ollason’s paper (1987): “Eight reasons why optimal foraging theory is a complete waste of time’’).

One major class of theories, termed Optimal Foraging Theory (OFT), provides a theoretical framework for deciding when to quit searching a display: the most influential idea is Charnov’s *“Marginal Value Theorem”* (MVT; Charnov, 1976), a model of animal foraging that can be successfully applied to humans. MVT is characterised by the simplicity of its basic idea, explained as follows. The animal wants to maximize his intake of food. As it forages in one location, it depletes the resource in that location. At some point, the rate of return from the current location drops below the average rate of return: now, MVT tells us that it is time to move. The average return will depend on the rate with which resources can be extracted from patches of resource and the time it will take to get to the next patch. In fact, you cannot collect resources while you are travelling to the next patch and if it is going to take a long time to get to it, you should exploit the current patch for longer (Stephens

& Krebs, 1986). Recapping, MVT suggests that we measure the rate of return (e.g., how many apples I am collecting per unit of time) and that we quit searching the current display when the rate of return falls below the average rate of return (Charnov, 1976; Mellgren, 1982; Stephens & Krebs, 1986; Wajnberg, 2000; Ydenberg, 1984). The theorem correctly predicts that if we increase travel time (e.g., increasing the distance between trees), people will search longer before moving onto a new display: targets cannot be acquired during travel, so increased travel decreases the average rate. Thus, people search longer because it takes longer for the current rate to fall to the average rate.

MVT, with its simple rule, has been highly influential because it can be used to study humans too (Cain, 2012; Wolfe, 2013). It requires an individual to keep track of only two pieces of information: the rate of target acquisition within the current patch and across all patches. But this approach has an important limitation: the theorem, in fact, leaves no room for an understanding of the environment (the context) to influence behaviour and does not take into account that we are not passive observers and that perception is inferential (Brady & Chun, 2007; Brady & Tenenbaum, 2013; Chun & Jiang, 1998; Feldman, Griffiths & Morgan, 2009; Fischer & Whitney, 2014). Other approaches within Optimal Foraging Theory propose that foraging behaviour is driven by very limited information and ignore the knowledge and beliefs individuals have about objects and/or the environment.

Optimal foraging models have largely been tested in tasks where trials are drawn from a randomized design matrix. Such designs minimize the contextual information provided by objects and events, leading to an environment that is unrealistic. The real world, in fact, has structure and inferences about the nature of the world can come from a variety of sources (e.g., foraging in an orchard will be more or less successful, depending on the ongoing season).

In the experiments in which MVT serves as a useful description of the results, observers “forage” in a realm of uniform, infinite resources. For example, suppose that there are multiple target types in the same patch (Wolfe, 2012b). Birds searching for insects tend to search for one type until it becomes rare and then switch to another type (Bond & Kamil, 2002). But what about humans: do they behave in a similar manner? There is some cost to switching from one target template to another

(Maljkovic & Nakayama, 1994; Rangelov, Muller & Zehetleitner, 2011; Wolfe, Horowitz , Kenner, Hyle & Vasan, 2004). This can be thought of as an internal travel time that will vary with the difficulty of searching memory (Mayr & Kliegl, 2000). Leaving the search for one item to begin the search for another is a form of patch-leaving behaviour (Hills, 2012). It is interesting to see how this interacts with the external visual search: suppose that the set of possible targets includes bananas and pears. If you are currently searching for bananas and your eyes happen to light upon a pear, there are several possible consequences: you might miss the pear entirely (*inattentional blindness*; Mack, Tang, Tuma & Kahn, 1992); you might ‘‘pick’’ the pear and continue searching for bananas; the pear might provoke an automatic task switch to search for pears (Beck, Hollingworth & Luck, 2012). Depending on the relative costs for switching templates, selecting items and moving between patches, it could be optimal to search for one target, then the next, or to determine if each item in the display matches any item in the memorized target set.

Anyway, there are endless complications/variations on basic foraging and MVT, starting with fundamental questions about what it would really mean to forage optimally (Stephens, Brown & Ydenberg, 2007). MVT assumes a uniform set of patches and an animal that knows the instantaneous and average rate. Obviously, an animal must learn those rates. But what happens if patches vary in quality? (As it happens in the real world, that tends not to be uniform in its distribution of resources). To investigate this issue, Wolfe (2013) took into consideration the search for blueberries in a field of blueberry bushes. This kind of visual search is quite straightforward: targets are round objects of a certain size and colour. There are many of these, it is not hard to find them and the ‘picker’ does not have to pick all of the berries. When does a forager leave one berry bush for the next one? Intuitively, we can consider that people do not pick all of the berries off one bush before moving on. In fact, one possible solution could be searching exhaustively, leaving when all the targets are found, but individuals (and animals too) rarely do this. MVT can give a good description of human behaviour for roughly uniform collections of patches but we see strong departures from it when patch quality varies and when visual information is degraded (Wolfe, 2013). The results of this experiment showed that patch-leaving behaviour in human visual search tasks is a strongly rule-governed behaviour. When searching through a world of roughly uniform, depletable resources, patch-leaving behaviour was consistent with the expectations of the MVT. As observers selected items from the current patch, those items became rarer and took longer to pick. As a result, the rate of yield from the patch drops. At some point, the rate drops below the average rate for the task, and at about that point, observers tended to move to the next patch. The behaviour was also influenced by the experimental conditions: observers stayed longer and picked to a lower yield when the picking was hard and they stayed longer if the travel time between patches was longer. Moreover, observers were influenced by the instructions: they searched longer when told to search exhaustively.

In sum, humans' visual foraging behaviour seems rule-governed: observers changed rules depending on the specific conditions of the foraging task. It seems likely that we share the basis for our foraging decisions with other animals but, at the same time, there are situations in our civilized world where those ancient rules are at odds with our modern desires. So, human ‘‘patch-leaving’’ behaviour is a complex domain: it is not explained by a single rule, anyway MVT is a fundamental determinant of it and a foundationally important concept in foraging.

If MVT behaviour was deeply ingrained in us, this could become a problem when we are faced with foraging tasks that demand that we pick all of the ‘‘berries’’. For example, if a radiologist is looking for a cancer, it would be obviously wrong to adopt a strategy of terminating search when the ‘‘yield’’ from the current patient drops below the average yield. Therefore, there must be other rules, implicit or not, that govern when it is time to move to the next patient. Hutchinson, Wilke and Todd (2008) analysed these rules, presenting observers with a fishing task in which they had multiple ponds to pull fish from. When is it time to move to the next pond? In their task, at any point subjects could move to a new pond: but travel took some time. They delayed this switch much too long. Subjects spent longer at ponds where they had found more items (contrary to optimality predictions). However, they apparently responded not to the number of captures directly (despite this appearing on screen) but to the current interval without a capture, to the interval preceding the last capture, and to the time spent at the current pond. Subjects often left directly after a capture, perhaps an example of the Concorde fallacy. High success rate in the preceding patch decreased residence time and subjects appeared to be learning to leave earlier over the latter two thirds of the experiment. The authors argued that minimization of delay to the next capture alone might explain some of the suboptimal behaviour observed.

It is possible to apply similar rules to ‘‘fishing’’ for items in a more broadly cognitive sense: for example, in memory (Wilke, Hutchinson, Todd & Czienskowski, 2009). As Hills (2006) wrote: ‘‘What was once foraging in a *physical* space for tangible resources became, over evolutionary time, foraging in *cognitive* space for information related to those resources’’. There is more than a merely analogical link between foraging for food resources and, for example, searching memory in order to name all the animals that you can in a fixed period of time (Hills, Jones & Todd, 2012). If you try the animal-naming task, you will find yourself naming a collection of animals from one ‘‘patch’’ (for example farm animals). You will leave the patch, not when you have named every farm animal that you know, but when the yield from the farm patch drops to a point that makes it worth ‘‘travelling’’ to the fish patch or the jungle one. Returning to a more visual domain of search, the ideas of OFT have been effectively applied to ‘‘information foraging’’ on the world wide web (Pirolli, 2007; Pirolli & Card, 1999). How do we decide when to leave a webpage for another? Pirolli (1997) introduced the useful idea of ‘‘information scent’’: for instance, if you are looking for the letter ‘‘T’’ and you know that it is white in a display of white and black letters, the “scent of white” will guide your foraging.

In the visual search literature, the aspect of foraging that has attracted the most work has been the study of the searcher’s paths through the visual display. Anyway, there has been very little work on foraging within the visual search literature and that is why this potentially is a large field of inquiry.

1.4 Influences of the context on the foraging behaviour

One important source of structure often ignored by optimal foraging models is the *temporal context*. Many psychological processes have well-studied hysteresis effects (current performance depends on past input). Strong effects of a previous trial on performance have been revealed (e.g., *priming of pop-out*: Maljkovic & Nakayama, 1994, 1996, 2000; *attentional capture*: Lamy, Carmel, Egeth & Leber, 2006; Leber & Egeth, 2006a, 2006b; Leonard & Egeth, 2008; *attentional blink*:

Potter, Chun, Banks & Muckenhoupt, 1998; *working memory*: Huang & Sekuler, 2010; *task switching*: Schneider & Logan, 2005). Studying how people perceive ambiguous or impoverished visual input (for example classic ambiguous figures like the duck-rabbit, popularized by Jastrow or the young girl/old lady), we find evidence that perception is an active and predictive process in which recent experience influences current perceptual processing (Bar, 2007; Brascamp, 2008; Corbett, Fischer & Whitney, 2011; Fischer & Whitney, 2014; Liberman, Fischer & Whitney, 2014).

Fougnie, Cormiea, Zhang, Alvarez & Wolfe (2015) explored how foraging is influenced by temporal structure. They created historical dependencies between trials by adding ‘‘seasons’’ to foraging tasks: the displays alternated between periods of plenty (many targets) and of scarcity (few targets). Of interest was whether foraging behaviour depended on whether participants were in rising (scarcity-to-plenty) or falling phases (plenty-to-scarcity). They found that temporal history influenced foraging behaviour in a foraging task for Ts among Ls: participants foraged longer during falling phases. We know that quitting rules such as MVT predict the opposite pattern. Since the authors found that people search longer as patch quality falls, their conclusion was that participants were using temporal context to infer display quality. Therefore, temporal history may alter foraging behaviour by altering participants’ beliefs about display quality. People may forage for longer in falling phases because the expected yield of search is influenced by the content of the previous displays (which is higher for falling phases), but not in the way predicted by MVT. This temporal context effect not only altered foraging behaviour, but also was found to influence explicit judgments of target density: there were higher quality ratings for displays during falling phases, even though display quality was equivalent in falling and rising phases. Taken together, these findings argue that foraging behaviour is driven by inferences about the current state of the world shaped by previous experience: temporal history alters both behaviour and beliefs, consistent with an active inference (or Bayesian) account of foraging.

Thus, these results highlighted the limitations of existing models and demonstrated that foraging theories need to consider richer models of observers’ representations of the world. Past experience can influence current perception, recognition, or memory through Bayesian inference (Crawford, Huttenlocher & Engebretson, 2000; Feldman, 2009; Fischer & Whitney, 2014). As a matter of fact, we come into a display with prior beliefs about the world, beliefs informed by experience. Classic optimal foraging models often give observers considerable information (such as the distribution of possible states of the world) but ignore how observers acquire this information (Charnov, 1976; Hutchinson, Wilke & Todd, 2008).

Context effects reveal the aspects of the environment that an observer uses to shape beliefs about the world and foraging theories will need to account for these context effects, as done by Zhang, Gong, Fougnie & Wolfe (2015), who found evidence of temporal effects in a laboratory analog of a berry-picking task: observers stayed longer when previous patches were better and this is the opposite of what would be predicted by a model in which the assessment of the average rate is biased in favour of recent patches. This result was found when patch quality varied systematically over the course of the experiment; smaller effects were seen when patch quality was randomized. Together, these data suggest that optimal foraging theories must account for the recent history to explain the current behaviour. The authors also investigated if one single patch can produce history effects on the foraging task. In order to answer this question, the berry patch quality changed randomly and the authors found that observers' assessment of the current patch was influenced by the preceding one: human foraging behaviour is influenced by recent experience.

1.5 Inhibition of return (IOR): a foraging facilitator

We know that when attention is focused on a location, stimuli at that location are detected more readily. For example, when their attention is summoned to a location by a flashed cue, people are faster to detect stimuli presented near this cue. However, if the delay between the flashed cue and the subsequent appearance of the stimulus is long enough, people are slower to detect the stimulus at the cued location than at other locations in the display. Moreover, after attention has been directed to an item and then withdrawn from that, it is harder to get attention back to that item

(Posner & Cohen, 1984). This inhibitory mechanism is now known as inhibition of return (IOR; Posner, Rafal, Choate & Vaughan, 1985).

Search is more efficient if participants attend to new items rather than repeatedly searching previously examined ones. IOR encourages orienting toward new information in the visual field and away from searched ones (Klein, 1988; Klein & MacInnes, 1999; MacInnes & Klein, 2003; Müller & von Mühlenen, 2000; Takeda & Yagi, 2000). Klein (1988) proposed that IOR might facilitate visual search when each display item requires an attention-demanding inspection to determine if it is the target (cf. Treisman & Gelade, 1980). Inhibitory tagging of display items that have already been examined attentively would, by repelling attention, help the observer avoid reinspecting them. The author tested this functional explanation of IOR by presenting luminance-detection probes immediately after the subject had performed an easy (pre-attentive; target "pops out") or difficult (requiring serial allocation of attention to array items) visual search. The probes occurred on half of the trials and were presented at locations where there had been an item in the search display (on probes) or at locations where no item had been presented (off probes). The rationale was: "In serial search if the presumed allocation of attention to each item is followed by inhibition of return, then detection of on-probes should be delayed compared with off-probes" (Klein, 1988). This is precisely what he found, providing support for a view of IOR as a foraging facilitator.

In another test by Klein and MacInnes (1999), participants searched for a character in the cluttered drawings of a "Where's Waldo?" book while experimenters monitored their eye movements. Participants also had to make a saccade to a flashed probe whenever it appeared. When the probe appeared in a previously fixated location, saccadic latencies were longer. Furthermore, saccades made prior to probe onset were typically biased away from previous saccadic directions, supporting the notion that IOR directs attention to new locations during visual search. There are three main findings from this study: first, when probe targets were presented in a scene during search, participants were slower to saccade to them when they were in the general region of preceding fixations than when they were in a new region. Second, this inhibition was not observed if the search array was removed when the probe was delivered: IOR is attached to objects in a scene (e.g., Abrams & Dobkin, 1994; Tipper, 1991, 1994). Third, the freely executed saccades of participants prior to the presentation of the probe showed the same bias that was evident in the time to acquire the probe; that is, each saccade was more likely to repeat the previous direction than to reverse it. This is precisely what one would expect if the IOR that was seen in the time to find the probe was operating equivalently on the freely made saccades during search. And it is precisely such freely made saccades during visual search of a scene that ought to be influenced by inhibition serving as a foraging facilitator.

The contribution of IOR was also investigated by Thomas, Ambinder, Hsieh, Levinthal, Crowell, Irwin, Kramer, Lleras, Simons and Wang (2006): participants searched for fruit on a tree in a fully immersive virtual environment and detected cues at previously searched and unsearched locations; their cue detection RTs were measured. Participants had to make head and limb movements to perform their search task. Because this task involved manual search, search rates were slower than those normally observed in IOR experiments. Participants also made a speeded response when they detected a flashing leaf that either was or was not in a previously searched location: responses were slower when the flashing leaf was in a previously searched location. Therefore, Thomas et al. found IOR in a foraging task that required slow, manual searches of a virtual environment: this result added ecological validity to the hypothesis that IOR acts as a foraging facilitator.

This phenomenon appears to be robust and long lasting and it occurs in tasks that approximate real-world foraging. In conclusion, thinking about foraging tasks in our daily lives — searching for house keys on a cluttered desk or scanning a crowded room for our partner — IOR aids our accomplishment of these tasks, preventing us from searching the same locations over and over.

1.6 Is visual search like foraging?

Little work has been carried out in humans to explore to what extent visual search tasks are similar to more general search and if visual search is a valid and good model for foraging. To investigate this unclear topic, Gilchrist, North and Hood (2001) created a large-scale three dimensional foraging task. Participants were situated within an array of film canisters and required to detect the presence or absence of a hidden target (a marble) by visiting each canister, picking it up and shaking it. Consistent with more traditional search tasks, search time increased linearly with the number of items, and the target-present to target-absent slope ratios did not differed significantly from 1:2. A number of authors have argued that this property of the search functions is a hallmark of serial self-terminating search in which each item is sampled in turn until the target is located (e.g. Treisman & Gelade, 1980). In this task, it is clear that search does occur in a serial manner, because participants could only sample one item at a time and then move on to the next one. Serial self-terminating models of visual search also assume that once an item is sampled it is excluded from the search set: Gilchrist et al. (2001) also measured the extent to which rechecking occurred in foraging. Participants, in a trial, made fewer erroneous revisits to locations they had already searched, compared to more conventional search (e.g. Gilchrist & Harvey, 2000). This suggests an increased role for memory. The authors argued that the increased effort required in foraging, or large-scale search, means that participants are more likely to remember the locations of visited stimuli in order to minimise costly revisits.

Let us compare this study with Gilchrist and Harvey (2000), who used a visual search paradigm and recorded eye movements arguing that, if search was supported by a perfect memory for which locations had been visited, then participants should never return to refixate a distractor. The overall search times of the two studies are radically different: there was a large increase in overall search time compared to the saccade study. This difference in search time also co-occurred with an increase in the number of visits or fixations that occur. It would appear, as previously noticed, that memory plays a more important part in determining foraging behaviour compared to search as reported by Gilchrist and Harvey (2000). This suggests that foraging and search differ in the extent to which they rely on memory to prevent revisits. In Gilchrist et al’s foraging experiment (2001), there is a substantial cost associated with revisiting a location that has been previously inspected: the participant has to walk across the room, lean over and shake the canister. We do not only need to remember which items have been visited or which is the identity of the target (Shore & Klein, 2000): search may also be supported by a long-term memory of a strategic route followed consistently on each trial (for example “search from left to right”). Such strategic scanning appears to be an important characteristic of eye-movement patterns in visual search (Gilchrist, Csete & Harvey, 1999) and refixation frequency is maybe modulated by the extent to which such a mechanism is employed. Refixation frequency may be influenced by the extent to which each individual item is tagged and the extent to which strategic scanning occurs: the relatively small revisiting frequencies in foraging could represent an increase in strategic scanning or in the use of a memory for which individual items have been inspected on any given trial.

To get to the point, some important similarities between visual search and foraging have been highlighted, but it has been underlined a difference too, explained in terms of different task demands. By the way, it has been argued that visual search is a valid model for human foraging (Wolfe, 1994) and that some mechanisms (IOR, for example) identified in visual search tasks are central to foraging. However, the two tasks differ greatly in terms of the coding of space and the effort required to search. The issue of physical effort in large-scale search was specifically addressed by Smith, Gilchrist and Hood (2005): an array of lights and switches was embedded in a raised floor of a square room. Children searched for a hidden target (a red light) by pressing switches at each potential location (defined by green lights). In one condition, participants searched with their dominant hand and in another they used their non-dominant one, which was deemed to engage more physical effort (e.g. Carlier, 1993). When searching with their non-dominant hands, children made more revisits to locations they had previously checked, suggesting that increased effort can also be associated with decreased memory for visited locations.

Revisit behaviour was also measured by Ruddle and Lessels (2006) in a virtual reality task, where participants searched for multiple targets hidden in an array of boxes. There were three different search conditions: whilst seated at a monitor, standing stationary whilst wearing a VR headset and actively walking through the virtual display. Subjects made far fewer revisits when walking through the display and benefited less from environmental cues in this condition, suggesting that search efficiency was related to spatial updating processes provided by body movement (e.g. Gopal, 1989). Tasks such as these have provided an insight into the nature of large-scale search, and how that might relate to visual search behaviour, even though their demands are not completely equivalent to those of conventional visual search.

Smith, Hood and Gilchrist (2008) describe the first direct comparison of visual search and foraging-like behaviour within the same experimental context: search locations were indicated by an array of lights embedded in the floor. Participants actively searched the space: this is closer to the demands of the environment naturally encountered by people. In the visually guided conditions, participants searched for targets that were visually defined by the presence or absence of a visual feature: they walked to the target location (defined by the presence of an additional red light amongst green distractors) and activated the respective switch. Larger displays were not associated with longer response times. Feature-absent targets usually lead to inefficient profiles in visual search experiments: participants tend to serially inspect each item (due to increased visual complexity) and so search times are longer for larger display sizes. Here participants walked to the target location (defined by the absence of a red light amongst red and green distractors) and activated the switch. In this condition, search time was linearly related to display size. Therefore, despite the expanded search scale and the different response requirements, these visually guided conditions followed the pattern found in conventional visual search paradigms. This demonstrated that efficient and inefficient search profiles, as measured in traditional visual search tasks presented on a monitor, can also characterise visually guided search in large-scale egocentric space. In a non-visually guided foraging condition, participants searched for a target that was only visible once the switch was activated (this is closer to the process of foraging as subjects were asked to physically inspect potential locations; moreover, foraging can often occur when no visual cue is available to exactly locate the target). Search time was linearly related to display size, as participants serially inspected each location. In the foraging condition, locations did not alter appearance after inspection (unless it was the target location) and so it was possible for participants to make revisit errors. However, these errors were comparatively small in number, and there was no relationship between the display size and the number of revisits made by the remaining participants. Compared to eye-movements in previous visual search studies, there were few revisit errors to previously inspected locations in this condition. This demonstrates that there is an important distinction between visually guided and non-visually guided foraging processes and suggests an equivocal role for the visual search paradigm in modelling and predicting large-scale search behaviour, and more general foraging (e.g. Wolfe, 1994).

By the way, there are differences that derive from the context requirements: first, large-scale body movements take longer to execute than saccades, and so search time is greater affected by additional items in the display; second, revisits to locations inspected previously in a trial are much less than those usually observed in eye-movement studies of refixations in visual search (Gilchrist & Harvey, 2000). In large-scale search, the increased effort required to actively search space could result in increased memory deployment for route, in order to avoid costly rechecking (Gilchrist et al., 2001). However, Smith, Gilchrist and Hood (2005) found that increased effort (searching with the non-dominant hand) was associated with poorer memory for inspected locations.

It seems that visual search tasks can partially equate large-scale search when the visual cues to target location are of an equivalent nature. In any case, the differences between visual search and foraging, in terms of visual guidance, scale, movement and spatial coding, would suggest that search in these two contexts is not qualitatively equivalent. More studies are needed to solve these issues, to develop a comprehensive model of human search behaviour (e.g. Gilchrist & Harvey, 2000; Horowitz & Wolfe, 1998; Peterson et al., 2001) and to investigate whether results from visual search can genuinely provide predictions about more general foraging.

In the next chapter, we will look further into another aspect linked to the foraging task: its connection with the reward. This psychological phenomenon will be illustrated and analysed.

CHAPTER 2

“REWARD AND VALUE-DRIVEN ATTENTIONAL CAPTURE”

2.1 Mechanisms of attentional selection and state of the art

Visual scenes contain a large amount of information: many different objects with many component features need to be processed by an observer. What is represented through our visual system will then be available for higher-order cognitive processes, such as decision making, reasoning and memory storage.

Stimuli compete to be represented in the brain, requiring a process of selection (e.g., Desimone & Duncan, 1995; Reynolds, Chelazzi & Desimone, 1999). The winners of this selection will become available to resource-limited cognitive systems: stimuli that are not attended often fail to reach awareness (Mack & Rock, 1998; Most, Simons, Scholl, Jimenez, Clifford, Chabris, 2001; Rensink, O’Regan & Clark, 1997). Failing to rapidly attend to a stimulus may result in a missed opportunity to obtain a reward or to avert a negative outcome.

Attentional control determines the contents of perceptual experience and the resulting awareness of one’s surroundings. Almost any behavioural or cognitive act like remembering, learning, perceiving or behaving depends on the control of attention. It has long been known that attentional selection in visual search depends both on voluntary, top-down deployment according to context-specific goals, and on involuntary, stimulus-driven capture based on the physical salience of stimuli and perceptual objects.

Goal-driven and salience-driven have been well defined in the literature for years as the only two mechanisms of attentional selection. Anderson (2011) was the first to argue that there exists another mechanism, driven by the learned associations between stimuli and reward. The author proposed the existence of a “*value-driven mechanism of attentional selection*”, in which stimuli that have been previously associated with reward through learning involuntarily capture attention, even when they are entirely task-irrelevant, non-salient and when rewards are no longer available: reward learning modifies the attentional priority of stimuli, allowing them to compete more effectively for selection (Anderson, Laurent & Yantis, 2011; Della Libera & Chelazzi, 2009; Hickey, Chelazzi, Theeuwes, 2010). This type of influence on the attentional control, mediated by reward, will be deeply investigated in the following sections of this chapter: reward has long been known to play a key role in cognition and learning (Pessoa & Engelmann, 2010; Schultz, Dayan & Montague, 1997; Platt & Glimcher, 1999; Sugrue, Corrado & Newsome, 2005).

2.2 Goal-driven attentional selection

Voluntary or top-down attentional control is driven by the current goals of the observer. When individuals are looking for a particular object or feature, or searching in a particular location, they can voluntarily direct overt attention (eye movements) or covert attention (without eye movements) to the task relevant object, feature, or location. Such deployments of attention increase the speed and accuracy of behavioural responses (e.g., Pashler, 1998) and evoke strong modulation of neural activity in the brain (e.g., Moran & Desimone, 1985; Yantis, 2008).

Our goals are often adaptive, flexible and can rapidly adapt to changes in expectations and task demands (e.g., Lien, Ruthruff & Johnston, 2010). Currently active goals play a powerful role in computing attentional priority. For example, attention can be deployed to a particular location when individuals are cued in advance to attend to it in preparation for an upcoming target (e.g., Posner, 1980). Goal-driven attentional control can also operate through the prioritization of stimulus features: knowledge of the specific features of the upcoming target increases the efficiency of visual search because the attentional selection will be limited to stimuli that possess a target-defining feature (Wolfe, 1994; Wolfe, Cave & Franzel, 1989). Goal-driven attentional selection is voluntary and intentional, but may proceed rapidly and automatically too. When the target of visual search is known in advance, stimuli that possess a target-defining feature capture attention and this mechanism is called *contingent attentional capture* (Folk, Remington & Johnston, 1992). Distractors that share the defining feature of the target selectively produce a spatial cuing effect consistent with attentional selection (Anderson & Folk, 2010, 2012; Folk & Anderson, 2010; Folk, Leber & Egeth, 2002; Folk & Remington, 1998). This goal-related selectivity in attentional selection is supported by eye movement measures

(Ludwig & Gilchrist, 2002, 2003) and neurophysiological indices of stimulus processing (e.g., Eimer & Kiss, 2008; Serences, Shomstein, Leber, Golay, Egeth & Yantis, 2005; Serences & Yantis, 2007). Contingent attentional capture rapidly orients attention to likely targets, facilitating more rapid target localization, at the possible expense of selecting feature-similar non-targets that need to be rejected.

2.3 Salience-driven attentional selection

This form of control is often referred to as bottom-up or stimulus-driven control (Itti & Koch, 2001; Parkhurst, Law & Niebur, 2002; Theeuwes, 1992, 2010; Yantis & Jonides, 1984; Yantis, 1993, 2000). When a salient, unexpected event occurs (e.g., the appearance of a new object, Christ & Abrams, 2006; Yantis & Hillstrom, 1994; or looming motion, Lin, Murray & Bointon, 2009), the observer will often orient to that event, even if it may interfere with other ongoing cognitive tasks.

Yantis and Jonides (1984) reported that the abrupt onset of a new perceptual object captures attention in a visual search task even when the onset does not reliably predict the target location. Visual search for a target is slowed by the presence of a physically salient non-target (Theeuwes, 1991, 1992, 1994, 2010; Yantis & Jonides, 1984), which unwillingly draws eye movements (e.g., Theeuwes, de Vries & Godijn, 2003; Van der Stigchel & Theeuwes, 2005). Neurophysiological measures show preferential processing of a salient distractor (e.g., Hickey, McDonald & Theeuwes, 2006).

The extent to which salience-driven attentional priority can be overridden by goal-driven attentional control is still a matter of debate. Physically salient stimuli that do not match a currently active target template have consistently failed to produce evidence of attentional capture using both behavioural (e.g., Folk, Remington, Jhonston, 1992; Folk & Remington, 1998) and neurophysiological measures (Eimer & Kiss, 2008, 2010; Lien, Ruthruff, Goodin & Remington, 2008). Salient but task-irrelevant stimuli most strongly capture attention when the features of the upcoming target cannot be anticipated (e.g., Bacon & Egeth, 1994; Folk & Anderson, 2010), suggesting that goal-driven attentional control may be capable of gating the influence of salience on attentional selection. However, salient visual events can carry important information concerning potential reward availability or danger.

2.4 Attention to reward-related stimuli

An adaptive system of attentional selection must also be understood in terms of the influence of prior reward learning. An attentional system that only factors goals and salience into the computation of priority for selection is likely to result in missed opportunities to obtain a reward or escape danger, in fact both goals and salience are only indirectly related to the value of a stimulus.

Previous studies have suggested that the learned association of an item with a reward can enhance motivation and benefit goal-directed behaviour (Pavlov, 1927; Rescorla & Wagner, 1972). Selective attention is allocated to items that have been previously associated with reward (Anderson, Laurent & Yantis, 2011; Della Libera & Chelazzi, 2006, 2009; Hickey, Chelazzi & Theeuwes, 2010, 2011; Hickey & van Zoest, 2012; Peck, Jangraw, Suzuki, Efem & Gottlieb, 2009; Raymond & O’Brien, 2009).

Engelmann, Damaraju, Padmala and Pessoa (2009) investigated the effect of motivation in a Posner cue–target task: participants were to use an endogenous cue (70% valid) to detect visually faint faces that appeared either on the left or the right side of fixation. It was shown that target detection performance improved with higher reward, without an increase in false alarm rates: therefore, reward boosts perceptual process capacity, enhancing detection sensitivity.

Savine, Beck, Edwards, Chiew and Braver (2010) used a switching task in which participants received a reward based on their performance. Faster response times and fewer errors were observed for trials within rewarded blocks, without any speed–accuracy trade-offs, and the facilitation was significantly stronger for mixed blocks (i.e., task-switching block) with high cognitive demands than for single-task blocks with low cognitive loads.

In a study by Veling and Aarts (2010), reward had the effect of reducing the Stroop interference.

Reward plays an important role in voluntary, deliberate deployments of attention in a variety of contexts. For example, Raymond and O'Brien (2009) showed participants several novel faces during a training phase, and consistently followed each face with different amounts of positive or negative monetary reward. Following the training phase, participants carried out an attentional blink task in which two targets, each followed by a mask, were shown in rapid succession. The second target was one of the faces that had appeared during the training phase: the probability of correctly recognizing a face was much greater when it had been associated with large positive or negative rewards during training than if it had been associated with low or no reward.

However, reward can also have an adverse effect on behavioural performance. Previous reward history could be detrimental if a reward had been associated with a stimulus feature, such as a colour. In comparison with studies that had rewarded participants on the basis of their overall performance in a given task, these studies associated a particular feature with reward, and through this association, attention was involuntarily attracted to the stimulus. A previously rewarded colour was shown to be detrimental to performance if the colour used as a distractor in a subsequent task (Anderson, Laurent & Yantis, 2011).

In a Stroop task by Krebs, Boehler & Woldorff (2010), responses to rewarded ink colours were faster than those to unrewarded colours. Moreover, when the to-be-ignored colour name was reward-related, it tended to magnify the usual slowing caused by colour-word conflict. This study shows that stimuli associated with high reward tend to draw attention even when those stimuli should be ignored.

Miranda and Palmer (2014) have recently shown that attentional capture can also be produced by presenting tasks in a videogame-like format, with points and sound effects serving as the rewards: participants were significantly slower at responding to the oddball shape when a colour previously associated with the x10 bonus multiplier was present in the background.

In another study by Palmer, Davies, Nguyen, Berndt and Miranda (2014), participants were rewarded for locating certain shapes in a training phase and then in a later test phase (during which shape was irrelevant to the task) they were significantly slower to identify oddball colour targets if a previously rewarded shape was present as a distractor. This means that participants’ visual systems learned to prioritize processing of rewarded shapes and automatically attend to them even when they were irrelevant to the task. This kind of result has a practical implication, in fact, it can be applied to socially-critical searches such as searching for guns, knives, or bombs in checked baggage or tumours in x-rays, and these are actually examples of foraging tasks. The idea could be to reward the user for finding important search targets during training so that these targets will be "tagged" by the visual system and automatically draw attention in the field.

The influence of learned value on attention may also contribute to explain clinical syndromes characterized by similar failures of cognitive control, including drug addiction, attention-deficit/ hyperactivity disorder, obsessive-compulsive disorder and obesity. These conditions tend to co-occur (Davis, 2010; Sheppard, Chavira, Azzam, Grados, Umaa, Garrido & Mathews, 2010), and correlations with individual differences in working memory capacity and impulsivity suggest that there may be common underlying mechanisms that make some individuals more susceptible to value-driven attentional capture and the disorders to which it may contribute.

2.5 Reward priming

Several studies have shown that reward delivery gives rise to involuntary deployment of attention on the very next trial, the phenomenon named "*reward priming*". For example, in the study by Hickey, Chelazzi and Theeuwes (2010a), participants searched for a shape singleton (e.g., a diamond in an array of circles) and reported the orientation of a small line segment contained in the target. On some trials, all the shapes were rendered in the same colour (red or green). On many trials, however, one of the non-target shapes had a unique colour (red among green or vice-versa). Each trial was followed by a feedback display containing the amount of reward that was received on that trial, either 1 point or 10, translated into monetary reward at the end of the experiment. Reward was randomly delivered. If on trial N the target and most of the non-targets were red (and the colour singleton was green), then on trial N + 1 the colour assignment could be the same, or it could swap so that the target and most of the distractors were green (and the colour singleton was red). On trials in which the colours did not swap, a high reward on trial N yielded faster responses on trial N + 1 than did a low reward. However, when the colours swapped, this pattern reversed. This outcome indicates that when a particular colour is rewarded, that colour appears to draw attention to itself on the immediately following trial, even though colour is not relevant to the task. A follow-up study revealed that the magnitude of reward-modulated priming across individuals is positively correlated with individual reports of the extent to which reward motivates behaviour (Hickey, Chelazzi & Theeuwes, 2010b). Thus, individuals who are the most motivated by rewards are also the most influenced by recent reward history in visual search.

Della Libera and Chelazzi (2006) reported a similar result employing a global-local number identification task pioneered by Navon (1977). Participants were shown a large number (global feature) comprised of identical smaller numbers (local features) on a given trial, and were cued in advance on which feature to perform an identity judgment. Subjects were randomly given a high or low monetary reward for correctly identifying the cued feature. These were referred as prime trials, each of which was followed by an unrewarded probe trial on which only one of the two feature judgments could be performed. Following a high reward, response time was faster on probe trials when the judgment from the prime trial was repeated and slower when the judgment switched, consistent with inter-trial priming of the rewarded feature. This pattern was reversed, however, following the receipt of a low reward, suggesting that participants were biased against repeating the same judgment in this case.

In Serences' work (2008), participants selected one of two coloured circles via a button press, and their selection either was or was not followed by the delivery of monetary reward. Recent reward history of each colour predicted both stimulus selection and stimulus-evoked response in early visual areas, as measured by functional magnetic resonance imaging (fMRI). Serences and Saproo (2010) showed that oriented gratings associated with larger rewards are represented with greater precision in early visual areas of the human brain. Shuler and Bear (2006) found that when light flashes predicted reward, responses in rat area V1 reflected temporal expectations concerning reward delivery, with activity being either maximal or minimal at the time of expected reward. In sum, these results argue that current stimulus-reward associations bias perception, consistent with attentional priority to high-value features.

2.6 Value-driven attentional capture's features

As previously discussed, this involuntary mechanism of attentional capture by stimulus–reward association is distinct from conventional stimulus or goal-driven attention: the attentional system chooses previously reward-associated stimuli over other, more perceptually salient items and under explicit instructions to ignore the stimuli.

Value-driven attentional capture can be evoked through brief training (stimulus-reward associations can be learned very rapidly compared to other forms of experimental learning such as perceptual learning) and it persists for several months and even though participants show no explicit memory for the previously experienced stimulus-reward contingencies (Anderson & Yantis, 2013). Individuals vary in the degree to which they are susceptible to the attentional bias and this variety depends on visual working memory capacity (low-capacity individuals exhibit more prolonged slowing due to value-driven capture) and trait impulsivity (high impulsive individuals exhibit stronger value-driven capture). The effect of value-driven attentional capture is spatially specific: RT to targets appearing in a location occupied on the previous trial by a high-value distractor are especially slow, a demonstration of inhibition of return (Theeuwes & Godijn, 2002). When a salient distractor captures attention, the subsequent active suppression of that item in order to direct attention to the target of search gives rise to a persisting inhibitory signal at that location. Subsequent voluntary deployment of attention is slowed by this inhibition. This IOR-based signature provides strong evidence for a spatially-specific instance of involuntary attentional deployment.

Summarising, when stimuli are learned to predict reward, these stimuli gain a competitive advantage in perception that promotes selection even when they are non-salient and not relevant to the task. This value-based attentional priority can be persistent, being robust to extinction in the absence of available rewards and can generalize to other stimuli and contexts, promoting the application of prior learning to new situations. In fact, while perceptual learning is typically very stimulus specific, value-driven capture occurs for different shapes (e.g., red diamond when the red target was previously a circle, Anderson et al., 2011a, 2011b; Yantis, 2012, 2013) and even for novel stimuli (e.g., red letter when the target was previously a geometric shape, Anderson et al., 2012).

It is important to point out and remember that reward learning can imbue stimuli with value that can override top-down intention and give rise to suboptimal behaviour. In fact, pairing target stimuli with reward may lead to undesired aftereffects, whereby a stimulus previously associated with reward attracts attention even when it would be more advantageous to ignore it.

2.7 Effects of monetary reward on the deployment of attention

Recent laboratory research has shown that attentional control is directly regulated by primary reward (e.g., food and sexual stimuli) and secondary reward (e.g., money; Awh, Belopolsky & Theeuwes, 2012; Chelazzi, Perlato, Santandrea & Della Libera, 2013). Particularly, financial reward enhances goal directed control by motivation in human participants, influencing how limited processing resources are prioritized (Anderson, 2013; Chelazzi, Perlato, Santandrea & Della Libera, 2013). Anderson, Laurent and Yantis (2011a) were among the first to show that task-irrelevant stimuli previously associated with high monetary reward captured attention. Many other studies reported similar findings (Anderson, Laurent & Yantis, 2011b; Failing & Theeuwes, 2014; Lee & Shomstein, 2014; Roper, Vecera & Vaidya, 2014; Theeuwes & Belopolsky, 2012; Wang, Yu & Zhou, 2013).

In the study by Della Libera and Chelazzi (2006), observers performed a task in which they had to respond to prime and probe displays, presented as sequential pairs within individual trials. After each correct response to a prime stimulus, observers were given a high or low monetary reward. The level of the reward did not depend on actual performance, but subjects were misleadingly told that high and low rewards respectively signified optimal and suboptimal performance. Negative priming (impaired response to a probe target that had served as the distractor in the preceding prime display; Tipper, 2001) occurred only if the attentional selection of the prime target had been highly rewarded and was therefore deemed successful by the subject. The authors found out for the first time that attentional processes are subject to an ‘‘efficiency check’’ system that dynamically adjusts attentional deployment toward specific items on the basis of previous outcomes. Every time a selection occurs, a memory trace is stored: a highly rewarded attentional selection will leave a stronger and longer-lasting trace than a selection that has poor consequences.

Della Libera and Chelazzi (2009) developed a training phase, in which correct attentional selection of specific visual items was rewarded with differential monetary gains and a test phase, run several days later, in which the effects of the history of rewards on attentional selection could be assessed in the absence of any ongoing reward manipulation. They demonstrated that the attentional processing of specific objects is durably adjusted, according to the more or less rewarding consequences of prior attentional episodes concerning the same objects. Therefore, the long-term learning to select and to ignore specific objects in the environment is shaped by a cumulative measure of gains (and losses) resulting from past encounters with those objects. The results showed that formerly reward predictive shapes impaired performance as the to-be-ignored shape in the matching task, but did not impair performance as irrelevant distractors in the visual search task. However, visual search was facilitated for goal-relevant targets that were formerly predictive of high reward.

Attention seems to be influenced not only by past encounters with specific objects and contexts, but also by the previous consequences of selecting or discarding specific objects. Failing and Theeuwes (2014) found that after an initial training phase in which one colour led to greater monetary reward than the other, the more highly rewarded colour later induced greater exogenous cuing and in this way they showed that monetary reward is a powerful driver of selective attention (Awh, Belopolsky & Theeuwes, 2012; Gottlieb, Hayhoe, Hikosaka & Rangel, 2014). However, these findings were not without controversies. For example, we cannot be sure that monetary reward drives attention in a value-dependent or value-independent manner. Jiao, Du, He and Zhang (2015) led participants to believe that they were performing the search task simultaneously with another participant, who may receive the same, more, or less reward relative to their own reward. When participants believed that the other individual was receiving the same or less reward, the previously reward-associated colours induced attentional capture, and the magnitude of the capture was greater for the previous high-reward than the previous low-reward colour. Value-dependent attentional capture was also observed in Anderson and colleagues' more recent work (Anderson, 2015; Anderson & Yantis, 2013; Anderson et al., 2011b), and in studies that trained participants to associate reward with a single stimulus. Other studies using primary reward such as chocolate odour or electric shock have also observed value-dependent capture effects by previously reward-associated stimuli (Miranda & Palmer, 2013; Pool, Brosch, Delplanque & Sander, 2014). In other experiments, it has been shown either no effects of reward training or attentional capture that was value-independent. For instance, Roper, Vecera and Vaidya (2014) did not find significant differences among high-reward, low-reward and baseline conditions. Other works reported increased capture by previously rewarded stimuli, but the capture effect was not greater for the more highly-reward stimulus (Anderson, Laurent & Yantis, 2013). In addition, some studies that reported monetary reward driven capture effects did not always report results from the low-reward colour, either because this condition was omitted from the design (e.g., Experiment 4 of Sali, Anderson & Yantis, 2014), or because no direct statistical comparisons were made between the high and low-reward stimuli, like in the study of Anderson et al. (2011). In fact, this comparison is sometimes made difficult by the small effects of monetary reward.

Another issue to investigate is: when does reward influence attention? During training when differential monetary reward is given, or during testing where there is no monetary reward? Some studies found that people were faster responding to the more highly rewarded target during training, others found no effect of reward in the training phase. For example, participants in Anderson et al. (2011a) were equally fast responding to the high and low reward targets during the training phase and this was the case in several subsequent reports (Anderson & Yantis, 2013; Gong & Li, 2014; Sali, Anderson & Yantis, 2014). Reward learning was expressed subsequently in the test phase when the previously rewarded colours were task-irrelevant and when monetary reward was no longer used. One explanation for the lack of training effects can be that the colour search task used in the training phase may have been relatively insensitive. In fact, colour search typically has fast RT, leaving little room for reward to further reduce RT. Some studies have found significant effects of monetary reward during the training phase either because a shape discrimination task has been used (Failing & Theeuwes, 2014) or because monetary reward has been additionally associated with response (Lee & Shomstein, 2014). Sha and Jiang (2015) showed, through their study, that both monetary reward and value-independent mechanisms influenced selective attention. Participants had to search for two potential target colours among distractor colours in the training phase; subsequently, they searched for a shape singleton in a test phase. Subjects were slower in the test phase if a distractor with the previous target colours was present rather than absent. Such slowing was observed even when no monetary reward was used during training.

In another experiment, they introduced monetary reward to the target colours during the training phase: participants were faster finding the target associated with higher monetary reward. However, reward training did not yield value-dependent attentional capture in the test phase. Attentional capture by the previous target colours was not significantly greater for the previously high-reward colour than the previously low or no-reward colour. Although monetary reward can increase attentional priority for the high-reward target during training, subsequent attentional capture effects may reflect, in part, attentional capture by previous targets. This finding indicates that previous targets can capture attention (Kyllingsbæk, Schneider & Bundesen, 2001; Shiffrin & Schneider, 1977) and fits with the widely accepted idea that switching one’s attentional set is challenging (Leber & Egeth, 2006; Monsell, 2003) and that attentional capture is influenced by the attentional control setting (Folk, Remington & Johnston, 1992).

The diversity of findings in the literature may mean that training using monetary reward can yield transferrable effects in some, but not all, measures of attention. Compelling evidence for greater capture by previously high-reward stimuli had been observed when no search was involved in the training phase. For example, Pool, Brosch, Delplanque and Sander (2014) associated one shape with chocolate odour (CS+) and another shape with just air (CS-): CS+ shape induced attentional shifting. In another study, Wentura, Müller and Rothermund (2013) presented colours one at a time, and associated different colours to different amounts of monetary reward: colours associated with higher reward induced greater capture. Finally, Mine and Saiki (2015) evidenced value-dependent capture in a test phase. What was in common among these studies was that participants did not perform any visual search during reward training. Because the reward-associated stimuli cannot be considered as previous targets (no search was performed on them), they are unlikely to produce target-induced capture. In addition, reward learning may be stronger when reward learning was the primary process in the training phase, as opposed to a process secondary to visual search.

In the studies that are going to be presented in the next chapter, it will be discussed the role of a training procedure in inducing value-driven attentional capture in a following foraging task.

CHAPTER 3

"REWARD CONDITIONING ON A FORAGING TASK"

3.1 Original study

The aim of the following studies is to verify how and if reward learning influences subsequent attentional priority. In order to do this, a modified version of the *value-driven attentional capture paradigm* (originally reported in Anderson, Laurent and Yantis, 2011) has been employed.

In the study of Anderson et al. (2011), in the training phase participants searched for a red or green target among differently coloured non-targets, and received visual feedback at the end of each trial consisting of an accumulating monetary reward for a correct response. The participants' response did not depend on colour: in fact, they discriminated the orientation of a bar within the target stimulus. One target colour was associated with a high probability ($P = 0.8$) of a high reward (5¢) and a low probability ($P = 0.2$) of a low reward (1¢); this mapping was reversed for the other target colour. Experimental subjects had to learn this reward contingency through 1,008 trials. Training thus imbued one colour with high value and the other colour with lower (but positive) value. The test phase was composed of 480 trials and no reward was provided: participants searched for a unique shape in an array of six differently coloured shapes. On half of these trials, one of the non-target items was rendered in red or green (each equally often); the target was never red or green, and participants were informed that colour was irrelevant to the task and so should be ignored. The sequence of trial events of this experiment is showed in figure 3.1.

Based on the reward contingencies to which observers were exposed during the training, trials during the test phase were classified as containing a high-value distractor, a low-value distractor, or neither. A repeated-measures ANOVA revealed that response times significantly differed among these three conditions [$F(2, 50) = 6.07$, $P = 0.004$]. High-value distractors slowed RT relative to when neither value-related distractor was present [$t(25) = 3.49$, $P = 0.002$]. Slower RTs on trials containing previously rewarded distractors is proof of an attentional capture effect: visual system prioritized the colour previously associated with monetary reward and allocated attention to it, even though that colour was irrelevant to the task. Thus, arbitrary and otherwise neutral stimuli imbued with value via associative learning capture attention powerfully and persistently during extinction, in a manner completely independent of goals and salience.

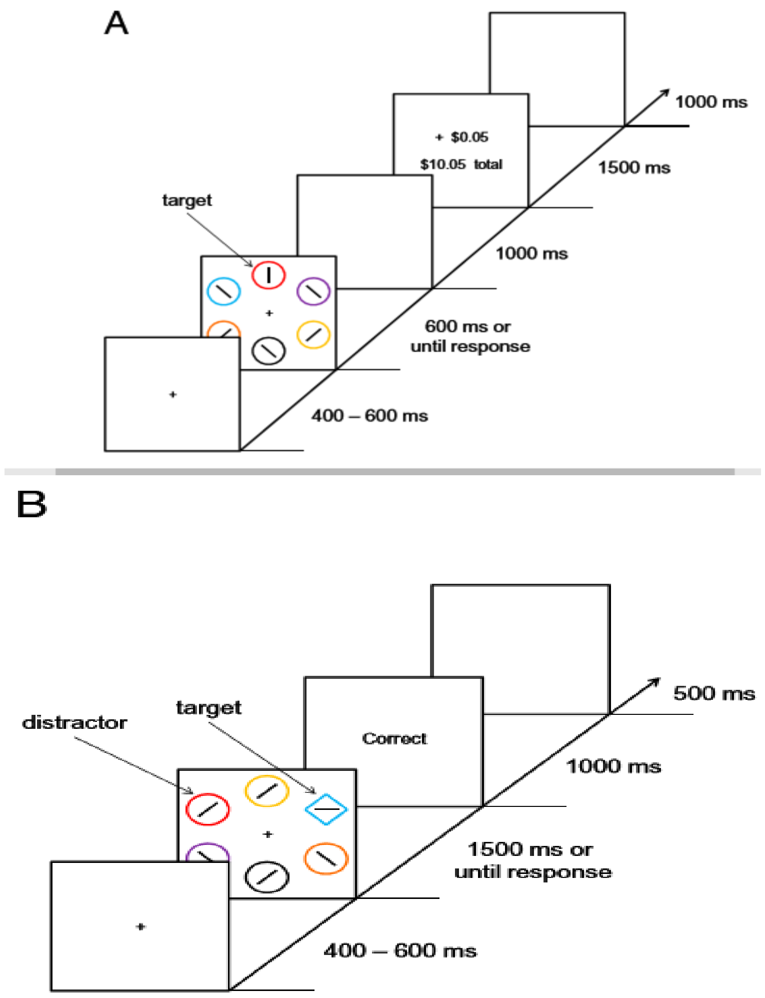

Figure 3.1 Sequence of trial events by Anderson, Laurent and Yantis (2011)

3.2 Study 1

The aim of Study 1 is to evaluate the influence of a previous reward on a foraging task, looking at the differences among three conditions: high rewarded / low rewarded / non-rewarded colours. A new training procedure, inspired by the one reported in Anderson et al. (2011), was tested: through a monetary reward, coloured stimuli are imbued with different values via associative learning. Then, a foraging task is presented to the experimental subjects. By comparing the three different conditions of the training phase, it is evaluated if, in the following testing session, rewarded stimuli automatically draw attention, even though colour is not-relevant to the task.

3.2.1 Participants

Twenty-four experimental subjects (16 males; mean age, 22.6 years) participated in Study 1. All participants completed two sessions (training and testing) and were paid for their participation on the basis of their performance in the training phase, as explained in more detail below. They were students from Peking University with normal or corrected-to-normal vision, and gave written informed consent. The study was approved by the Committee for Protecting Human and Animal Subjects, Department of Psychology, Peking University (China).

3.2.2 Stimuli and apparatus

Six colours were selected and matched in luminance. All stimuli were presented against a black background and displayed on a high quality touch-screen LCD monitor (Display ++ Version R07, Cambridge Research Systems Ltd). The screen size was 32 inches diagonal (active area: 710 mm x 395 mm) and the resolution was 1920 x 1080 pixels (10-bit RGB, 120 Hz refresh rate). The touchscreen had the following characteristics: spatial accuracy: 3-4 mm; timing: 22 ms resolution; optical clarity: near 100% optical transmission.

During the traning phase, stimuli (that is dots, squares and diamonds) were displayed on the touch-screen, but participants used the keyboard to perform the task. Only in the testing session they performed the task (foraging) through the use of the touch-screen. In this phase of the experiment, stimuli were letters (Ns) and their mirror images. The experimental program was written in Matlab and functions from the Psychtoolbox (Brainard, 1997; Kleiner et al., 2007; Pelli, 1997).

3.3.3 Procedure

The experiment consisted of two parts: a training phase and a testing phase, performed individually by subjects in a room with normal interior lighting. At the beginning of the experiment, participants were advised that a specific amount of money would have been awarded for responses that met predefined parameters of speed and accuracy (as explained below). The total duration of the task was about 100-120 minutes.

Training phase (reward)

Before the beginning of the training phase, subjects were provided with instructions directly shown through a slide on the screen and then performed 5 blocks, each of 6 practice trials, to get familiar with the task. The distance from the screen was 60 cm: participants used a chin-rest in order to maintain the eyes at a constant distance from the screen and to feel more comfortable during the execution of the experimental session. The training session was made up of two parts, each composed of 99 trials for 5 blocks, for a total of 990 trials. Participants were given a break at the end of each block.

Each trial of the training phase started with a cue display with a centrally positioned coloured dot (size 0.25° x 0.25°), followed by a search display that presented participants with a ring of 6 shapes: three squares and three diamonds. The sequence of trial events of the training session is shown in figure 3.2. Each shape (size 3.35° x 3.35°) was located at equal eccentricity (11.7°). The cue appeared for 1.15 ms and the following shapes for 1.45 ms. Six colours were present in each trial, but only three of them were rewarded. To control for intrinsic differences in the perceptual salience of different colours, the colour assignments were counterbalanced across participants.

Subjects had to remember the colour of the dot, shown in the cue display, and then match it to the shape rendered in the same colour, shown in the next visual search display. Each target was assigned to one of two responses (different keypresses): if the cue colour appeared as a square, subjects had to press F on the keyboard; if it was a diamond, they had to press J. Participants were instructed to perform the task as fast as possible (time-out response <0.75 s: no points were awarded for longer responses) and as accurate as possible, since both factors (missing rate and accuracy) would have influenced the amount of the final payment.

The reward for a correct answer could be either high “+10 points”, low “+2 points” or “+0 points” (non-rewarded condition). So, if participants answered correctly on a trial, they were awarded points and received visual feedback indicating an accumulating monetary reward. The total score was incremented, depending on subject’s performance, for each correct answer and was visible all the time. Through this trial-by-trial reward feedback, subjects could monitor their ability and were continuously motivated to do better. One third of the trials presented a “+10” bonus, one third a “+2” bonus and the last one third a “+0” bonus. This balanced “reward schedule” was thought to equally imbue three different colours with three different values.

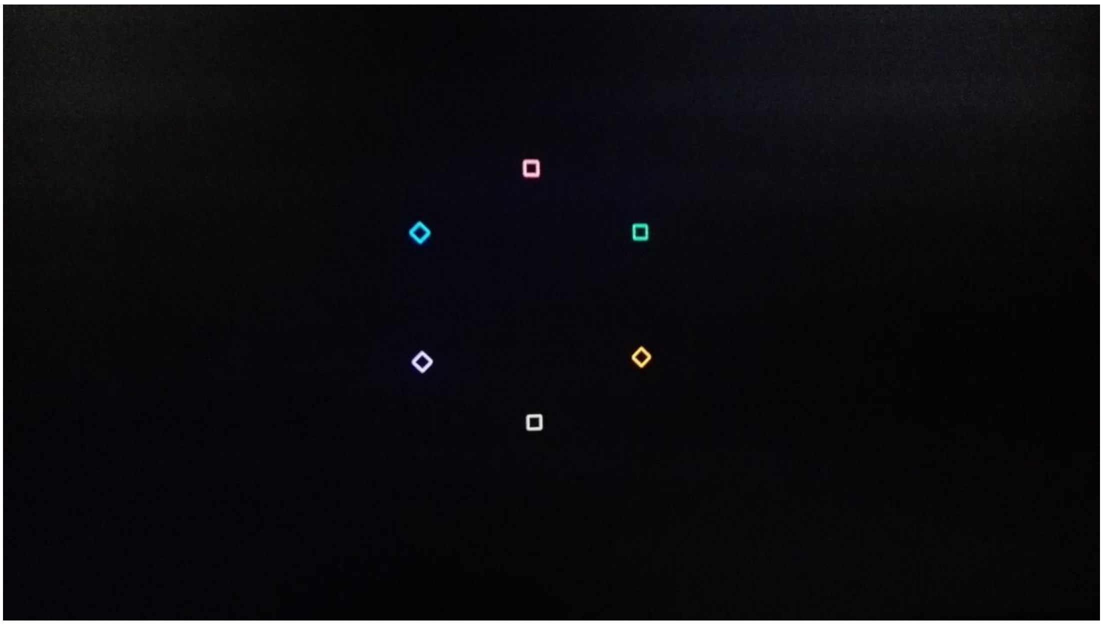

Figure 3.2 Sequence of trial events in the training session (from the image above to the one below)

Testing phase (no reward)

Before the beginning of the testing phase, subjects were provided with instructions directly shown on the screen and then performed 5 practice trials, followed by 100 experimental trials. They could take a break, if they wanted to, at the end of each trial. The distance from the screen was 35 cm (in this phase no chin-rest was used, since the task required the use of the touch screen).

The visual field of the task consisted of 144 letter stimuli (size 1.9° x 1.9°), one-twelfth of which were targets. The target proportion was kept low, otherwise subjects could collect fluently without searching. During this phase, participants' task was to collect, using their own fingers, only the letters N presented on the touch-screen, trying to avoid the distractors, that is mirror-Ns. In each trial, both targets and distractors were rendered in the three colours previously rewarded during the training session. In the testing session, subjects were not rewarded for their performance.

Importantly, the foraging task was time-limited: subjects only had 15 seconds of time to collect as much targets as they could.

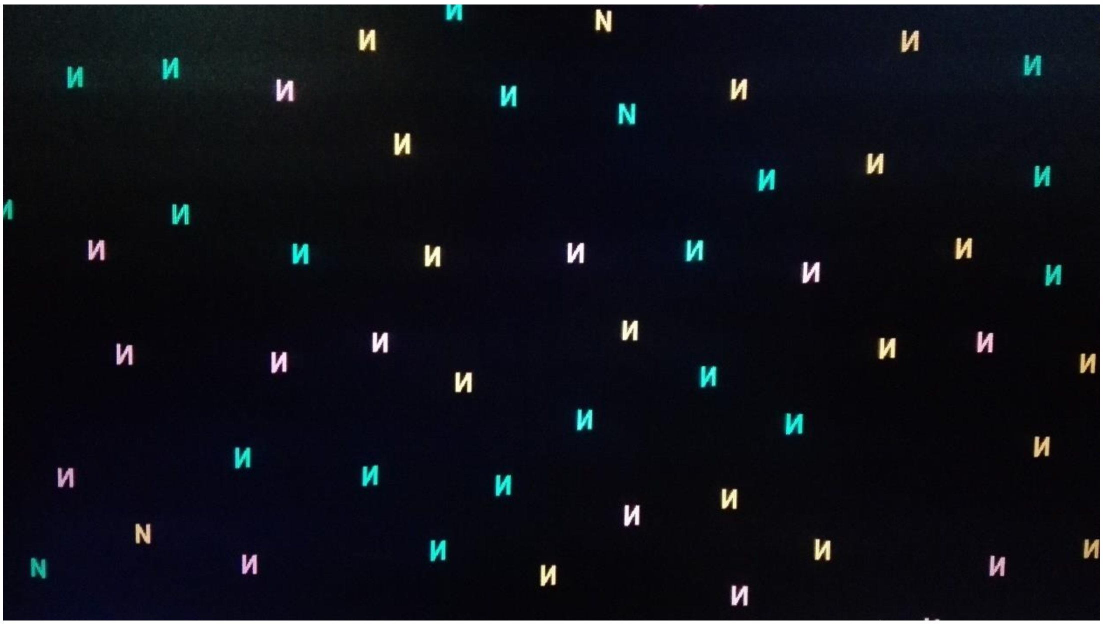

Figure 3.3 Screenshot of a portion of the screen in the test session (foraging task)

Assessment of Explicit Memory

At the end of the testing phase, participants were asked if they recalled which colours were followed by higher, lower and no reward during the training phase. Interestingly, all of them reported memory for the colour associated with the high-value reward.

3.3 Data Analyses and results

Statistical analysis was performed with the software package IBM SPSS Statistics Version 20. Data were expressed as means ± standard deviation (SD). Comparisons between groups were performed by means of parametric tests.
A value of $P < 0.05$ was considered statistically significant.

Training phase

During the training phase, RTs and accuracy were measured. To test the effect of the reward on performance, a repeated-measures ANOVA (within subjects) was performed on each variable.

As for RTs, there was a significant difference between the three differently rewarded conditions: [F (2, 46) = 10.402, p = <.001]. Post hoc analysis with Bonferroni correction showed that subjects were faster when responding to the high-rewarded colour (M = 562.497, SD = 32.998) than when responding to the low-rewarded colour (M = 576.633, SD = 33.248, p = .011) or the non-rewarded colour (M = 579.804, SD = 33.385, p = .001), whereas there was no significant difference between the low-rewarded colour and the non-rewarded one.

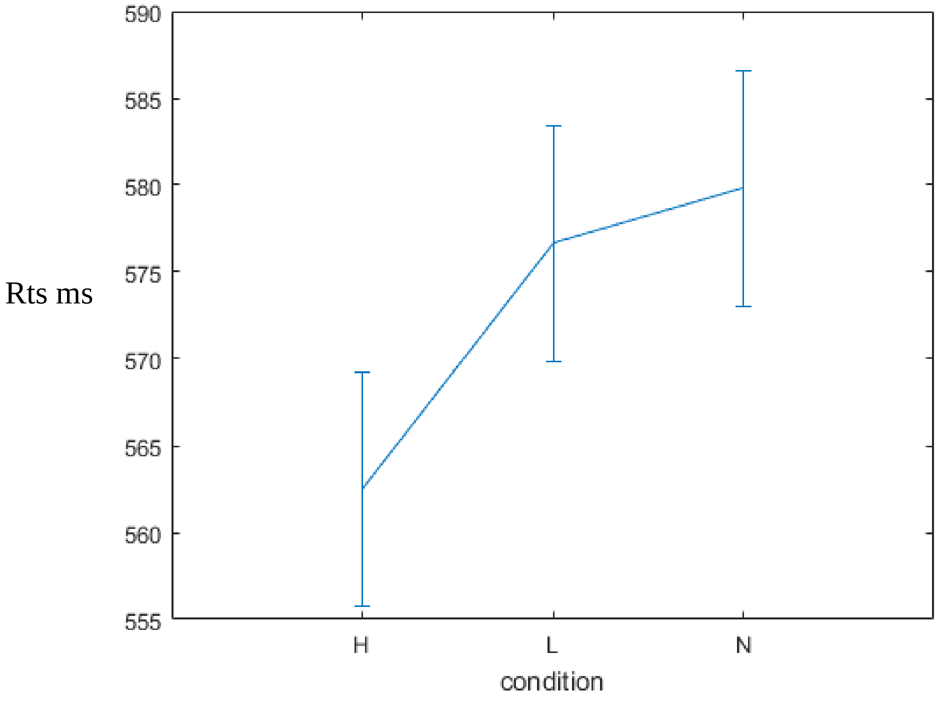

Figure 3.4 Training phase: RTs (ms) in the three differently rewarded conditions

As for accuracy, Anova reported a significant main effect: [F (2, 46) = 4.001, p = .025]. Post hoc analysis with Bonferroni correction revealed that subjects were more accurate when responding to the high-rewarded colour (M = .841; SD = .068) than when responding to the non-rewarded colour (M = .803; SD = .088, p = .019), whereas the difference between the low-rewarded colour (M = .815; SD = .081) and the non-rewarded one was not significant.

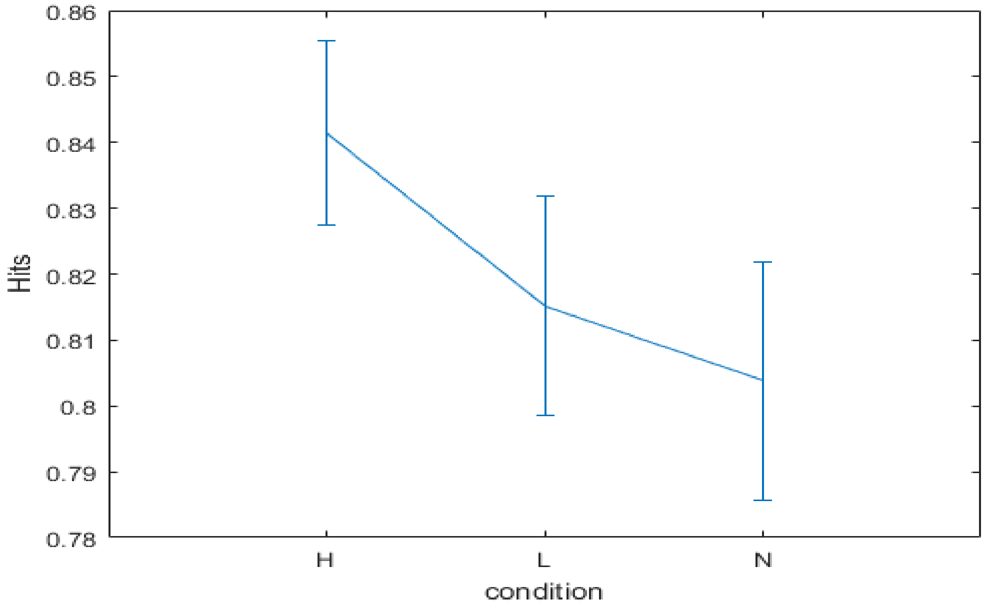

Figure 3.5 Training phase: accuracy in the three different rewarded conditions

After having evaluated that during the training phase participants were faster and more accurate in responding to the high-rewarded colour, the testing phase aimed to assess whether this colour still captures attention.

Testing phase

During the testing phase, only accuracy was measured, since the foraging task was time-limited.

Foraging accuracy

Anova reported a not significant main effect: [F (2, 46) = 1.94, p = .16], but post hoc analysis with Bonferroni correction revealed a significant difference between the previously high-rewarded colour (M = .349; SD = .047) and the previously non-rewarded colour (M = .320; SD = .023, p = .046): participants collected more items when responding to the previously high-rewarded colour than when responding to the previously non-rewarded colour. In contrast, there were no significant differences between the other pairs of conditions.

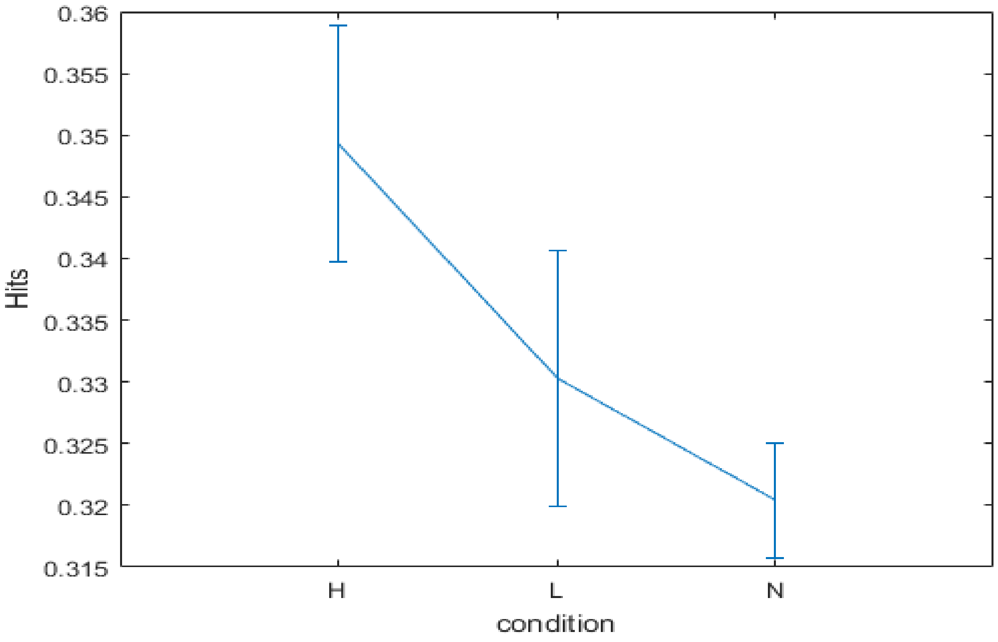

Figure 3.6 Testing phase: accuracy in the three conditions

3.4 Study 1: Conclusions

The goal of this first study was to verify the influence of a previously learned reward on a subsequent foraging task. A new training procedure, through the use of a monetary reward, imbued coloured stimuli with different values (that is, high, low and no reward), via associative learning. Then, a following testing session was presented to the participants. By comparing the three different conditions of the training phase, it was evaluated if, in the foraging task, rewarded stimuli automatically drew attention, even though colour was not-relevant to the task.

An effect of the reward on performance was found: in particular, for RTs, there was a significant difference between the three differently rewarded conditions and subjects were faster when responding to the high-rewarded colour than when responding to the low-rewarded colour or the non-rewarded one. Regarding the accuracy, subjects were more accurate when responding to the high-rewarded colour than when responding to the non-rewarded one. Therefore, during the training phase participants were faster and more accurate in responding to the high-rewarded colour. This colour still captured attention during the testing phase: participants collected more items when responding to the previously high-rewarded colour than when responding to the previously non-rewarded colour. This means that, even though the search behaviour is not limited to one item but concerns the collection of several targets, the effect of the previously learned reward associations is still present.

Support for value-dependent capture can be provided by two means: greater attentional capture by prior targets previously associated with high-value reward than with low-value reward, or greater attentional capture by prior targets following rewarded training than following unrewarded training (no reward). Study 2 tests the first hypothesis, comparing high-rewarded condition with the low-rewarded one; study 3 tests the second hypothesis, comparing high-rewarded condition with the non-rewarded one. Specifically, it is investigated the cue-effect as a top-down influence and in particular whether the cue influences the foraging task (testing phase) depending on previous imbued values (training phase). In these studies, colour is relevant to the task.

3.5 Study 2

It is well known that high-rewarded items are more difficult to disregard when serving as distractors and easier to select when serving as targets. As previously seen, pairing target stimuli with reward can modulate the voluntary deployment of attention, but there is little evidence that reward modulates the involuntary deployment of attention to task-irrelevant distractors. Yantis, Anderson, Wampler and Laurent (2012) showed that attentional capture by physically salient distractors is magnified by a previous association with reward and demonstrated that physically inconspicuous stimuli previously associated with reward capture attention persistently during extinction, even several days after training.

In Study 1, the reward-associated colours could be both the target and the distractor in the foraging task, and RTs and hit rates were measured for the three differently rewarded conditions. The results showed an effect of the previous reward, that is reward associations influenced attentional allocation.

In Study 2, the reward-associated colours can only be the distractors. In the first session, subjects are trained as in Study 1. In the testing session, participants perform the same foraging task with the following change: they are cued to ignore a colour. The aim of Study 2 is to assess whether valuable distractors show evidence of attentional capture that is attributable to prior reward learning. There are only two conditions: a high-rewarded condition compared with a low-rewarded one. Thus, it is evaluated whether the reward associations can benefit the top-down attentional control. Reducing the conditions from three to two, it is possible to deeply highlight the effect of the high-rewarded value, simplifying the task.

3.5.1 Participants

Fourteen experimental subjects (7 males; mean age, 21.6 years) participated in Study 2. All of them completed two sessions (training phase and testing phase) and were paid for their participation, on the basis of their performance in the training phase. All participants were students from Peking University with normal or corrected-to-normal vision, and gave written informed consent. The study was approved by the Committee for Protecting Human and Animal Subjects, Department of Psychology, Peking University (China).

3.5.2 Procedure

The study consisted of a training phase and a testing phase, performed individually by subjects in a normally lit room. At the beginning of the study, participants were informed that a specific amount of money would have been awarded for responses that met predefined parameters of speed and accuracy. The total duration of the task was about 100-120 minutes. Stimuli and apparatus were the same used in Study 1.

Training phase

In the training session, colour-reward associations were trained as in Study 1, with the only difference that there were only two conditions rather than three (high-reward and low-reward).

Before the beginning of the training session, subjects were provided with instructions directly shown through a slide on the screen and then performed 5 blocks, each of 6 practice trials to get familiar with the task. The distance from the screen was 60 cm: participants used a chin-rest in order to maintain the eyes at a constant distance from the screen and to feel more comfortable during the execution of the experimental session.

The training phase consisted of two parts, each including 70 trials for 5 blocks, for a total of 700 trials. Participants were given a break at the end of each block. Each trial of the training phase started with a cue display with a centrally positioned coloured dot (size 0.25° x 0.25°), followed by a search display that presented participants with a ring of 6 shapes: three squares and three diamonds. Each shape (size 3.35° x 3.35°) was located at equal eccentricity (11.7°). The cue appeared for 1.15 ms and the following shapes for 1.45 ms.

Six colours were present in each trial, but only two of them were rewarded. To control for intrinsic differences in the perceptual salience of different colours, the colour assignments were counterbalanced across participants. Participants had to remember the colour of the dot, shown in the cue display, and then match it to the shape rendered in the same colour, shown in the next visual search display. Each target was assigned to one of two responses (different keypresses): if the cue colour appeared as a square, subjects had to press F on the keyboard; if it was a diamond, they had to press J.

Subjects were instructed to perform the task as fast as possible (time-out response <0.75 s: no points were awarded for longer responses) and as accurate as possible, since both factors (missing rate and accuracy) would have influenced the amount of the final payment.

The reward for a correct answer could be either high “+10 points” or low “+2 points”. So, if participants answered correctly on a trial, they were awarded points and received visual feedback indicating an accumulating monetary reward. The total score was incremented, depending on subject’s performance, for each correct answer and was visible all the time. Through this trial-by-trial reward feedback, subjects could monitor their ability and were continuously motivated to do better. Half of the trials presented a “+10” bonus, the other half a “+2” bonus. This balanced “reward schedule” was thought to equally imbue two different colours with two different values.

Testing phase

Before the beginning of the testing phase, participants were provided with instructions directly shown through a slide on the screen and then performed 5 practice trials, followed by 120 experimental trials. They could take a break, if they wanted to, at the end of each trial. The distance from the screen was 35 cm (this time no chin-rest was used, since the task required the use of the touch screen). The visual field of the task consisted of 144 letter stimuli (size 1.9° x 1.9°), one-twelfth of which were targets. The target proportion was kept low, otherwise subjects could collect fluently without searching. During this phase, participants’ task was to collect, using their own fingers, only the letters N presented on the touch-screen, trying to avoid the distractors, that is mirror-Ns.

Before being exposed to the foraging screen, observers saw a cue: a coloured dot (size 0.25° x 0.25°), centrally positioned on the screen; it appeared for 500 ms, following a fixation point. The cue colour informed subjects that they could never find a target in that colour and so they were instructed to ignore the cue colour.

In Study 1, the reward-associated colours were both targets and distractors in the foraging task: in each trial, both targets and distractors were rendered in the colours that had been previously rewarded during the training session.

In Study 2, subjects performed the same foraging task as in Study 1, with the difference that, in each trial, only the distractors were rendered in the two colours previously rewarded during the training session. The other four colours (which were not imbued with a value during the training) that had been presented in the training phase were randomly used to render the colour of the targets. Each of the reward-associated colours (high and low) were equally possible to appear as distractors. The foraging task was time-limited: subjects only had 15 seconds of time to collect as much targets as they could.

A difference in performance between the high-rewarded and the low-rewarded conditions was expected, with a better performance for the high-rewarded colour.

3.6 Data Analyses and results

Training phase

RTs and accuracy were measured during the training phase. Repeated-measures ANOVA (within subjects) was performed to test the effect of the reward.

As for RTs, there was a significant difference between the two conditions: [F (1, 13) = 22.928, p = <.001]. Participants were significantly slower when responding to high-rewarded stimuli (M = .564, SD = .031) than when responding to low-rewarded ones (M = .551, SD = .027).

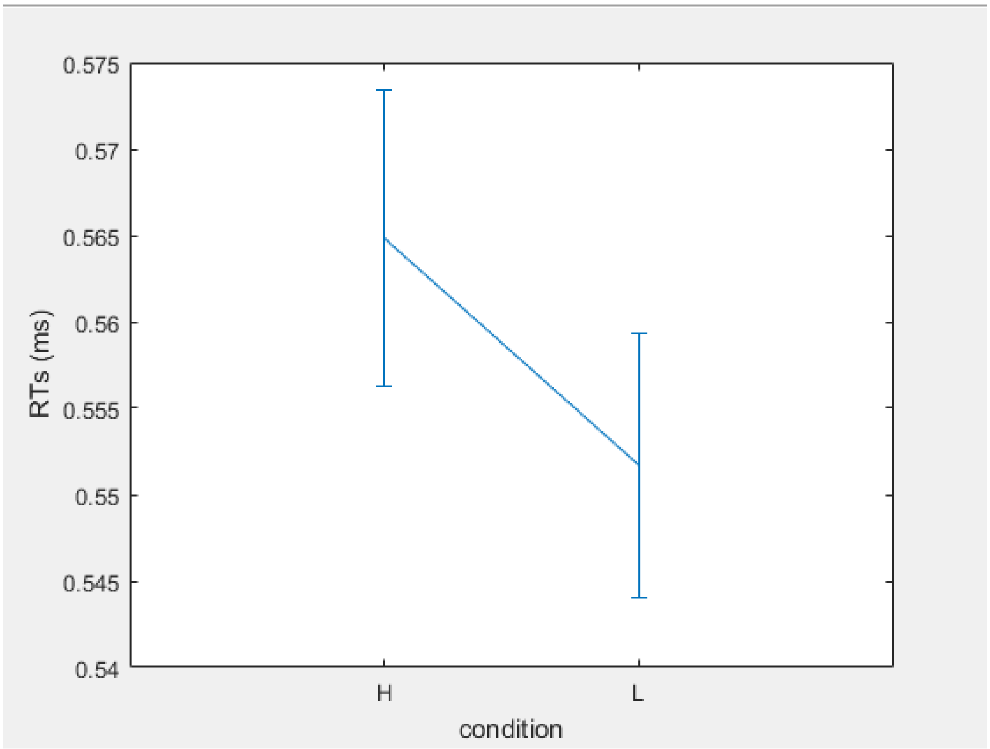

Figure 3.7 Training phase: RTs in the two differently rewarded conditions

As for accuracy, there was a significant difference between conditions: [F (1, 13) = 13.888, p = .003]. Participants were significantly less accurate when responding to high-rewarded stimuli (M = 303.846; SD = 35.047) than when responding to low-rewarded ones (M = 316.076; SD = 26.784).

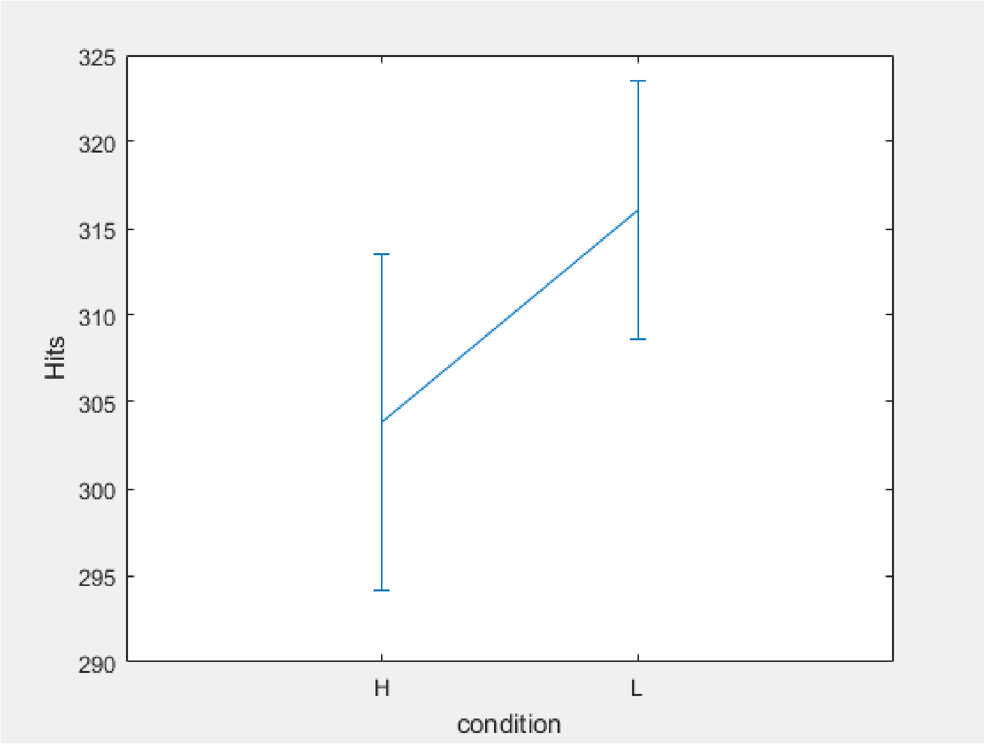

Figure 3.8 Training phase: accuracy in the two differently rewarded conditions

Testing phase

There was no significant effect (F = .438, p = .520) of the cue colour on the foraging accuracy (high-rewarded condition: M = 145.307; SD = 34.721; low-rewarded condition: M = 139.538; SD = 26.222).

3.7 Study 2: Summary of the results

The aim of this second study was to evaluate if valuable distractors showed evidence of attentional capture, attributable to prior reward learning. There were only two conditions: a high-rewarded condition compared with a low-rewarded one. Thus, it was assessed if the reward associations could benefit the top-down attentional control.

During the training phase, participants were significantly slower when responding to high-rewarded stimuli than when responding to low-rewarded ones and significantly less accurate when responding to high-rewarded stimuli than when responding to low-rewarded ones. In the testing phase, there was no significant effect of the cue colour on the foraging accuracy.

3.8 Study 3

As for Study 2, the aim of Study 3 is to evaluate whether valuable distractors show evidence of attentional capture that is attributable to prior reward learning. This time, a high-rewarded condition is compared with a non-rewarded one.

3.8.1 Participants

Fourteen experimental subjects (8 males; mean age, 20.3 years) participated in Study 3. All participants completed two sessions (training and testing) and were paid for their participation, on the basis of their performance in the training phase. They were students from Peking University with normal or corrected-to- normal vision, and gave written informed consent. The study was approved by the Committee for Protecting Human and Animal Subjects, Department of Psychology of Peking University (China).

3.8.2 Procedure

The experiment consisted of two parts: a training phase and a testing phase, performed individually by subjects in a normally lit room. At the beginning of the experiment, participants were advised that a specific amount of money would have been awarded for responses that met predefined parameters of speed and accuracy. The total duration of the task was about 100-120 minutes.

Training phase

In the training phase, colour-reward associations were trained as before. There were the following two conditions: high-rewarded and non-rewarded conditions. Before starting the training session, subjects were provided with instructions directly shown through a slide on the screen and then performed 5 blocks, each of 6 practice trials to get familiar with the task. The distance from the screen was 60 cm: participants used a chin-rest, in order to maintain the eye at a constant distance from the screen and to feel more comfortable during the execution of the experimental session.

The training session was made up of two parts, each composed of 70 trials for 5 blocks, for a total of 700 trials. Participants were given a break at the end of each block. Both stimuli and apparatus were the ones used in Study 1 and 2.

Each trial of the training phase started with a cue display with a centrally positioned coloured dot (size 0.25° x 0.25°), followed by a search display that presented participants with a ring of 6 shapes: three squares and three diamonds. Each shape (size 3.35° x 3.35°) was located at equal eccentricity (11.7°). The cue appeared for 1.15 ms and the following shapes for 1.45 ms.

Six colours were present in each trial, but only two of them were rewarded. To control for intrinsic differences in the perceptual salience of different colours, the colour assignments were counterbalanced across participants. Observers had to remember the colour of the dot, shown in the cue display, and then match it to the shape rendered in the same colour, shown in the next visual search display. Each target was assigned to one of two responses (different keypresses): if the cue colour appeared as a square, subjects had to press F on the keyboard; if it was a diamond, they had to press J.

Subjects were instructed to perform the task as fast as possible (time-out response <0.75 s: no points were awarded for longer responses) and as accurate as possible, since both factors (missing rate and accuracy) would have influenced the amount of the final payment.

The reward for a correct answer could be either high “+10 points” or “+0 points” (non-rewarded condition). So, if participants answered correctly on a trial, they were awarded points and received visual feedback indicating an accumulating monetary reward. The total score was incremented, depending on subject's performance, for each corrected answer and was visible all the time. Through this trial-by-trial reward feedback, subjects could monitor their ability and were continuously motivated to do better.

Half of the trials presented a "+10" bonus, the other half a "+0" bonus. This balanced "reward schedule" was thought to equally imbue two different colours with two different values.

Testing phase (no reward)

Before starting the testing session, subjects were provided with instructions directly shown through a slide on the screen and then performed 5 practice trials, followed by 120 experimental trials. They could take a break, if they wanted to, at the end of each trial. The distance from the screen was 35 cm (this time no chin-rest was used, since the task required the use of the touch screen).

The visual field of the task consisted of 144 letter stimuli (size 1.9° x 1.9°), one-twelfth of which were targets. The target proportion was kept low, otherwise subjects could collect fluently without searching. During this phase, participants' task was to collect, using their own fingers, only the letters N presented on the touch-screen, trying to avoid the distractors, that is mirror-Ns.

As in Study 2, before being exposed to the foraging screen, observers saw a coloured dot: this cue (size 0.25° x 0.25°), centrally positioned on the screen, appeared for 500 ms, following a fixation point. The cue colour informed subjects that they could never find a target in that colour and so subjects were instructed to ignore it.

As in Study 2, in each trial, only the distractors were rendered in the two colours previously rewarded during the training session: so, in the current study, cue colours (reward-associated colours) could only be the distractors. The other four colours (the ones not imbued with a value during the training) that were present in the training phase were randomly used to render the colour of the targets.

Each of the reward-associated colours (high-rewarded and non-rewarded) were equally possible to appear as distractors, both of them in half of trials. The performance difference between the high-rewarded and non-rewarded conditions is considered the benefit of reward association for attentional suppression: we would expect to see high benefit for the high-rewarded colour.

The foraging task was time-limited: subjects only had 15 seconds of time to collect as much targets as they could.

3.9 Data Analyses and results

Training session

RTs and accuracy were measured during the training phase. Repeated-measures ANOVA (within subjects) was performed to test the effect of the reward.

Training Rts

The training performance showed no significant difference (F = .273, p = .610) between condition 1 (M = .529, SD = .076) and condition 2 (M = .526, SD = .064).

Training accuracy

There was no significant difference (F = .980, p = .340) between condition 1 (M = 279, SD = 45.493) and condition 2 (M = 282.857, SD = 51.485).

Foraging accuracy

A significant difference was found (F (1, 13) = 5.720, p = .033) between condition 1 (M = 135.714; SD = 36.256) and condition 2 (M = 151.142; SD = 39.551). High-value distractors capture attention, impairing the performance.

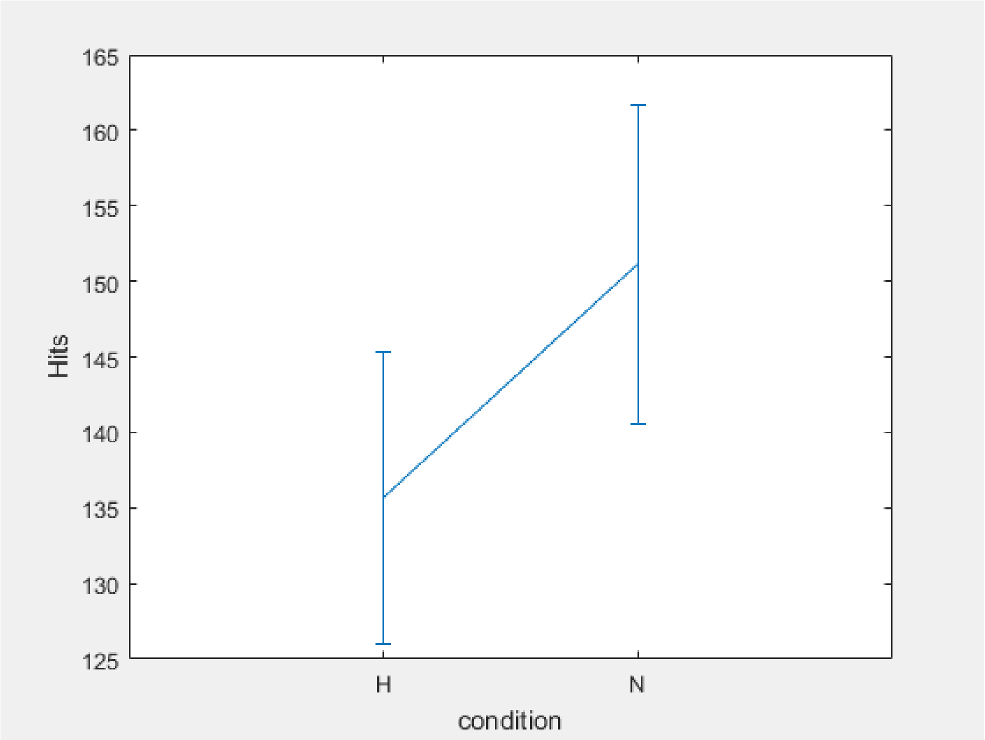

Figure 3.9 Foraging task's accuracy in the two different rewarded conditions

3.10 Study 3: Summary of the results

The aim of this third study was to evaluate if valuable distractors showed evidence of attentional capture, attributable to prior reward learning. There were only two conditions: a high-rewarded condition compared with a non-rewarded one. Regarding both RTs and accuracy, the training performance showed no significant difference between condition 1 and condition 2. In the following testing phase, a significant difference was found between the two conditions, that is high-value distractors captured attention, impairing the performance.

CHAPTER 4

“GENERAL CONSIDERATIONS AND CONCLUSIONS”

“All our knowledge has its origins in our perceptions”.

Leonardo Da Vinci

The evaluation of the functional properties of visual attention has in past decades been dominated by the study of single-target visual searches: in these tasks, participants have to detect the presence of a single target among a group of distractors, and the search ends when the target is found. But, in real-world scenarios, our goals unlikely involve only one target: for this reason, we need paradigms involving visual foraging for multiple targets to investigate visual attention from a more realistic point of view.

Allocation of attention is typically conceptualized as due to bottom-up influences from salient objects or top-down control settings from the observer. However, attention is also automatically allocated to objects that have value to the organism and that “mean something” to it, based on previous experience (Anderson et al., 2011; Della Libera & Chelazzi, 2006; Hickey, Chelazzi & Theeuwes, 2010; Lee & Shomstein, 2013). Such value-driven attentional capture is a form of attentional control based on *reward conditioning*.

Attentional capture driven by reward history, that is, *value-driven attentional capture* (Anderson et al., 2013) is a psychological phenomenon in which rewarded stimuli become more salient, automatically drawing attention when encountered later. It can be reliably produced in the laboratory, usually by paying participants money (in fact, money can be considered as a form of reward) for finding targets in a visual search task.

The aim of the present work was to evaluate the role of a previous reward (learned through specific reward-contingencies presented during a training phase) on the performance of a following testing phase, in which a foraging task was conducted. Much is known about RTs and accuracy of single-target search tasks, but less attention has been dedicated to understanding how human beings search for multiple-targets, that is how they perform foraging tasks. At the same time, much is known about bottom-up and top-down mechanisms of attentional deployment but value driven attentional capture still needs to be deeply investigated, expecially in a foraging context.

Previous work has revealed that reward training can cause certain colours to capture attention in a visual search task (e.g., Anderson et al., 2011). By the literature, we know that stimulus-reward associations can be learned very quickly compared to other forms of learning, such as perceptual learning, and prove to be robust: they can persist even when there is no explicit memory for the previously experienced stimulus-reward contingencies (Anderson & Yantis, 2013).

The training procedure in Study 1 revealed its effectiveness, based on reaction times and accuracy. There was a main effect of reward, in that the response to the three differently-rewarded colours was significantly different. In particular, participants responded significantly faster and were more accurate when the cued colour was a high-rewarded one than when it was a low or non-rewarded one. In the subsequent foraging task of Study 1, those items rendered in the previously high-rewarded colour were significantly preferred by participants compared to the previously non-rewarded items and consequently they were collected first and more frequently.

This was the first description of the presence of a reward conditioning effect in a foraging task, which is different from the classic visual search task. These results agree with the proposal that reward association modifies attentional priority based on a factor other than bottom-up physical salience or top-down task goal (Awh et al., 2012; Chelazzi et al., 2014).

It is important to make some considerations and underline some factors about the foraging task used in these studies:

- Targets were rare (as it happens in medical or airport screening, that can be seen as real examples of foraging tasks): in these cases, observers usually shift response criteria, leading to elevated miss error rates, and they also speed target-absent responses, making more motor errors;

- Letters N were used as targets. It is well known that familiarity speeds visual search and it does so principally when the distractors, not the targets, are familiar (Wang, Cavanagh & Green, 1994). In fact, an unfamiliar target is detected more rapidly among familiar distractors, as compared with the reverse situation;

- In the training phase of these studies, stimuli were squares and diamonds, whereas during the foraging task the previously reward-associated stimuli were letters. Value-driven capture can occur for stimuli that are not an exact match to the formerly rewarded targets. In fact, prior reward learning extends to newly encountered stimuli and contexts (Anderson et al., 2011a, 2011b; Yantis, 2012, 2013): the presence of a previously reward-associated feature, like for example the colour, is enough to modify the attentional priority of even a novel stimulus, reflecting generalization of reward learning.

Thus, there is an effect of the reward in the foraging task, in that recent reward history modulates value-driven attentional capture. In these studies, reward influenced the task even though targets were rare, different from those used in the training phase, presented with unfamiliar distractors and even if there was a high time pressure for the participants to complete the task, since the trial was time-limited.

In Study 2 and 3, it was evaluated the top-down influence through a cue-effect. It is acknowledged that reward learning can imbue stimuli with value that can override top-down intention and give rise to suboptimal behaviour. Pairing target stimuli with reward may lead to undesired after-effects, whereby a stimulus previously associated with reward attracts attention even when it would be better to ignore it (Lynn & Shin, 2015). In fact, both in Study 2 and 3, the cue tells observers that they will never find a target of that colour and so it is beneficial to ignore it. But reward modifies performance so that attentional priority is given to stimuli previously associated with a high reward. A stimulus associated with reward attracts attention even when it is no longer relevant. That is why it is interesting to explore whether or not strategic top-down control can be employed to overcome the attentional bias due to a recent reward–stimulus association. It is interesting also because of its ecological validity: maladaptive attentional biases (e.g., addiction) may be counteracted by treatments that control motivation by increasing the subjective relevance of rewards that are less detrimental (Lynn & Shin, 2015).

In the training phase of Study 2, contrary to what initially hypothesised, an unexpected result emerged: in the low-rewarded condition, subjects were significantly faster and more accurate, compared to the high-rewarded condition. It seems that the operational learning procedure implemented in this training phase, in which there are only two rewarded colours rather than three, as in Study 1, was harder to perform than the training phase of Study 1. In the foraging phase of Study 2, no significant difference was found.

In several studies (Della Libera & Chelazzi, 2006; Hickey et al., 2010; Serences, 2008; Serences & Saproo, 2010; Shuler & Bear, 2006), positive effects of reward — faster and/or more accurate responses to high-rewarded stimuli — were observed when the task involved currently rewarded stimuli and/or stimuli that were currently task-relevant, as in Study 1. Researchers have in a few cases examined the effect of a to-be-ignored stimulus previously associated with reward, as done in Study 2 and 3: Gong, Yang and Li (2016) suggested that reward association can modify the priority map during active distractor suppression and benefit behavioural performance, as a result of the interaction between a top-down inhibition mechanism and enhanced WM representation of the reward-associated feature. However, in most of the cases, the previously reward-related stimuli failed to capture attention (Della Libera & Chelazzi 2009; Krebs et al. 2010; Brien 2009). In these experiments, stimuli were typically complex multi-feature or multidimensional objects, like complex shapes, words, or faces. This aspect of the stimuli may have precluded them from exerting a significant and persistent effect on observable behaviour.

Therefore, the choice of which stimuli will characterise the task can exert a different effect. Maybe the nature of the stimuli used in the present research (letters and their mirrored-images) could explain why the cue-colour fails to capture attention in Study 2.

In the training phase of Study 3, no significant effect was found. However, in the following testing session, it seems difficult to suppress the response to the to-be-ignored cue (high-rewarded condition): if the previously high-rewarded colour was the cue, and so the distractor, even though observers were instructed to ignore it, this colour still captured attention. In other words, there is an effect of the to-be-ignored stimulus that has been previously associated with a reward.

It is important to note that, during the training phase, accuracy is emphasized but, in the non-rewarded condition present in Study 3, even though subjects are correct they receive a “+0” bonus: it is possible that this can be seen by them as a form of punishment. It is well know that punishment, and not only reward, is able to capture attention. This could explain why subjects collected more items rendered in the non-rewarded colour. Moreover, top-down cognitive control is effective when there is enough time to respond, but this foraging task was time-limited, an aspect of the design that may have influenced foraging accuracy. Anyhow, learned reward association show they have a flexible role on cognitive control (Pessoa, 2009).

An action repetitively followed by a reward will be more readily elicited on subsequent encounters with the same stimuli and context, a phenomenon known as the law of effect (Thorndike, 1911). These consequences of rewards are important because they reinforce adaptive behaviours at the expense of competing ones, increasing fitness of the organism in its environment.

Future studies need to investigate whether similar influences regulate covert mental processes, such as visual selective attention in general and foraging behaviour in particular. It is clear that reward learning influences subsequent attentional priority: in some contexts, failing to notice targets can have dramatic effects (e.g., missing a malignant tumor in an X-ray), so it could be important to develop strategies that could limit such errors. This can be done exploiting the knowledge that different reward patterns can differently impact search behaviour.

Since there is a big discrepancy in the results illustrated in the literature, it will be interesting to deeply test different training procedures in order to understand the reasons why reward effect exerts less or more power.

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