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## Coding of object significance and reward in the visual and frontal cortex

Stanisor, L.

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# Chapter 1

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## Introduction

Let us imagine for a moment the very beginning of one's life. How the newly born baby learns to recognize mother's soothing voice even before being able to see, how he understands that her presence means protection and nourishment and how he later learns to smile upon seeing her face. The wonder of discovery when faced with a new and fascinating world, how one by one he attaches meaning to colors, objects, how he begins to express himself through articulate words. Then he learns to walk and so his universe quickly expands including more and more possibilities to communicate and interact with everything he sets his eyes on. During his exploration he realizes that some actions yield positive or negative results, that the refrigerator in the kitchen holds tasty rewards but the gas oven next to it can produce warmth as easily as burning the skin if one gets too close to the red-bluish flames.

As he grows older, the boy goes to school. There he learns about more abstract matters, about shapes and objects. He finds that nature displays certain patterns, that there are some rules that he can use in order to classify and identify objects. He learns that black patches can be grouped in complex patterns and even landscapes, that visual cues such as color and symmetry can be used to identify the different elements of scenery. And so, day by day he adds to his knowledge what it takes to fully appreciate the world.

\* \* \*

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Each of us experiences the world much like in the example above. In order to survive, one must learn quickly since their first minutes of life. Although sight fully develops in a baby around the age of eight months, it quickly outranks hearing and becomes the major source of information. It is difficult to quantify exactly how much we rely on eyesight when interacting with the world, but nevertheless we find that most of our experiences and memories are of a visual nature. Not surprisingly then, scientists have tried to explain how vision is carried out since the times of ancient Greek philosophical schools (starting with Plato). Throughout the centuries, we have increased our understanding of vision a great deal (for progress made in the last century see Albright et al, 2000), but still many aspects of the visual processing continue to escape a proper explanation. The reason for this situation is that the complexity of our surrounding world is reflected in the very complex structure and function of the part of our brain dedicated to vision (25% of the human cortex – van Essen 2005). A large number of cortical areas that spread from the occipital to the frontal lobe are subject to interaction in order to process the various visual cues of the scenery that we see and give rise to what is called perception, which is our representation of the outside world. In many cases, what we see demands that we also take action, which in turn produces a positive or negative result. Based on these experiences, we learn to avoid unpleasant outcomes and pursue the pleasant ones. Our behavior is therefore shaped by what we learn, and this intertwining between perception, action and outcome is reflected in our brain by the interactions between areas that are involved in visual processing, reward-related signal, decision making and learning. In this section I will briefly discuss these aspects and in each case formulate the specific questions that I will address in this book.

## 1. General considerations about the visual system

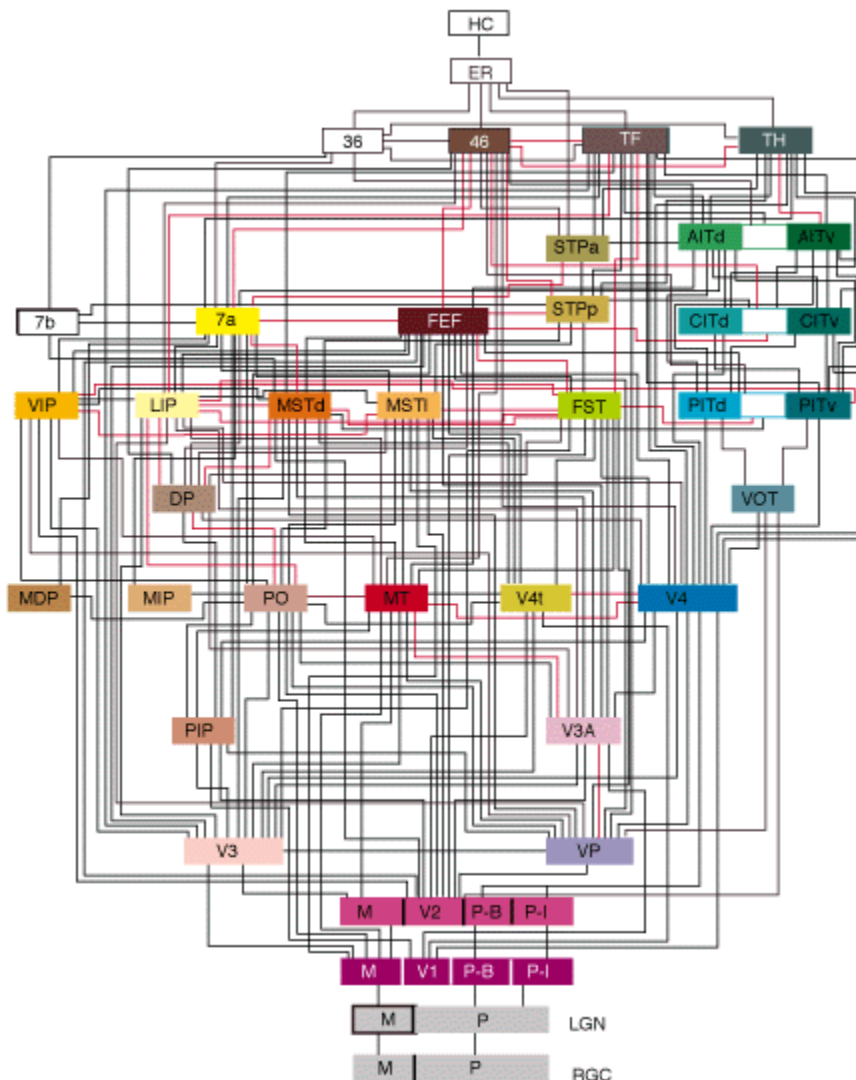


Figure 1. The anatomical organization of the visual cortex as first described by Felleman and Van Essen (Felleman and Van Essen, 1991)

As shown in the above figure, multiple densely interconnected visual areas take part in the processing of visual information (Felleman and Van Essen, 1991). As a matter of fact, the role of many of these areas had been described before the intricate pattern of connectivity among them was reviewed by Felleman and Van Essen. For example, it was already known

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that the primary visual cortex (area V1) is involved in processing of edges and oriented contours (Hubel and Wiesel, 1968), area V4 processes information about color (Zeki, 1976), the IT (inferotemporal) cortex is involved in processing of face and object-related information (Gross et al., 1969), and area FEF (frontal eye fields) coordinates the generation of saccades (Ferrier 1875).

When the pattern of connectivity between different visual areas was described (1991), a concerted effort has started in neuroscience with the intention of linking the functions of different parts of the visual system. This endeavor resulted in the determination of several principles that govern the functional organization of the visual system. The first emerging principle was the hypothesis that the visual system is hierarchically organized (for a review see Van Essen, 1985). Hubel and Wiesel first suggested in 1962 that the properties of a visual stimulus which are processed at each stage result, in part, from selective convergence of information from the previous stage. As an example, a large number of retinal ganglion cells project unto a cell in the LGN (lateral geniculate nucleus) and many of those cells converge in turn to one single simple cell in area V1. More importantly, while the activity of a retinal cell or a LGN cell only codes the luminance contrast of a stimulus, the activity of a simple cell in area V1 reflects a higher level of abstraction, namely the presence of an oriented light bar in neuron's receptive field. The same process is believed to take place in the cortex and it led to the second principle of functional organization of visual system, namely that at successively higher stages neurons have larger receptive fields and code more complex and abstract features of a stimulus. A schematic representation of these two principles at the level of the visual cortex is shown in figure 2 (for a review see Roelfsema, 2006).

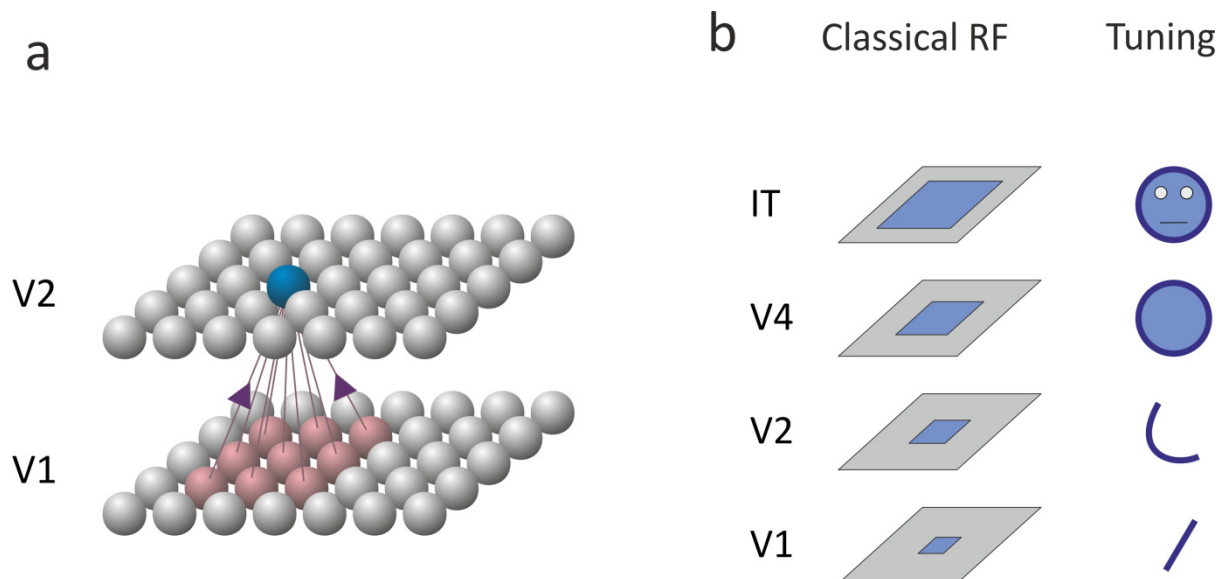


Figure 2. Representation of a) signal convergence and b) stages of cortical feedforward processing of a visual stimulus (adapted from: Roelfsema, 2006)

The last and probably the most important principle of functional organization of vision is that the visual system is organized in parallel streams. The incoming information is routed through these distinct streams in such a way that the output of each pathway serves a unique function. The most well known type of this streaming is the existence of the so-called dorsal and ventral system in the visual cortex (figure 3) (Ungerleider and Mishkin, 1982).

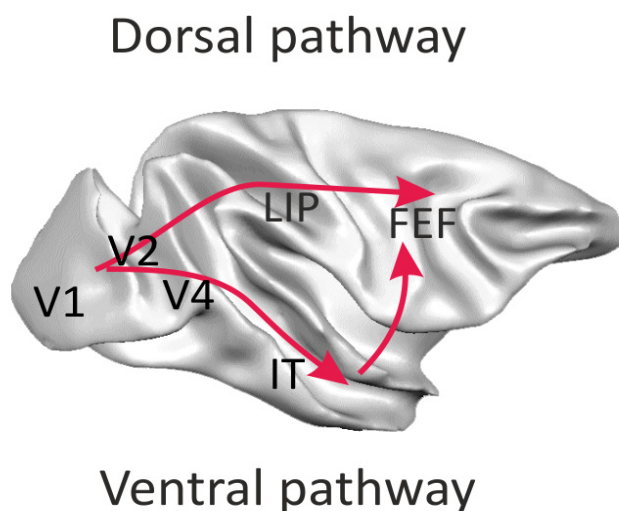


Figure 3. The dorsal “where” and the ventral “what” pathways

Both streams of information begin in the occipital cortex (area V1). The dorsal stream reaches as far as the parietal lobe and is implicated in spatial awareness and

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guidance of actions. It detects and analyzes movements (area MT) and is involved in the decision making process when making saccades to a certain location (LIP). On the other hand, the ventral stream goes from the occipital to the temporal lobe and is associated with object recognition and form representation. Among other areas, it comprises area V4 (relevant to color and simple spatial processing) and IT, which has a role in object and face perception. These two pathways are densely interconnected with each other, as well as with areas of the prefrontal cortex (FEF among others). This connectivity reflects the complexity of our surrounding universe, the fact that although parts of our brain are diversely specialized, they need to cooperate in order to fully process what we see, and also the necessity that perception leads to action, that what we see makes us act or react so that we integrate ourselves into the world.

I will now proceed to discuss a few examples of visual processing and refer to specific questions that will be answered by the different aspects of this thesis.

## **2. Perception and brain activity**

Since the beginning of human race, people have tried to understand the world as well as their own bodies. When it comes to investigating our brain, many methods have been employed, from theoretical hypotheses to mathematical models and from recording or delivering electrical impulses to the brain to monitoring the reactions of subjects given a specific task. I will show how a connection can be made between theoretical psychology and practical electrophysiology and how these two different approaches can be used together in an effort to understand how the brain works.

## 2.1. The psychology of perception

### 2.1.1. General considerations

Psychology as a science has always been trying to understand how we think. When it comes to perception in particular, there is a theory of mind and brain called gestaltism or Gestalt psychology developed by the Berlin school which proposes that the operational principle of the brain is holistic, parallel, and analog, with self-organizing tendencies. The German word Gestalt translates as essence or shape of an entity's complete form and the Gestalt effect refers to the form-forming capability of our senses, particularly with respect to the visual recognition of figures and whole forms instead of just a collection of simple lines and curves.

The idea of Gestalt has its roots in theories by Johann Wolfgang von Goethe and Immanuel Kant, but the concept of Gestalt was first introduced in contemporary philosophy and psychology by Christian von Ehrenfels (1890). The theory was completed later by the three scientists that are considered the founders of Gestalt psychology, namely Max Wertheimer, Kurt Koffka and Wolfgang Köhler. The phrase "The whole is greater than the sum of the parts" is often used when explaining Gestalt theory. The classic Gestalt example is a soap bubble, whose spherical shape is not defined by a rigid template, or a mathematical formula, but rather it emerges spontaneously by the parallel action of surface tension acting at all points in the surface simultaneously. This is in contrast to the "atomistic" principle of operation of the digital computer, where every computation is broken down into a sequence of simple steps, each of which is computed independently of the problem as a whole. A cognitive form of problem-solving learning stems in the Gestalt theory, as well as a dedicated branch of therapy and psychotherapy.



### 2.1.2. Elements of the Gestalt theory on perception

The fundamental principle of Gestalt perception is the law of *Prägnanz* (German for *pithiness*) which says that we tend to order our experience in a manner that is regular, orderly, symmetric, and simple. Gestalt psychologists attempt to discover refinements of the law of *Prägnanz*, and this involves writing down laws which hypothetically allow us to predict the interpretation of sensation, what are often called Gestalt laws or perceptual grouping criteria. I will shortly describe the most important of them.

- 1) Law of Closure — The mind may experience elements it does not perceive through sensation, in order to complete a regular figure (that is, to increase regularity). Therefore, in figure 4 below we easily perceive two known geometrical figures (a rectangle and a circle) although they are not continuously delimited.

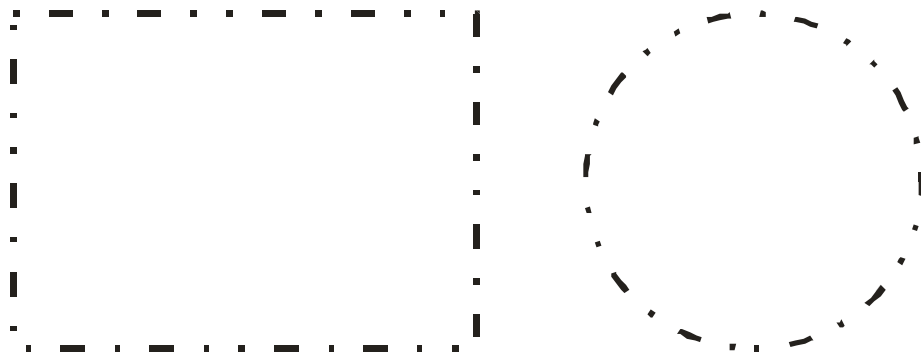


Figure 4. Perceptual grouping by closure

- 2) Law of Similarity — The mind groups similar elements into collective entities or totalities. This similarity might depend on relationships of form, color, size, or brightness. In the following example, the grid made up of circles is grouped in different rows based on the different color cues.

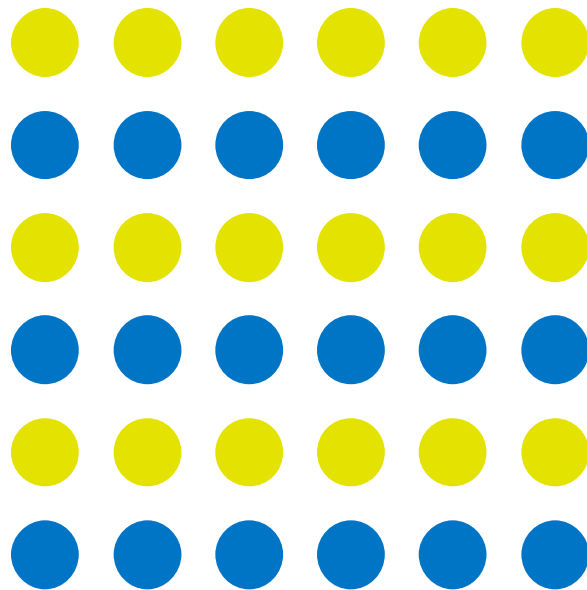


Figure 5. Perceptual grouping by color similarity

- 3) Law of Proximity — Spatial or temporal proximity of elements may induce the mind to perceive a collective or totality. In figure 6, the same amount of circles is first perceived on the left panel (a) as making up the larger pattern of a square, while in the right panel (b) the elements seem to self organize in three smaller rectangles due to their spatial proximity.

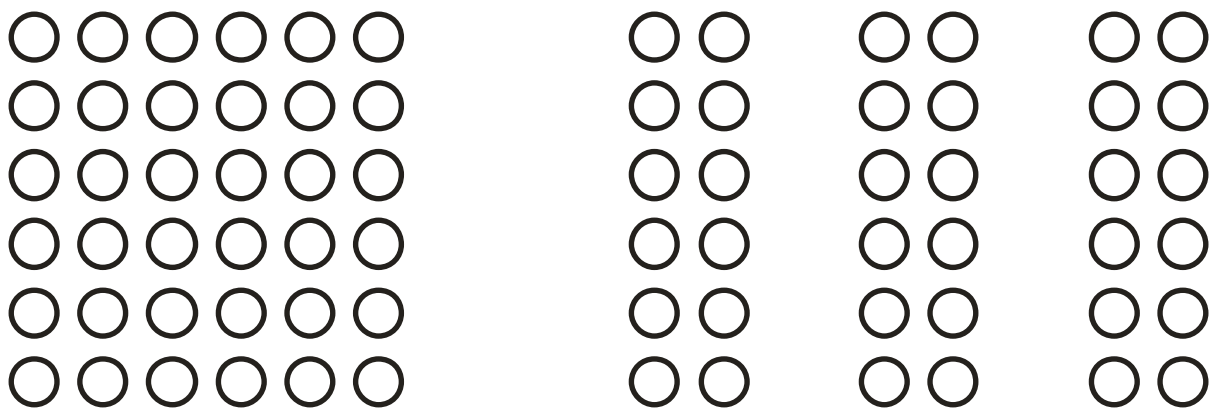


Figure 6. Perceptual grouping by proximity

- 4) Law of Symmetry (Figure ground relationships) — Symmetrical images are perceived collectively, even in spite of distance. In the figure below, the symmetrical areas tend to be seen as figures against asymmetrical backgrounds.

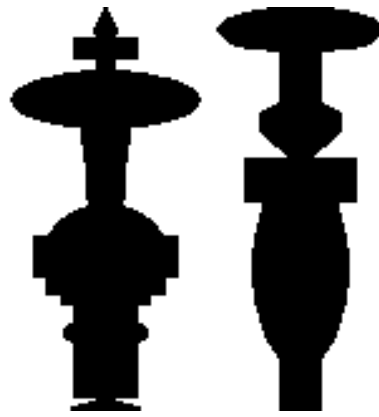


Figure 7. The law of symmetry

- 5) Law of Common Fate — Elements with the same moving direction are perceived as a collective or unit.
- 6) Law of Continuity — The mind continues visual, auditory, and kinetic patterns. Contours based on smooth continuity are preferred to abrupt changes of direction. Here, for instance, we are more likely to identify lines a-b and c-d crossing than to identify a-d and c-b or a-c and d-b as lines.

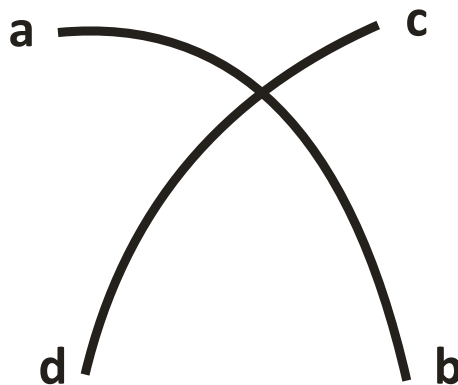


Figure 8. The law of continuity

### 2.1.3. Connection to neural activity

All the grouping criteria mentioned above refer to processes which seem to affect our whole mind. How can they be translated at the level of activity of single neurons in one specific cortical area? Our group has already demonstrated that when a monkey directs its attention to a curve such as a-b in figure 8, the neurons in the primary visual cortex that have their receptive fields on that curve

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enhance their activity compared to those corresponding to the other curve (Roelfsema 1998). Stronger even, the same neuron has a higher firing rate when its receptive field falls on the curve attended by the monkey (target curve) compared to when the monkey attends the other curve (distracter curve – see also figure 9).

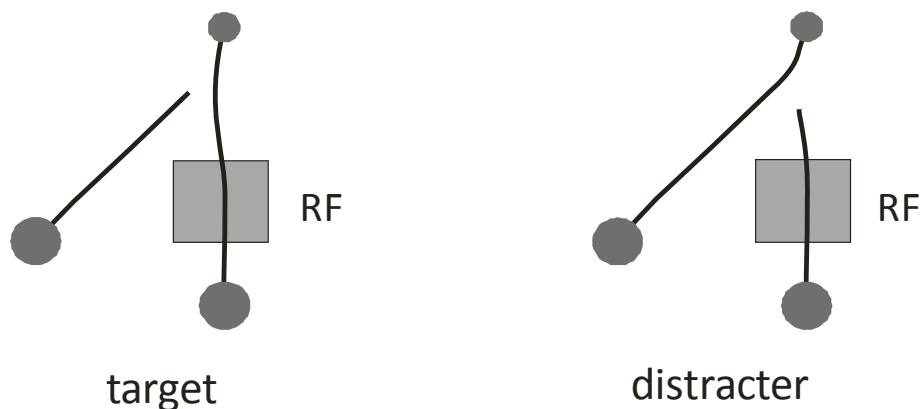


Figure 9. Example of a curve-tracing task. The receptive field (RF) of a V1 neuron falls on the attended curve in the left panel (target curve) and on the not attended curve in the right panel (distracter)

These data prove that neurons at the earliest level of the visual hierarchy are influenced by attention and as such visual processing is not carried out only via feedforward but also via feedback streams on information. This mechanism also explains how a Gestalt law is translated in terms of neural firing pattern in our so-called curve tracing task.

The target-distracter modulation of activity in V1 is produced by the difference in attention. Several studies have shown that attending a stimulus enhances the neural activity corresponding to it (for a review see Desimone and Duncan 1995) and this effect is also present when directing attention even to a certain region of visual space (Connor and van Essen 1997). The effects in all our curve-tracing experiments are based on the spread of attention due to one Gestalt law, namely that of continuity. Starting from this point, one can imagine that also other Gestalt grouping criteria will produce similar effects. I will elaborate on this hypothesis in the second chapter on this thesis, presenting the effect of other grouping cues on the pattern of neuronal activity in the primary visual cortex.

### **3. Reward and vision**

#### **3.1. The importance of reward**

If we think of our development, we realize that we are what we are because of reward. Throughout our lives, we come in contact every day with new situations which need solving and we take decisions based on our previous experience and the data in question. These decisions in turn produce outcomes that have either a positive or negative meaning and enable us to learn and accumulate experience. Whether we are risk takers and play high stakes at the roulette or careful planners and invest money with annual interest rates, all our behavior is shaped by the outcomes that we either pursue or avoid. We are the end product of our reward expectations.

#### **3.2. Significance for neuroscience**

It is understandable that such a widespread signal as reward could not go unnoticed in the brain. There is an entire sub-field in neuroscience dedicated to studying the effects of reward and a vast literature has been published (for a review of the extent of these signals see Schultz 2007). Numerous cortical and subcortical structures, from substantia nigra (Fiorillo and Schultz 2003) to frontal cortex (Watanabe 1996) and from amygdala (Paton et al 2006) to motor cortex (Roesch and Olson 2004), are involved in the processing and effects of incentives. Up to date two streams have been described, which mainly use dopamine as their neurotransmitter. One of them is the *mesolimbic pathway*, which begins in the ventral tegmental area of the midbrain and connects to the limbic system via the nucleus accumbens, the amygdala, and the hippocampus as well as to the medial prefrontal cortex (Tisch et al 2004). It is known to be involved in modulating

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behavioral responses to stimuli that activate feelings of reward (motivation) and promotes reinforcement through the neurotransmitter dopamine. Another major dopamine route is the *mesocortical pathway*, which connects the ventral tegmentum to the cerebral cortex, particularly the frontal lobes. This one is essential to the normal cognitive function of the dorsolateral prefrontal cortex (part of the frontal lobe), and is thought to be involved in motivation and emotional response. These pathways are part of the brain reward circuitry, a distributed, multisynaptic system that determines both brain stimulation reward and natural reward function (reviewed by Milner in 1991 and Wise in 1996). This complex circuit was demonstrated to act abnormally in disorders such as addiction, depression and schizophrenia and targeted as such with specific pharmacological therapy (Diaz 1996, van den Heuvel 2008).

The pathways processing reward have been shown to affect neurons in areas that are considered part of the visual brain, such as the frontal eye fields and supplementary eye fields (Roesch and Olson 2003) and superior colliculus (Ikeda and Hikosaka 2003). This pattern of interconnectivity suggests that reward-related effects can be investigated in the visual cortex.

As I have previously shown, the primary visual cortex is the first station where the incoming visual signals are processed and sent forward, but which at the same time can be influenced by feedback activity from other areas. Although the neurons present here only seem to process simple cues such as the orientation of a bar, they enhance their activity when attention affects their receptive fields (even when the direct stimulation remains the same). Given that the pathways processing attention and reward processing are both widespread throughout the cortex, a question comes to mind: how are these two represented in the brain and what is the relation between them? In a recent assertion,

Maunsell (2004) argued that many of the studies that attempted to investigate one of these processes could in fact not make the distinction between the two and that perhaps such an attempt would fail because the brain could use the same signals in order to mediate attention and reward. This drove us to imagine a series of experiments with the purpose of investigating if changing reward in a task which demanded the same amount of attention allotted to the stimulus will influence the V1 neurons and if a special setting is necessary in order to obtain modulation. Furthermore, we wished to test if the effects of attention and reward could be disentangled at this level. The third chapter of my thesis will describe the results of this endeavor.

## **4. Learning in the visual system**

### **4.1. Introduction on learning**

Vision is at the same time our blessing and our curse. It delivers information at an amazing speed and rate, but that also means that our brains work continuously to make sense of all this sensory assault. We see new things all the time and we in order to find our way in the middle of them, we must quickly find means to classify and recognize them, to make adequate decisions that are benefic for us. By means such as standardization, generalization and association, we get better and better at discerning in the universe around us what is useful or not, what is helpful and what is harmful and in such a way we can improve ourselves. Without continuous learning, life as we know it could not exist.

A simple definition of learning would describe it as the acquisition of new knowledge, behavior or skills. This activity is presumably as old as life itself. The treasured ability of learning is not only possessed by humans but also animals and the more advanced machines. Several mathematical models of learning have been discussed by Fadul in 2006.

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In case of humans, learning can occur consciously or without any conscious awareness, since it has been demonstrated even prenatally, in which a form of learning called habituation appears as early as 30-32 weeks of gestation (Sandman et al 1997). This indicates that our brain is sufficiently developed and primed for learning and memory to occur very early on in development. Learning occurs as result of habituation and classical conditioning, seen in many species of animals, or as a result of more complex activities such as play, seen only in relatively intelligent animals such as octopuses (Kuba et al 2006) and humans. I will now elaborate on the different types of learning and their relevance.

### **4.2. A classification of learning**

Several classifications exist when one approaches the process of learning. The one that I will refer to in this thesis distinguishes, among, other types, the associative and non-associative learning. The (simple) non-associative learning is characteristic to both humans and animals and knows two different types. The first one is habituation, a process in which there is a decrease in psychological and behavioral response to a stimulus after repeated exposure to that stimulus over a long period of time. It has been described in virtually all species of animals and even in a protozoan (Wood 1988) and in humans, both conscious and unconscious. Habituation seems to be mainly a psychological phenomenon and is believed to be mediated by processes such as neural adaptation. The second type of non-associative learning is sensitization, described as the progressive amplification of a response that follows repeated administrations of a stimulus (Bell et al 1995). Sensitization has been implied as a causal or maintaining mechanism in a wide range of apparently unrelated pathologies including substance abuse and dependence, allergies, asthma, and some medically unexplained syndromes such as fibromyalgia and multiple chemical sensitivity. An



interesting sub-type is drug sensitization which occurs in drug addiction and is defined as an increased effect of drug following repeated doses. Addiction may also be related to increased (sensitized) drug craving when environmental stimuli associated with drug taking, or drug cues, are encountered. This process may contribute to the risk for relapse in addicts attempting to quit (Robinson and Berridge 1993).

#### **4.2.1. Associative learning**

The type of learning more relevant to the purpose of this thesis is associative learning. It is defined as the process by which an element is learned through association with a separate, pre-occurring element. The assumption is that the two elements reinforce one another and will be linked in order to promote learning. Two variants of associative learning have been described, namely the classical conditioning and the operant conditioning. I will briefly describe these two forms and explain how we used one of them in our experiments.

The classical or *Pavlovian conditioning* is well-known in the scientific world and it makes use of the paired and repeated presentation of two different stimuli. One of them is neutral to the subject and it is called conditioned stimulus (CS), while the other one is significant and necessarily evokes an innate, often reflexive, response and is named unconditioned stimulus (US). After many occurrences of the two stimuli, they eventually become linked and the subject begins to produce the same response to the US presented alone. This is called a conditioned response.

Several types of classical conditional exist, based on the timing and succession in the presentation of the two stimuli. Variations have also been described, depending on the number of CS and US being paired and these methods can be used with the purpose of making the subject distinguish between different CS or different modalities of presenting

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the CS (discrimination or reversal conditioning) or prevent the subject from developing a response to a second CS (blocking). These methods of classical conditioning are used in human psychology. An example is aversion therapy, in which unpleasant sensations are paired with a certain stimulus in order to stop a specific behavior (for instance an emetic drug with alcohol in addiction therapy). Two other related therapy methods are flooding and systematic desensitization, which are used in the treatment of phobias when the patients are exposed to their painful memories in order to integrate their feelings with their current awareness, either abruptly as in flooding (Sundel 2005) or in a gradual exposure as in desensitization.

The other form of associative learning is *operant conditioning*, which consists of the use of consequences to modify the occurrence of behavior. The difference between this and the Pavlovian conditioning is that it concerns voluntary behavior. Operant behavior acts on the environment and is maintained by consequences, while classical conditioning implies responses elicited by antecedent conditions. Behaviors conditioned via a classical conditioning procedure are not maintained by consequences (Domjan 2005). The main dependent variable is the rate of response that is developed over a period of time.

It is important to define a few terms pertaining to operant behavior. *Reinforcement* is a consequence that causes a behavior to occur with greater frequency, *punishment* is one that causes a behavior to occur with less frequency and *extinction* is the lack of any consequence following a behavior (i.e. when a behavior is no longer reinforced it leads to a decline in the response). These lead to four contexts of operant conditioning. *Positive reinforcement* (or simply called reinforcement) occurs when a behavior or response is followed by a favorable (pleasant) stimulus, which increases the frequency of that behavior. This context is widely used in the experimental world and in particular in all the

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experiments described in this thesis. *Negative reinforcement* (escape) occurs when a behavior or response is followed by the removal of an aversive (unpleasant) stimulus and thereby increases the frequency of the response. *Positive punishment* (punishment) occurs when a behavior (response) is followed by an unpleasant stimulus and *negative punishment* (penalty) when a response is followed by the removal of a pleasant stimulus, both of them determining a decrease of the response frequency.

The effectiveness of operant conditioning can be influenced by several factors. The first and most often confronted is deprivation/satiation - when the subject has high appetite for the stimulus, the reinforcer is more effective and vice versa. The principle of satiation is explained by the homeostasis of the biological organisms, i.e. when the blood sugar is low then the efficiency of sugar as reinforcer is high. In our experiments, monkeys were rewarded with a drop of water mixed with juice on a trial basis for making the correct stimulus choice and one can assume that as the session progressed, this reinforcement gradually lost its effectiveness and that eventually determined the monkey to stop responding.

Another influencing factor is immediacy, that is to say that the more promptly the response is followed by its consequence, the more effective this response will be affected. A third factor is contingency – if a consequence does not reliably (consistently) follow a response then its effectiveness is reduced and vice versa, or in other words the consistent schedule of reinforcement (reward) leads to faster learning. Finally, a factor better known in human psychology is size - if the amount of the consequence is large enough to be worth the effort, the consequence will be more effective upon the behavior.

### 4.2.2. Emerging theories

Based on the findings of operant conditioning, a family of philosophies has evolved which is named behaviorism or learning perspective. This current of thought proposes that all that living organisms do can be seen as behaviors, including processes as acting, thinking and feeling. As such, everything can be described scientifically without using hypothetical constructs like the mind (Baum 1994). Although this theory was mainly influenced by the classical and operant conditioning methods, with the predominant investigators Ivan Pavlov and B.F. Skinner respectively, it also shared commonalities with the Gestalt movement. In the second half of the twentieth century, behaviorism was however largely replaced as a consequence of the rising cognitive revolution. Cognitivism believes by opposition that psychology can be fully explained by using experiment, measurement and scientific method. That is based on the assumption that cognition is nothing else than a series of discrete, internal mental states whose manipulation can be described in terms of rules of algorithms.

The cognitive revolution had significant sources in British, French, and German psychology of the early part of the 20th century. Behaviorism had been much of an insular American movement and the cognitive movement can be seen as a natural development of earlier modern psychology. Although the two schools of thought do not agree theoretically, they have complemented one another in more than one occasion. The contemporary view in neuroscience seeks reconciliation between these two conceptions (see figure 10 for a schematic representation of their relations). In fact, cognitive psychology is not a wholesale denial of behaviorism, but rather an expansion that accepts that mental states exist, while behaviorists denied the existence of complex intermediary mental states that cause

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behavior. That is in part due to the fact that modern neuroimaging technology has made it possible to observe brain states, but how these correspond to mental structures is still a challenge.

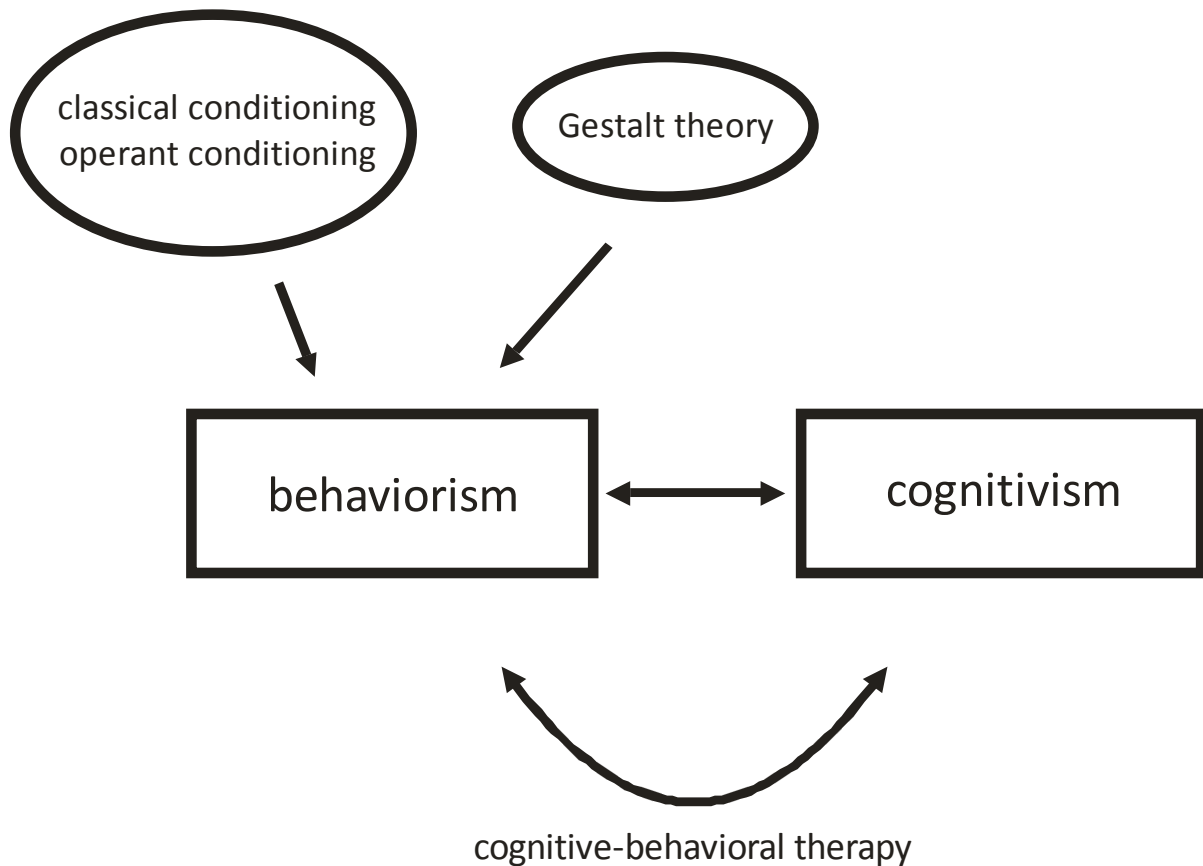


Figure 10. The 'smiley face' (Gestalt): Relationships between behaviorism with its origins and cognitivism

One of the most prominent examples of fusion between the two theories is Cognitive-Behavioral Therapy, a popular treatment that uses cognitive models alongside behaviorist techniques such as *systematic desensitization* that have demonstrable utility in helping people with certain pathologies, such as simple phobias, posttraumatic stress disorder (PTSD) and addiction.

### **4.2.3. Learning and cortical areas**

Just as psychology is the part of neuroscience investigating cognitive processes and has since long developed theories in order to understand the brain, neurophysiology comes to complement with experiments that directly investigate the neuronal or more global cortical signals in an effort to uncover the underlying mechanisms. I will explain further how the principles of associative learning have enabled us to create the paradigms that we used in our experiments.

#### **4.2.3.1. Operant conditioning in monkey research**

A usual recording session in electrophysiology requests the monkey to make hundreds, perhaps thousands of trials. When presented with the visual stimulus, the animal is required to make a choice and when performing the task correctly is rewarded with a drop of juice mixed with water (positive reinforcement). In that way, the animal is stimulated to keep working until either sufficient data is acquired or it stops spontaneously according to the principle of satiation.

As I have shown before, all our curve-tracing experiments (Roelfsema 1998) are based upon the Gestalt principle of continuity, because the monkeys mentally trace the curve connected to the fixation point (target) and not the broken curve (distracter). The experiments presented in the third chapter focus on investigating if other Gestalt cues also lead to perceptual grouping and attentional enhancement of activity in V1. The second chapter looks at the effects that changing reward has on activity in the primary visual cortex when the visual stimulation is constant. The fourth and the fifth chapters address two different cortical areas using similar paradigms that use an object-based learning task in order to assess neuronal modulation.

#### **4.2.3.2. Curve tracing and learning in frontal eye fields**

The frontal eye fields (FEF) is an area situated in the premotor cortex, which is part of the human and primate frontal lobe. It lies at the executive end of the visual system and not surprisingly it is involved in the coordination of eye movements, such as voluntary saccades and pursuit eye movements (Mustari 2009, Ilg 2008). The neurons in this area have large response fields (RF) and intriguing properties which were described by Schall in 1995. More specifically, some of them are activated by passive viewing of a stimulus situated in their RF and are called visual neurons. Some of them increase their firing rate just before the monkey makes a saccade (pre-movement or movement neurons) and some of them show both types of activity (visuo-movement neurons), sometimes with prolonged, tonic discharges.

Since this cortical area seems to make the coupling between perception and action, it was also thought to be implicated in the decision-making process. The visuo-motor neurons in particular, because they are influenced by both perception and intent, should be strongly influenced by the acquisition of new associations. For instance, it has been shown that FEF neurons have different activations when novel stimuli are presented in contrast with previously seen/learned stimuli (Chen and Wise 1995). The third chapter of this thesis investigated how the pattern of activity from visuo-motor neurons is influenced by the learning of a new stimulus (i.e. when the monkey improves its accuracy of selecting the relevant stimulus).

The paradigm we used presented two new objects every day to the monkey, with the purpose that one would be selected over the other. In order to make this task

easier, we had to use curve tracing by showing the two objects attached to curves. I will show how this task that mixed Gestalt cues with operant conditioning succeeded in making the monkeys improve their performance between the beginning and the end of each recording session and what the consequences were for both behavioral and neural parameters.

#### **4.2.3.3. From FEF to V1: bridging the cortex with learning**

We have seen that the activity of neurons in primary visual cortex is modulated by attention. In addition, visual processing of a stimulus seems to occur not only via feedforward signals, but also through lateral connections within an area and feedback connections, from higher to lower level in the hierarchy (Lamme and Roelfsema 2000, Roelfsema 2006). In this context, one can imagine that while viewing a (complex) stimulus arises cortical processing that involves all visual areas from the occipital to frontal lobe and back, and that both the sensorial and executive parts are engaged in this activity. This would further imply that during a trial-by-trial progression of a learning task, the (changing) feedback signals from the parts of the brain responsible for learning will echo as far as primary visual cortex. This is the rationale that stands behind the experiment described in the fifth chapter of my thesis, where I use a similar paradigm as in FEF but this time investigating area V1.

In *chapter 6* I will briefly discuss all these results and attempt to integrate them in a global view that shows their connectedness and can improve our understanding of the cortical processes.



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