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An enactive approach to size constancy

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Introduction

An object appears of the same physical size despite the fact that its retinal image continuously change in size while we move around and interact with the environment. This is size constancy, the manifestation of a more general phenomenon, namely perceptual constancy, that allows our perception to be “tuned” to the permanent properties of the surrounding environment (size, colour, shape etc.) despite the fragmented and continuously changing stream of row information reaching our senses. Constancy is of paramount importance for all living organisms allowing them to perceive a stable world, to accomplish their goals and, in the end, to survive.

Although motion and variability play a key role in size constancy, most of the current knowledge comes from empirical studies designed upon a static model of visual perception. If we look at the literature, the most common experimental situation used is that of an immobile observer that looks at one or more static stimuli. The purpose of my work is to explore the dynamical aspects of size constancy with a research approach that gives more emphasis on embodiment and situatedness. Drawing inspiration from the enactive approach to cognition (Valera, Thompson, & Rosch, 1991) especially in its recent formulation by Marieke Rohde (2010), I study the role of active motion in size constancy with an interdisciplinary approach that combines two different methodologies, artificial life modeling and adaptive psychophysical methods.

Artificial life modelling (Langton, 1997) allows the experimentation with minimal brain-body-environment systems through the creation of artificial environments populated by organisms that has simple cognitive systems like artificial neural networks. Organisms are typically created with an evolution process that selects organisms based on fitness criteria. In spite of their minimalism, these models permit the exploration and manipulation of the foundational aspects of embodiment and situatedness, which is hard to achieve with other techniques. They give insights about the basic aspect of cognition from an evolutionary perspective giving particular emphasis to the relation between cognition and adaptive behaviour. In this work, I describe an Artificial Life model where artificial organisms exhibit size constancy abilities through a simple sensory motor behaviour.

Adaptive psychophysical methods are modern psychophysical methods that allow the estimate of psychometric functions with a reduced number of trials. The stimulus intensity is adapted interactively from trial to trial based on the participant responses. In chapter four, I describe how I used a particular adaptive method called *PSI Method* to estimate the differential threshold in a kinetic size constancy task where participants were asked to discriminate between two spheres of different sizes at different distances. The experiment was conducted in a 3D virtual environment in which participants could move and change their point of view. The goal of this experiment was to study Size Constancy in a dynamical context where the observer moves and can actively control the visual input.

The structure of my work is as follows. In the first chapter, I give an overview of the size constancy problem in its classical stance and I briefly review the classical literature. Traditionally, size constancy has been viewed as the problem of understanding how the physical size of an object is recovered combining information about its distance and retinal image size. The main factors studied in the literature concern the richness of depth cues, age differences, stimulus familiarity and the effect of experimental instructions.

In the second chapter, I recall the basic theoretical principles of the enactive approach to cognition and I try to translate them into practical principles more relevant for the study of size constancy. Some of the questions that the "enactive approach to size constancy" poses are of interdisciplinary nature and have already been started to be investigated in the literature about kinetic size constancy, optic flow, evolutionary robotics, and comparative psychology. All these works together form a good starting point for an enactive approach to size constancy, but need a more integrated research approach and a shared vision.

In the third chapter I present a minimalistic model of size constancy where a population of artificial agents, endowed with a feed-forward neural network, are evolved based on their ability to discriminate between small and big circles. The emerged size constancy abilities are based on a pure sensory motor strategy that is nonetheless functional to the complex task assigned. These and similar results obtained in the past research could form the basis for an integrated research approach on size constancy that may unveil unexplored aspect of this phenomenon.

In the fourth chapter, I first discuss some recent research on the role of active motion in visual perception, and then I present my own experiment in which I investigate the role of self-motion in kinetic size constancy when depth information is derived from optic flow. Results support the hyphothesis of a two visual system in humans, with a “vision for action” and a “vision for perception”. With the vision for action system, size perception results from the interpretation of row sensory information with sensory motor strategies. Self-motion plays an important role in this case. With the vision for perception system, sensory information is interpreted based on previous knowledge and inference-like processes. In this case, motion information is nearly ignored.

1. Classical Literature on Size Constancy

The scientific literature on size constancy is composed by a corpus of psychophysical experiments that covers nearly a century of research starting from the1930s. In this chapter, I review the main themes of this literature in which the prototypical experiment involves an immobile observer that judges the size of a static stimulus and is therefore characterized by a static model of visual perception. Size constancy is viewed as a phenomenon that emerges from the relation between the perceived distance and the angular size of an object. I call this literature “classical” as opposed to a different kind of research that I will discuss in the next chapter when I explain the enactive approach to size constancy.

1.1. The size constancy problem

The physical size of an object, as many other permanent properties of the objects around us, cannot be perceived directly, but must be somehow “reconstructed” integrating different sources of information. Traditionally, three main elements have been considered to play a major role in size perception: physical size, angular size and distance. Depending on its *distance* from the eye, an object of a certain *physical size* can project on the retina images of different *angular size*. This is illustrated in Figure 1 where the object in position A projects an image on the retina that is bigger than the image projected by the object B that is more distant but has the same physical size. Size constancy refers to the fact that, despite the continuously changing size of the retinal image associated with an object, our perception of its size remain stable.

At a first glance, size constancy seems a simple problem that can be interpreted as a manifestation of the constant mathematical relationship between visual angle and distance. It is not by chance that the main explanation proposed for size constancy is the size distance invariance hypothesis (see 1.1.2). However, as we will see next, things are much more complex than they seem. Distance, for example, is not perceived directly but is derived from at least 13 different cues that have different ranges of applicability (e.g. short, mid and long range) and different scales (e.g. linear cues like binocular convergence or discrete cues like occlusion).

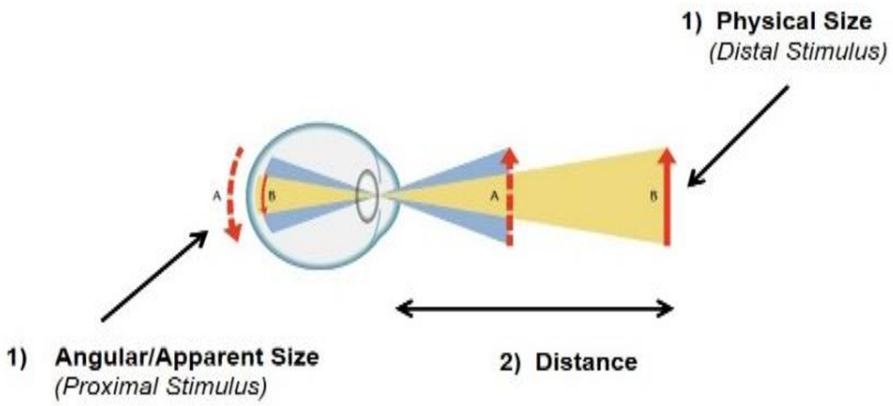

Figure 1- Three main elements involved in size perception

The relation between size and distance has a long history that dates back to Euclid who studied how visual angle varies with distance and analysed the problem in a geometrical manner (Euclid, Optics, 300 B.C). Ptolemy in his Optics (2nd century A.D) discussed the relation between size and distance and concluded that these two information in conjunction were the determinants of perceived size. A longer discussion about this hypothesis can be found in the work of the Arab physicist Ibn al-Haytham, also known by the Latinization Alhazen, who writes (Ross & Plug, 1998): "When human vision perceives the size of visible objects, it perceives it from the size of the angles that visible objects project to the centre of vision, and from the degree of intervening space, and by comparing the angles with the intervening space". The same idea was carried on by many other successors like Descartes, and later on by Helmoltz who was one of the most influential proponents of the size distance invariance hypothesis.

Aside from these long antecedents, the size constancy problem began to be investigated empirically in the late 1920s by Brunswik who was the first to propose a theoretical framework to explain size constancy, and was also the first to propose a measure for it (Brunswik, 1956).

1.1.1. First experiments and measures

The prototypical size-constancy experimentation was set out by Martius (Martius, 1889) who asked observers to compare a set of rods placed far away from them, with a standard rod placed nearer. This procedure, with some variations, was used by Brunswik in his pioneering experimental work on size constancy that is reviewed by himself when explaining his representative design of psychological experiments (Brunswik, 1956). According to Brunswik, size perception is the result of two different perceptual attitudes: objective and subjective. Objective attitude allows the perception of physical size of objects and is the result of multiple functional interaction of a person with his surrounding environment in everyday life (Brunswik, 1940). The subjective attitude is based on the apparent size of an object and reflects the object-observer relation at a particular time. Brunswik introduced his constancy ratio (also called Brunswik Ratio) to express how much the size judgments obtained in the experiments were influenced by the objective attitude or the subjective attitude. The brunswik ratio ranged from 0.0 to 1.0 and was obtained with the following formula:

$$BR = \frac{P - A}{R - A}$$

Where P is the perceived size, A is the angular size and R is the real size. As can be seen, a brunswik ratio of zero indicated that the size judgment was purely subjective and matched angular size. A Brunswik ratio of one indicated a perfect true physical size judgment. Thouless later introduced an alternative formulation of the Brunswick ratio that did not depend on which object was the standard and which was the comparison (Thouless, 1933) and gave more linear values. Thouless called this modified version of the brunswik ratio “Index of Phenomenal Regression”:

$$TR = \frac{\log P - \log A}{\log R - \log A}$$

Empirical research done with these two formula gave interesting results. First of all the attempt to obtain a pure subjective attitude (a zero value of the ratios) proved to be very difficult. In other words, it was very difficult for the participants to match the angular size. This phenomenon was described as “regression to the real”. Secondly, in some experiments the values of the thouless ratio exceeded one, which was a theoretically impossible result (Holaday, 1933). This was described as “overconstancy”.

1.1.2. The Size Distance Invariance Hypothesis (SDIH)

The mathematical relation between angular size, physical size and distance is depicted in Figure 2, and can be expressed by the following formula:

$$\tan\alpha = \frac{S\ \sin\beta}{D - \cos\beta}$$

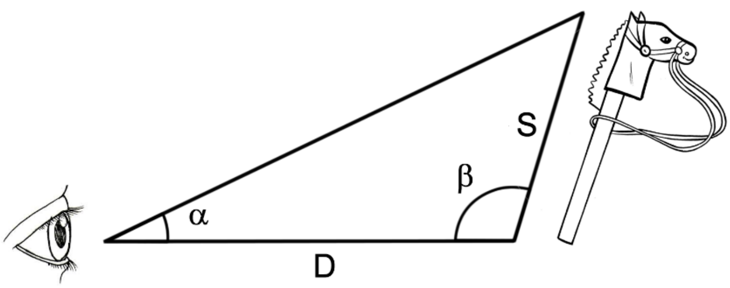

Figure 2- Size (S), distance (D) and angular size (α) geometry

If the object is perpendicular and the angle α is sufficiently small, this relation can be approximated to the following:

$$\alpha \approx \frac{S}{D}$$

It follows that a given visual angle can be produced by infinitely combinations of size and distance. It also follows that visual angle and size can be used to infer distance, and visual angle and distance to infer size. As we have seen in section 1.1, these relations were known since ancient time and proved to be very appealing as explanations of size constancy. As Kilpatrick and Ittelson noted (1953) “Such applications of Euclidean plane geometry to psychological relationships, with their consequent, often uncritical, mixture of physical and psychological variables, offer attractively simple solutions”. What the size-distance invariance hypothesis (SDIH) suggests is that the above mentioned geometric relation between size and distance is also a perceptual relation, that is, the ratio between perceived size and perceived distance is constant for a given visual angle.

This hypothesis has been at the center of numerous empirical studies that gave controversial results. Some of them have found that perceived size and perceived distance are actually related to visual angle in the way that the hypothesis predicts (Epstein, 1965; Flock, 1965; Gogel, 1971; Hartman, 1964; Rump, 1961; Ueno, 1962). Kilpatrick and Ittleson (1953), however, cite a variety of studies where the predictions of the SDIH were not confiremd. Many studies measured the relation between perceived size and perceived distance and have generally found weak support for a constant psychological relation between the two. In some cases, perceived distance was found to change in the opposite direction than predicted by the SDIH (Gruber, 1954; Higashiyama, 1977; Higashiyama, 1979; Jenkin & Hyman, 1959; Rump, 1961; Ueno, 1962). According to these results for example, of two objects subtending the same visual angle, one may appear to be both larger and closer than the other. Gruber (1954) has called this effect the size-distance paradox.

Some results are only partially in accordance with SDIH. Perceived size and perceived distance have been found to change in the direction predicted by the invariance hypothesis, but not to the amounts predicted by the geometric size-distance relation (Baird & Biersdorf, 1967; Epstein & Landauer, 1969; Vogel & Teghtsoonian, 1972).

This, as suggested by Joynson (1949), makes suspect that there is not a direct functional connection between perceived size and perceived distance. It is also possible that perceived size and perceived distance are determined by independent perceptual processes, and the fact that they are linked by a geometric relation tend to maintain their perceptual relation. Oyama (1977), for example, examined the causal relations within several sets of data from size-distance experiments and found that in most cases the results could be best explained by assuming that perceived size and perceived distance were independently determined by the stimulus situation. For a few subjects in some circumstances, however, he found indications either that perceived distance exerted a causal influence on perceived size or that perceived size exerted a causal influence on perceived distance.

Some studies have compared average group results with results form single participants to see if the relation between perceived size and perceived distance is present at both levels. Results, however, generally showed weakly or no correlation at all between perceived size and perceived distance (Epstein, 1963; Epstein, 1965; Gruber, 1954; Gruber, 1956; Over, 1963).

An other common hypothesis about the size-distance invariance relation postulates that the perceived sizes of an object is derived from its perceived distance by scaling the object visual angle which value is assumed to be accurate enough (Epstein, 1973). This "taking distance into account" hypothesis, however, does not takes into account the contextual determination of perceived size that derives from the optic array and static indices. This type of static information, as Gillam suggests (Gillam, 1995), have shown that the size of an object often can be specified independently of its distance, so that the theoretical need to explain size perception as being derived from distance perception is correspondingly diminished.

A phenomenon that is sometimes invoked to support the size-distance invariance hypothesis is the Emmert's law. It happens when an afterimage is looked against a surface placed at a certain distance. The perceived size of the afterimage is approximately proportional to the perceived distance of the surface on which it is projected. Since the visual angle of the afterimage is constant, the fact that the perceived size is proportional to changes in its perceived distance seems in accordance with the size-distance invariance hypothesis. The extensive literature concerning the Emmert's law is reviewed by Epstein et al. (1961). As pointed out by J. Hochberg (1971), this phenomenon does not provide any proof of a strict relation between perceived size and distance and leaves open the possibility of an independent determination of perceived size and distance as we have discussed above.

To conclude, what emerges from the literature is that the size-distance invariance hypothesis should not be regarded as an overriding principle of size and distance perception. Rather, the geometric size-distance relation must be seen as one source of information among many other and can be expected to exert an influence on perceptual judgments of size and distance that will depend both on the other information available and on the perceptual strategies of the subject.

Early reviews of the empirical studies on the SDIH can be found in Epstein, Park, and Casey (1961) and Hochberg (1971). A more detailed and complete review, instead, can be found in Sedgwick (1986).

1.2. Factors affecting size constancy

Four main factor affecting size constancy have been studied in the literature. One is the availability of depth cues. More depth cues are available and the more size perception approximates to the real size. A second factor is age. Size constancy improves during development and become stable in adulthood with a slight tendency to overconstnacy. The third factor is familiarity. Knowing an object will influence its size estimate. The fourth and most powerful factor is experimental instructions. Size constancy varies a lot depending on how instructions are given in the experimental procedure.

1.2.1. Depth cues

The effect of depth cues on size constancy was first studied in a classical research by Holway and Boring (1941).

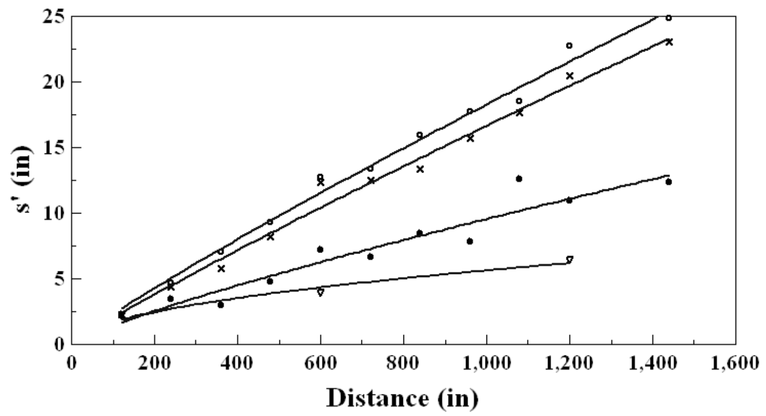

Figure 3- Classical experiment by Holway and Boring (1941). Progressive reduction of depth cue reduces size constancy toward angular size.

Five observers were asked to match the size of a circular test target presented at distances ranging from 10 to 120 ft. The test stimulus subtended always the same visual angle. Depth information varied across four experimental conditions. In the full cue conditions, the stimuli were viewed binocularly. In the three reduced cue conditions stimuli were viewed 1) monocularly, 2) monocularly through an artificial pupil and 3) monocularly through an artificial pupil and a long reduction tunnel who limited the peripheral view. Size constancy degraded alongside depth cue reduction. Interestingly, even in the worse cue condition, performance never matched perfect angular size.

Subsequent studies demonstrated that the original experimental setup might have contained residual depth cue coming from small light reflectance and textures. Lichten and Lurie (1950) managed to obtain perfect angular size matches by eliminating residual light reflection.

1.2.2. Age differences

The interest in the developmental aspects of size constancy was revived by Zeigler and Leibowitz (1957) who studied 7 to 9 year old boys in comparison to adults in judging apparent size. The boys showed strong underconstancy especially with far stimuli. Numerous other studies have reported the tendency for young subjects to display undercontsancy. Rapaport (1967) found differences in size judgment for 13 to 20 years old boys when different instruction were given. Objective instruction resulted in more overconstancy than apparent instructions. Judgments of boys between 5 and 11 years, instead, were insensible to instructions.

Other researches have found the tendency for youngest participants to display underconstancy and an increased tendency for constancy and overconstancy as age increases (Brislin & Leibowitz, 1970; Cohen, Hershkowitz, & Chodack, 1958; Leibowitz, Pollard, & Dickson, 1967).

Size constancy have also been tested in infants for example in Bower (1966), Day and McKenzie (1981), McKenzie et al. (1980), Granrud (2006), Slater et al. (1990). The method used to investigate size constancy in infants is usually based on conditioning and habituation. For example, if an infant is conditioned to respond to a cube of a certain size and show the same response if the cube is placed at different distances one can conclude that some form of size constancy takes place. All these studies mentioned above used similar procedures and found that infants show size constancy behavior.

1.2.3. Familiarity

If the size of a familiar object is know in advance it is logical to expect that this information will be used to judge distance. Distance judgment, in this particular case, should be somehow “overridden” by previous knowledge.

Some studies confirmed this idea. Baird (1963) showed objects of different sizes under reduced cue conditions and told participants that the objects where of the same size of familiar objects. The resulting distance estimates were consistent with the SDIH, and the known size was somehow used to infer distance. Similar results were replicated in other studies (Fitzpatrick, Pasnak, & Tyer, 1982; Gogel, 1968; Gogel & Mertens, 1967; Higashiyama & Kitano, 1991; Park & Michaelson, 1974).

Gogel (1969; 1990; 1998; Gogel & Silva, 1987) and others (Predebon, 1987; 1990; 1993; 1992) (Haber & Levin, 2001) have proposed a more complex interpretation of judgments based on familiar size questioning the fact that the size is actually perceived in accordance with the known size of the familiar object. They have introduced the distinction between sensory and cognitive determinants of spatial judgments and hypothesized that in the condition of familiar size the judgments is based on a higher cognitive response that infer size based on previous knowledge. The cognitive layer operate on top of sensory processes in an attempt to maintain perceptual coherence.

1.2.4. Instructions

One of the most powerful variable affecting size constancy performance in experiments concerns the instructions given to participants to carry out their size judgments. Four main types of instructions have been used in the literature on size constancy: objective, apparent, projective and perspective. In the objective instructions, participants of an experiment are asked to judge the real physical size of an object. In the apparent instructions, they are asked to judge the angular size. In the projective instructions they are asked to imagine a plane in front of them on which the image of the object is projected and then to judge the size of the projected object. In the perspective instructions, participants are explicitly asked to take in consideration the laws of perspective (Carlson, 1962).

One of the first example of the effects of instruction can be found in the work of Gilinsky (1955) who found that objective instructions produced overconstancy with respect to projective instructions. Other works confirmed these results (Carlson, 1960; Carlson & Tassone, 1967; Chalmers, 1952; Jenkin N. , 1957; 1959; Smith, 1953). Apparent instructions, on the other hand, have generally produced performances that approximate constancy or underconstancy (Carlson, 1960; Carlson & Tassone, 1967).

1.3. Conclusions

The classical literature on size constancy is characterized by a static model of visual perception where size is more or less implicitly viewed as an objective property of the external world that must be recovered combining the information about angular size and distance. The perceived size of an object is seen as an approximation of real physical size and is influenced by a series of factors that affect its precision and accuracy.

2. Towards an enactive approach to size constancy

In the previous chapter, I gave an overview of the classical literature on size constancy, which is mainly psychological. It is my conviction that, at least in part, the advancement of research on size constancy is limited by two main factors. First, the implicit assumption of a static model of visual perception. Secondly, the lack of a cognitive science perspective and an interdisciplinary effort to understand the phenomenon from different point of views.

The prototypical size constancy experiment used in the literature employs a static observer looking at static stimuli. There have been only few attempts to study size constancy during motion, or in relation with purposive behaviour (I review some of these studies in section 2.2). This “stronghold of the static model” (Johansson, 1977) is not a prerogative of size constancy research but still pervades many areas of psychology and cognitive science including artificial intelligence and robotics. Moreover, there have been a lack of interest in size constancy outside the psychological domain. The few non-psychological works on size constancy that I discuss in section 2.4 and 2.5 are more multi-disciplinary than inter-disciplinary because they lack a common conceptual framework and are not reciprocally informed to a good extent. The need for a cognitive science perspective is well portrayed by Thompson (2007) who notes that what “set cognitive science apart from earlier approaches in psychology and philosophy, was the goal of making explicit the principles and mechanisms of cognition”.

Given these premises, the aim of my work is to suggest an interdisciplinary approach to size constancy under the conceptual framework of the enactive cognitive science, to explore the embodied, situated and dynamical aspects of size constancy that have been largely disregarded in the classical literature.

In this chapter, I briefly recall some of the basic principles of the enactive approach to cognition and then I review some research that points in that direction, such as the works on kinetic size constancy, the ecological approach to perception, the Evolutionary Robotics methodology and some comparative studies. These researches offer uncommon perspectives on size constancy and can provide the basis for what I call "the enactive approach to size constancy".

2.1. The Enactive Approach to cognition

The enactive approach to cognition was conceptualized by Valera, Thompson and Rosch in their book "The Embodied Mind" (1991). These authors have tried to build a unified framework to understand cognition where the dynamical interaction among the brain, the body and the environment plays a central role. Autonomy, sense-making, emergence and embodiment are some of the key ideas involved (Thompson, 2005).

Autonomy refers to the ability of living organisms to be self maintaining and self regulating but, in the enactive view, the concept extends beyond the biological processes and at the higher levels involves cognition. Cognitive structures are the higher expression of the self-organizing and self-maintaining processes that emerges from the sensory motor interaction of the organism with the world. Resilience and adaptation are two of the resulting features that an autonomous system possesses.

The concept of sense-making expresses the constructivist view of the enactive approach by which meaning and information are not prebuilt in a cognitive system, as a pure cognitivist approach would suggest, nor are they simply extracted from the external world, as in the direct perception theory of Gibson. Perception and knowledge result from the mutual dynamical interaction of an organism with its environment.

Emergence emphasises the fact that cognition is not breakable into single components or processes that can be studied separately, and brain activity cannot be reduced to neural processes. On a larger perspective, Cognition cannot be studied in separation from the body and the environment.

Embodiment is a key concept in the enactive view. Cognition is conceptualized as embodied action. The role of the body is not just that of influencing and shaping cognition. The body takes part in the sensory motor coupling between an organism and its environment that is considered the essence of cognition.

The heuristic potential and explanatory power of these concepts can be shown when they are applied to the study of a single phenomenon. A good example is the analysis of comparative Colour vision discussed in the work of Thompson, Palacios and Varela

(1992). They compare works on colour vision from different disciplines and make it a case study in cognitive science, showing how the enactive approach to cognition can be applied to the problem of colour constancy.

2.2. Kinetic Size Constancy

Size constancy as a perceptual/cognitive process can be viewed as the solution to the problem of angular size variability caused by object motion, observer motion or both. Since motion plays a central role in this phenomenon, it is rather astonishing, that nearly all research on size constancy has been conducted displaying static objects to static observers. This has been pointed out by Johansson (1977) who observed: "Consult the classical sources like Thouless(1931), Holaday (1933), Koffka (1935), Boring (1942), Stavrianos (1945), Woodworth (1938) or the newer ones like Woodworth and Scholsberg(1945), Epstein and Park (1963), Epstein, Park, and Casey (1961), Graham (1965), Day (1969), or Murch(1973). Rarely do we find treatment of kinetic constancies; that is, spatial constancy during perceived motion. This neglect must be regarded as rather astonishing. In everyday life perceptual object constancy during motion play a most essential role for purposive behaviour. The stronghold of the static model is nowhere more evident than in Brunswik's writing. Brunswik stressed ecological validity, yet he neglected to consider kinetic situations."
The same point has been made few years later by Noguchi and Taya (1981) that restated the problem of static experimental conditions: "In general, studies of spatial constancy have attempted to explain the perceptual structure of three-dimensional space through analyses of static displays, while neglecting their dynamic aspects during perceived motion**.** On the other hand, studies on perceived motion have mostly been concerned with angular motion in two-dimensional space, neglecting motion in depth. Taking a unified approach, in order to bridge the gap between these two separate research areas, we are proposing that size constancy in three-dimensional motion, which is called kinetic size constancy (Johansson 1977) should be more intensively investigated".

At the time that Johansson writes, there have been already some attempts to study size constancy during motion, or Kinetic Size constancy as Johansson defines it. Radial motion of circular objects was studied by Ittelson (1951), Gregory and Ross (1964), Brosgole et al. (1976). Noguchi and Taya (1981) were the first to study Kinetic Size constancy in a quantitative way. They measured both perceived size and perceived distance of a diamond shape luminous target that moved forth and back and then stopped at different distances from the subjects. Experiment was conducted both under monocular and binocular viewing conditions. They found that forward-motion facilitated a tendency to see an object with an approximately constant size and that, most importantly, size constancy was retained even under cue reduction conditions, in which static constancy usually become greatly impoverished.

Hershenson (1992) makes a step forward and states that the normal viewing condition involves kinetic stimulation and suggests the following kinetic invariance hypothesis (KIH): an expanding or contracting solid visual angle produces a constant perceived size and a changing perceived distance. In his view, the size distance invariance hypothesis, usually studied in stationary experimental situations, is a special case of the kinetic invariance hypothesis. Hershenson also provide some explanations of the size distance paradox and the moon illusion by attributing them to the “unnatural” static condition in which they are observed.

I consider kinetic size constancy as a step forward in the direction of an enactive view because it considers the phenomenon in a dynamical context. Another step forward, which I have tried to do with my experiment described in chapter 4, is to consider the reciprocal interaction between the perceiver and the environment.

2.3. Direct perception and optic flow

The ecological approaches to perception (Gibson J. J., 1950; 1966; 1979) is an important and influential exception to the static view of perception that dominated research on visual perception in the XX century. According to Gibson, we receive a lot of “ready-made” information about the invariant properties of the environment without the need of complex information processing. This information must be found in the ratios and the gradients of the optic flow, and visual stimulation must be looked more as a motion picture than a static collection of single fames. In this perspective, perception is conceived as direct detection of information already present at proximal level.

A prototypical definition of direct perception mechanism has been proposed by Sverker Runeson (1977) with the metaphor of “Smart Mechanisms”. Runeson distinguishes between “rote” and “smart” mechanisms and proposes the polar planimeter as an example of the latter. The polar planimeter is a mechanical instrument similar to a compass, invented by the German mechanic Jacob Amsler and is used to measure the area of irregular shapes. The measurement procedure is really simple. It consists in following the outline of the shape with the index attached to one of the two arms of the instrument (see Figure 4), and then reading the final measure on the measuring roller. What strikes is that the planimeter is a simple object with just two arms, hinges and a wheel. It does not contain strange mechanical parts and most importantly, it does not seem to rely on any elaborated information processing mechanism. The other striking characteristic of this smart mechanism is that measurement of area is very precise while linear measurement is not. This sounds as paradoxical if one think at area measurement as a complex calculation based on more simple linear measurements. The smart mechanism could be taken as an alternative metaphor to explain cognition in place of the classical information processing approach.

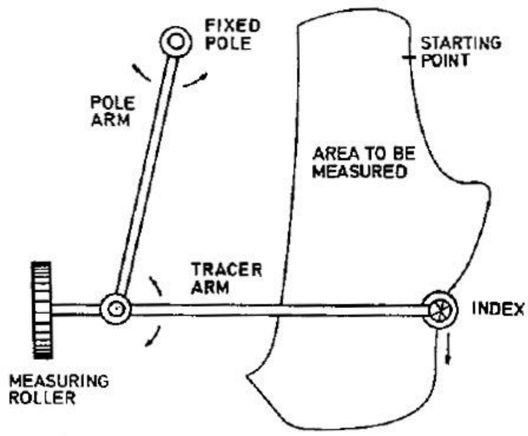

Figure 4 - Main parts of a Polar Planimeter

The work of Gibson, inspired a stream of research in optic flow especially in the field of Engineering and Robotics with detailed analysis of motion vector fields and models of visually guided behaviours (Koenderink, 1986; Longuet-Higgins & Prazdny, 1980; Prazdny, 1983; Ullman, 1979).

The ecological approach, especially in its radial and nearly provocative conception of direct perception, shifts the attention from the brain to the external world and stimulates the reconsideration of the relationship between the organism and the environment. The original research program and its subsequent developments go in the direction of the enactive approach because they highlight the links between action and perception that are not conceptualized as separate but as intertwined processes.

Another important and influential concept of the ecological approach to perception is the concept of *affordances* that implies a deep link between perception and action. According to Gibson, objects provide not only visual information about their shape and structure but also about their possible uses and ways of interaction. A chair, for example, affords sitting, a street affords walking and so on. Affordances are not universally defined but depend on the perceiver functional characteristics and physical constraints. Perception, therefore, results from the animal-world relationship.

2.4. Evolutionary Robotics

As Nolfi and Floreano described it (Nolfi & Floreano, Evolutionary robotics, 2000), Evolutionary Robotics (ER) is a "technique for the automatic creation of autonomous robots inspired by the Darwinian principle of selective reproduction of the fittest". In a typical evolutionary robotic experiment a robots, or a simulated agent, is placed in an environment with a specific task to carry out. The robot controller is a neural network that is evolved through a genetic algorithm in order to improve the robot performance in the task assigned. The criterion used to evaluate the robot performance is called fitness function.

One of the major advantages of using evolutionary robotics is that it does not require any prior knowledge about the tasks and their possible solutions. In fact, the programmer needs only to specify the general constrains imposed on the control system of the robot (i.e. the neural network architecture) and a fitness function for quantifying the robot's performance. The evolutionary process is left free to exploit the interactions between the robot and its environment for accomplishing the task and usually after few hundreds of generations the robot performance reaches an acceptable level.

By reproducing an environment-brain-organism model, Evolutionary Robotics is the methodology that more than other try to translate the principles of the Enactive Approach into a practical research methodology. The robot of an Evolutionary robotics experiment is *autonomous* in its environment and does not require human intervention and feedback of any kind. The neural controller and robot behaviour are not designed in advance but *emerges* as the result of an evolutionary process that is shaped by the interaction of the robot with its environment. The neural controller interacts with the environment through the robot sensors and actuators and, in this sense, it is an example of *embodiment*. Moreover, as the sense making principle suggests, the perceptual and knowledge capabilities of the robot, even if minimal, result from the mutual dynamical interaction of an (artificial) organism with its environment.

2.5. Size Constancy in lower vertebrates

Size constancy is of such a great ecological relevance that we might expect that most biological organisms, other than human, possess a constancy mechanism. Size-dependent food selection, evaluation of predator size and distance, foraging in different daylight conditions are some example of behaviours in which a constancy mechanism could be advantageous. If we look at the literature on animal behaviour, we can find some interesting studies showing constancy abilities (but also failures) even in lower vertebrates.

Size constancy has been studied in frogs and toads for example by Ingle (1968), Ingle and Cook (1977), Lettvin, Maturana, McCulloch and Pitts (1959). Ingle (1968) studied size-dependent pray selection and found that frogs show size constancy behaviour but in a limited distance range which corresponds approximately to the area in which they are able to snap their prey. These results have been confirmed in more extensive studies by Ingle and Cook (1977) and Ewert and Gebauer (1973) and are supported by the already cited classical study about the bug detectors by Lettvin, Maturana, McCulloch and Pitts.

Size constancy has also been studied in the fishes. Douglas et al. (1988) trained fishes to discriminate between two targets of different size viewed at the same distance. In a test the two target were positioned in order to subtend the same visual angel. Fishes were able to discriminate the targets based on their real size instead of the apparent size. Another interesting experiment was made on the archerfish (Schuster, Rossel, Schmidtmann, Jager, & Poralla, 2004). Schuster et al. placed discs of different sizes on glass plates at different distances from the water surface. The archerfish showed the ability to fire at discs based on their physical size.

The utility of the comparative perspective in the enactive approach has already been mentioned in section 2.1 when describing the work of Thompson et al (1992) which provides a detailed description of how animal studies contributes to widen our view of cognition which sometimes is too much anthropocentric.

2.6. Conclusions

In this chapter, I have outlined an enactive approach to size constancy based on an interdisciplinary effort to understand this phenomenon with an emphasis on the dynamical, embodied and situated aspects of cognition. I have also indicated some existing research areas and methodologies, like kinetic size constancy, Evolutionary Robotics and Comparative Psychology, which point in that direction.

A similar interdisciplinary effort has been fruitfully adopted in studying colour vision and is described by some of the founders on the enactive approach to cognition (Thompson, Palacios, & Varela, 1992). The experimental work that I describe in the next chapters is a small attempt to apply the same principles in the study of size constancy.

3. Size constancy: insights from Evolutionary Robotics and Artificial Life

Evolutionary Robotics and Artificial Life are research methodologies that uses evolutionary computation to generate robots that adapt to their environment through a process that mimics natural evolution. They put a strong emphasis on embodiment and situatedness, and on the close interaction among the brain, body, and environment, which is considered crucial for the emergence of adaptive behaviours and cognitive processes (Clark A. , 1997; Chiel & Beer, 1997; Nolfi & Floreano, 2002). In this respect, they incorporate most of the basic principles of the enactive approach to cognition.

In this chapter, I introduce these techniques and I review some of the researches done in these fields that is strictly related to the problem of size constancy. Then I describe the model that I have created to explore size constancy with an Artificial Life simulation.

3.1. Evolutionary Robotics and Artificial Life

Evolutionary Robotics (ER) and Artificial Life (AL) use genetic algorithms to evolve the controllers of robots or simulated agents that interact with real or artificial environments (Nolfi & Floreano, 2000). The difference between these two techniques is that Artificial Life uses only computer simulation and is less concerned with the reproduction of the evolved behaviours in a real world setup.

The robot controllers are usually neural networks with a certain amount of neural units whose connection weights are not specified by the experimenter but are shaped by the genetic algorithms. The neural networks are initially generated with random weights. Successive generations of robots are left to interact with their environments in order to accomplish a specific task assigned by the experimenter. At the end of each generation, the performance is measured based on a fitness function, and then the best robots are selected, mutated, and used to generate a new population of robots. This process continues for several generations until a satisfactory level of fitness is reached.

The main advantage of using this technique is that no prior knowledge is required about how the robot should solve the task. One has only to specify a fitness function for evaluating the robot performance and the constraints imposed on the controller and the environment without having to make strong assumptions on how the robot should behave and what kind of process should take place inside the neural controller. The solution is the result of a self-organizing process that arises from the interaction between the robot and the environment. As clearly demonstrated in Nolfi and Floreano (2000), even in simple obstacle avoidance tasks, the evolved neural controllers are better than hand crafted ones inspired by Braitenberg's vehicles (1986).

The emerged solution can be analysed with different techniques and typically involves a neuroethological approach (Cliff D. , 1991; Cliff D. , 1991) where the behaviour of the robots/agents is analysed along with the activity of the neural controller. Sometimes is useful to test the evolved agents in different experimental conditions and to modify and lesion the neural network to understand its functioning.

With AL and ER modeling techniques, it is possible to study how a neural like parallel distributed system can solve a particular cognitive task without prior knowledge or hypothesis about its structure and information processing. Like biological evolution, AL and ER techniques have an impressive ability to find optimal behavioural solution in highly dynamical environments with little computational power. Results from this kind of experiments are usually very useful when compared to existing hypothesis and models. As stated by McClelland (2009) “Models are not intended to capture fully the processes they attempt to elucidate. Rather, they are explorations of ideas about the nature of cognitive processes. In these explorations, simplification is essential. Through simplification, the implications of the central ideas become more transparent”

In the next paragraph, I describe more in depth examples of how evolutionary robotics research can be applied to tackle problems like size constancy.

3.2. Size constancy in evolved autonomous robots: the Aliasing Problem

The size constancy problem has been studied in Evolutionary Robotics as one of the foundational aspects of robot-environment interaction. However, we will not find any reference to the term "size constancy" in this literature. The key terms to look for are "aliasing" and "Type I-Type II" problems. The sensory aliasing refers to the situation where, given a robot position in the environment, different objects correspond to the same sensory pattern. This is a general problem that is not specifically related to object size but could occur with all physical features like colour, shape and location.

In the case of the visual detection of size, the problem occurs when object of different size produce the same image size on the robots visual system. The aliasing problem is closely related to the Type I and Type II problems raised by Clark and Thorntorn (1997). To put it simply, Type I problems are those in which the robot response can be built with a simple input-output mapping. Suppose we have a robot that has to react differently to object of different sizes. If an object size corresponds to a set of specific input pattern, the problem becomes that of creating a sort of correspondence table in which the various patterns are associated to different responses. This cannot be done in the case of the aliasing problem because the same input could correspond to objects of different sizes. In this case we have a Type II problem and the robot response must be more complex than a simple input-output mapping. This is the case where sensory motor coupling can solve the problem. This will be clearer showing some examples of research on robot size discrimination.

Nolfi and Marocco (2000) has made some experiments with evolved robots that were asked to visually discriminate between objects of the same shape but different sizes by navigating toward one of the two.

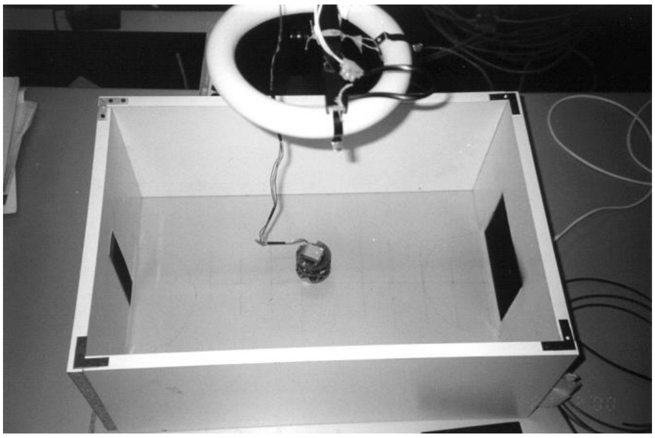

Figure 5 - Experiment by Nolfi and Marocco (2000)

The mobile robot was Khepera robot equipped with a vision module and placed in an environment like the one shown in Figure 5. It was a rectangular arena surrounded by white walls with two black stripes of different sizes. The robot task was to approach the bigger but not the smaller stripe. In other words, it had to discriminate the two objects visually. One interesting aspect of this task was that often the robot received the same sensory patterns from both the big and the small stripe. At certain distances, the big stripe looked of the same size of the small stripe at a closer distance Therefore the robot had to solve a size constancy problem.

The sensory system was based on eight infrared sensors distributed around one side of the body and a linear camera. The infrared sensors could detect the walls at a maximum distance of approximately 4 cm. The linear camera consists of one array of 64 photoreceptors providing a linear image composed of 64 pixels of 256 gray-levels each and subtending a total view-angle of 36°.

The robot controller consisted of a simple feed-forward neural network, with 14 sensory neurons encoding the state of 6 frontal infrared sensors, 8 photoreceptors of the camera (i.e. only the 6 frontal infrared sensors and only 8 evenly spaced photoreceptors out of the 64 provided by the camera were used) and two motor neurons encoding the speed of the two wheels.

The evolved individuals solved the problem by exploiting sensory-motor coordination. The robot rotated clockwise until it started to perceive one of the two objects with the camera. At this point, it started to move forward by slightly turning clockwise. This allowed the robot to loose visual contact with the object after some time. At this point the robot started to rotate clockwise again and then to move toward the other object for a while by slightly turning clockwise. The robot thus moved back and forth between the two objects. However, given that it lost visual contact more slowly with the larger and more distant than with smaller and closer objects, it tended to move more toward B than toward S (see the sub-parts of the trajectory indicated with empty and full arrows respectively). This in turn allowed the robot to finally reach B after a certain number of back and forth segments (where each segment consisted in a certain number of forward movements toward one of the two objects).

More recently, Williams & Beer (2010) described an artificial life model in which a simulated agent was evolved to discriminate between small and big circles.

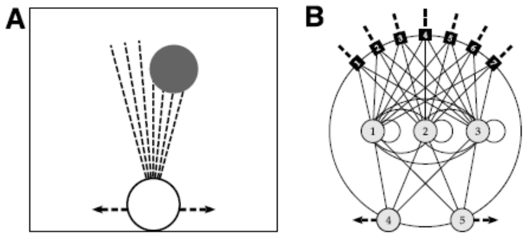

Figure 6 - Simulation by Williams and Beer (2010)

In this case, the agent could not freely move in the environment but could only move laterally and should detect the size of circles falling from the top of the environment, by catching the small circles and to avoid the big ones. The neural controller used by these authors was a Continuous Time Recurrent Neural Network with seven inputs, three internal neurons and two motor outputs.

At the end of the evolution process the best individuals showed an impressive performance with 90% of correct responses or higher.

3.3. A functional definition of Size Constancy

Size constancy is usually defined as a perceptual process that allows us to *perceive* the physical size of an object. This, and other similar definitions, put the emphasis on the (unknown) perceptual processes allowing constancy while neglegting behavioural and functional aspects. This is common to most of the recent theories and computational models of perceptual constancy. They focus on the presumed underlying mechanisms, but tell us very little about how they translate into functional behaviours. Some examples of constancy mechanisms proposed in the literature are mental rotation (Jolicoeur & Humphrey, 1998), perceptual compensation (Bridgeman, 2010), 3D reconstruction (Edelman & Weinshall, 1998), and hierarchical feature extraction (Foldiak, 1998). If we consider the comparative studies on size constancy the term "perceptual" becomes inappropriate, and even more so when we refer to evolutionary robotics models like the ones described in the previous paragraph. Moreover, it is not only a matter of definitions. As claimed by Ittelson (1951), "Any complete theory of perceptual constancy must encompass all its aspects" and therefore should consider both the mechanisms and the behaviours.

An alternative functional definition of size constancy can be inspired by the work of Brunswik (1940). In a size constancy experiment he placed a set of wooden cubes of different sizes in front of an observer at distances of 2,4,6,8 and 10 meters. The observer was then asked to assess the size of some cubes comparing them with a scale of predefined cubes set at 12 meters. He then calculated thre types of correlations: 1) the *distal-proximal correlation*, calculated between the physical size and the angular size 2) the *proximal-perceptual correlation*, between angular size and perceptual size 3) the *perceptual-distal correlation*, between the perceptual size and the physical size. He found a high value in the perceptual-distal correlation (0.98) but low values in the distal-proximal (0.10) and proximal-perceptual (0.26). This work put the emphasis on the functional aspects of size constancy and suggest a correlational definition. According to this definition, any behavior that is highly correlated with the physical size of objects is to be considered a manifestation of a size constancy ability.

3.4. An Artificial Life model of Size Constancy

In this section, I describe some Artificial Life simulations in which a situated model agent controlled by a feed-forward neural network has to solve a simple categorization task involving size constancy abilities in an online fashion. The results confirm previous findings (Nolfi & Marocco, 2000; Williams & Beer, 2010) showing that even a simple neural controller without internal recurrent dynamics is capable of solving a non-trivial size categorization task by exploiting the dynamical interaction of the agent with its environment. Even if at an early stage, this work suggests two possible implications for the study of size constancy and perceptual constancy in general. First, approaching the problem from a functional point of view may open new perspectives on the possible underlying mechanisms. Second, the adoption of an embodied and situated approach may help to explore the links between size constancy as a process and size constancy as a behaviour.

The experimental setup proposed here is a computer simulation that represents a simplified model of a brain-body-environment system with the following characteristics:

1) A simulated agent with a sensory-motor system acts in a virtual environment

2) Sensory input and its variations are coherent with the environment structure and its laws

3) Variation of the input is partly determined by the motor system

4) The neural controller of the agent evolves through a Genetic Algorithm, with no prior hypothesis about its functioning

5) The fitness function used to evolve the neural controller is based on the agent performance in a task that requires some degree of size constancy

The main goal of this experimental setup is to provide an embodied and situated context in which a simulated agent can evolve a size constancy behaviour.

3.4.1. Simulation Environment

The simulation environment is described in Figure 7. A simulated agent moves in a 2D square arena with sides of length 60 populated with circles randomly placed in a grid of 5x5 cells positions (Figure 7 top part). The diameters of the circles can be small (0.5) or big (1.0). There are 10 small and 10 big circles for a total amount of 20 objects. The agent (see Figure 7 bottom part), represented by a small circle of size 0.5, is provided with a linear array of visual receptors by which it is able to “see” objects in front of it with a field of view of 60°. The activation of the receptors is calculated with a perspective projection of the objects in the field of view of the agent so that a near small circle and a distant one can have the same retinal projection (as depicted in Figure 7). Distance cues are provided through a sort of “fog effect” (not shown) that makes the circles appear lighter and lighter as the viewing distance increases. The fog effect and the grid configuration of objects make the agent input clean and avoid cluttered input patterns. The fog effect in particular avoids that too many objects are visualized at the same time on the retina. This would require the agent to develop some kind of attentional mechanism that would deserve a dedicated work.

The controller of the agent is a three layer feed-forward neural network. The input layer is the above mentioned linear retina with 30 receptors whose activations range from 0.0 to 1.0. The hidden layer has 10 units and the motor layer consists of four output units.

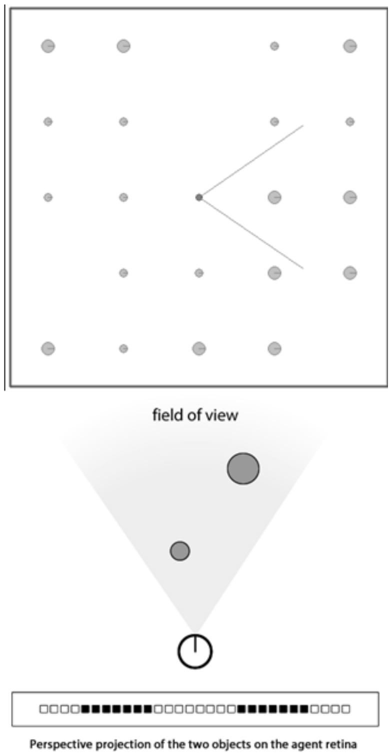

Figure 7 – Simulation environment

Both hidden and motor layer neurons use a sigmoid activation function. Each layer is fully connected with the next one. Therefore, there are 300 input-hidden weights (30x10) and 40 hidden-output weights (10x4). Figure 8 shows the structure of the neural network.

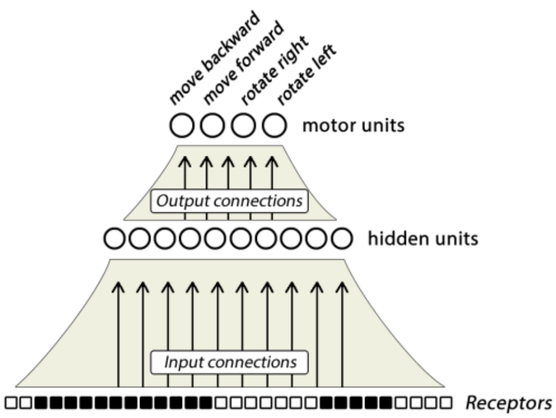

Figure 8 - Neural network controller of the agents

The agent can move forward or backward with a certain velocity and can rotate around its centre to change direction. The four motor units control the movement of the agents with two couples of opposing real units. The linear movement of the robot is determined by the results of two opposing units that determines the forward and backward linear velocities. The agent moves forward if the output of the forward velocity unit is higher than the backward one, and vice versa. The agent direction is determined by two opponent units controlling the right and left angular velocity.

3.4.2. Task

The goal of the agent is to hit as much small circles as possible and to avoid the big ones during its lifetime that lasts 10,000 simulation steps. Circles hit by the agent are removed from the environment.

The simulation environment has been designed to reproduce the same relationship between angular size and distance that characterizes the size constancy problem. The retinal extent of a circle is not correlated with its size but depends on the distance from the agent. To accomplish the discrimination task, the artificial agent must develop a constancy mechanism able to exploit the relation between angular size and distance.

The task is similar to the one proposed in the aleready mentioned works by Scheier, Pfeifer, Kunyioshi (1998), Nolfi and Marocco (2000) and more recently by Williams and Beer (2010). The motor system proposed here, however, is different allowing for fast forward and backward linear movements. Moreover, the task is not based on single separate trials but requires an online behaviour in which the discriminations occur seamlessly during the entire life of the robot without resetting the experimental setup after each robot response.

3.4.3. Genetic Algorithm

A genetic algorithm is used to evolve the weights of the neural network to solve the simple size discrimination task described above. As mentioned before, the goal of the agent is to hit as much small objects as possible and to avoid the big ones. Objects hit by the agent are removed from the environment. The fitness function is calculated with the following formula:

$F = Cs - Cb$

where Cs and Cb are the number of small and big circles hit at the end of the agent life. Since there are a total of 10 small circles and 10 big ones, the highest fitness score is 10 and the lowest is -10. The evolutionary experiment consists in evolving the weights of the neural controllers in a population of 100 agents for 100 generations with a selection criterion based on the fitness function described before.

The weights of the neural networks in the first generation are initialized in the range (-1/sqrt(d), +1/sqrt(d)) where d is the number of input to each neuron. When all the individuals of one generation have been tested, they are sorted based on their fitness scores and the 20% of the best individuals are selected to produce the next generation of agents. The genetic operator consists of a mutation mechanism that changes 10% of the weights of the neural network adding a random number between -0.5 and +0.5. The genetic algorithm uses elitist selection allowing the best individual of one generation to carry over to the next generation with unaltered connection weights.

3.4.4. Results and discussion

Ten seeds of the same simulation were run with the genetic algorithm described above. The best results in terms of fitness curve and best fitness score achieved are shown in Figure 9 which shows the best and mean fitness along each generation of one of the best seeds. The fitness score of the best individual in the last generation reaches nine, which is nearly the maximum fitness score possible (ten). This score can be obtained approaching and hitting nine small circles and avoiding all the big ones (F=9-0), or hitting ten small circles and one big one (F=10-1).

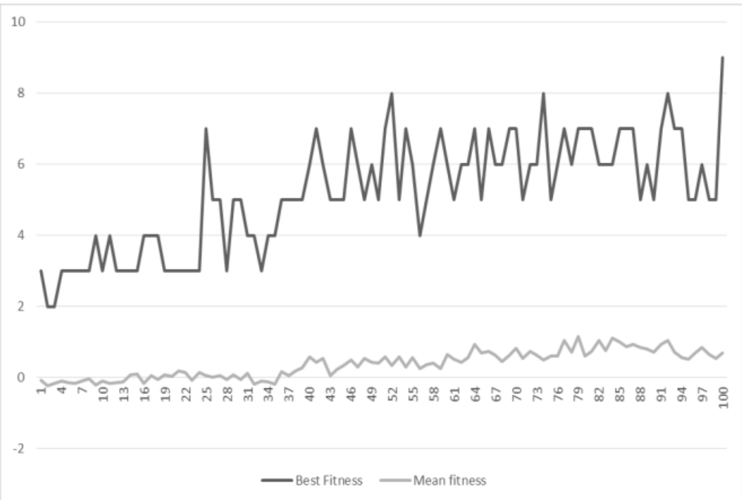

Figure 9 - Graph of the best and mean fitness for each of the 100 generations of the best run

To understand which was the case, and to analyse the agent behaviour I have visualized the movements of the best individual during its life cycle reproducing the same conditions of the last generation. The trial begins with the artificial agent at the center of the arena. The first behaviour displayed is a sort of exploratory movement that the agent performs by spinning around and translating in one direction. Spinning serves to scan the surrounding environment at 360 degrees in order to catch object in the visual field. Translation serves to spatially explore the environment. This behaviour continues until some object fall in the agents field of view. In this case the agent behaviour changes. If the object is too distant, the agent exploratory behaviour is only perturbed a little and tipiccaly this results in a change of the translation direction that favours a more complete environment exploration.

When an object falls in the field of view of the agent and is sufficienly close to it we can observe two different behaviours depending on the size of the object. In both cases the agent first approaches the object going straight towards it and then starts to oscillate back and forth. After a small oscillation the behaviour changes depending on the object size. In the case of small circles the agent continues to go forward and "hit" the circles causing it to disappear. Having no objects in the surrounding the agent starts again the exploration behavior. In the case of big circles, the oscillation starts earlier and lasts longer. After the oscillation the agent go backwards away from the circle at an angled direction with respect to the one used for approaching, and far enough not to be "captured" by the same object. Figure 10 and Figure 11 show the plot of the distance of the artificial agents from the object in both the small and big cases.

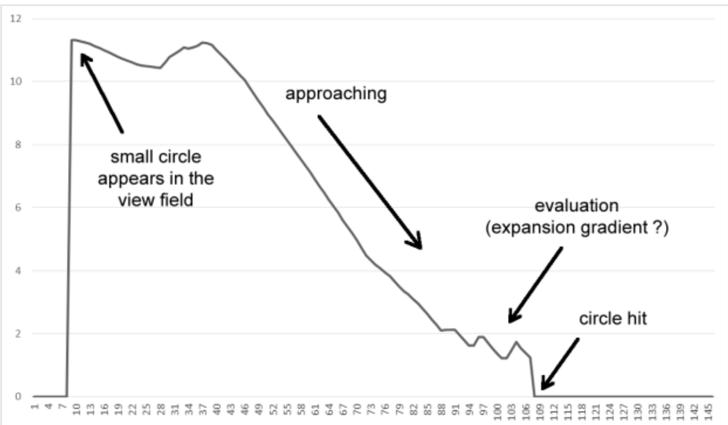

Figure 10 – Graph showing the plot of the artificial agent distance from a ***small circle*** *during the interaction phase that starts when the object appears in the view field while spinning around.*

Despite the simplicity of neural controller used in this experiment, the behavior of the agent is rather articulated and we can distinguish at least four different sub components: exploration, approaching, decision and action. Moreover, every component is not a one-shot atemporal response as the one of an abstract symbolic system, but has a time course that makes it more biologically plausible.

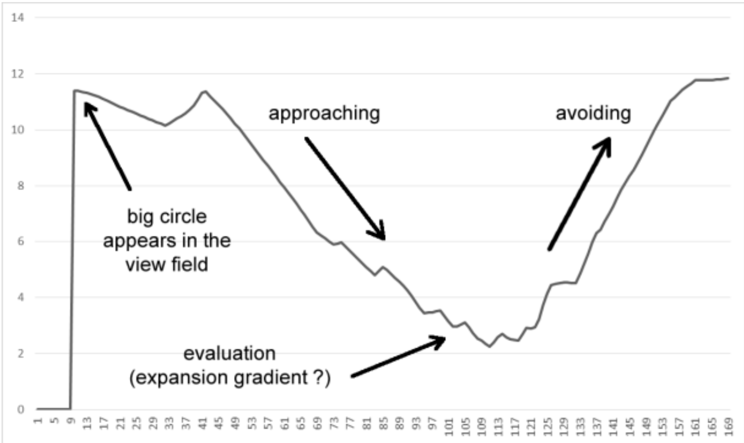

*Figure 11 - Graph showing the plot of the artificial agent distance from a **big circle** during the interaction phase that starts when the object appears in the view field while spinning around.*

Anyway, it is not the complexity in itself that makes the final behavior interesting. What is remarkable is the fact that it emerges from a simple feed-forward neural network that has no recurrent units and no internal states, and is therefore not capable of complex information processing like the one that seems to be required here. The complexity of the task has been demonstrated by Nolfi (1997; 1998; 2002) who trained three types of feedforward neural networks to discriminate between static input configurations showing small and big circles at different distances. The neural networks were trained with a powerful back-propagation algorithm and three different architectures were tested: a perceptron, a two layers architecture with 4 hidden units, and two layer architecture with 8 hidden units. None of the three network reached more than 8% of correct responses.

The apparent paradoxical result of the artificial life simulation can be explained if we consider that the neural network is not isolated as in the Nolfi experiment, but is part of a brain-body-environment system. This model, even if minimal, reproduces the dynamics of an embodied and situated cognitive system whose sensor and motor apparatus allow it to interact with its environment (Figure 12). Each input, at a given time, produces an output that is used to move the agent. The agent movement, in turn, changes the next input, which produces a new output and so on. It is this sensory motor circularity that generate the complex dynamical behavior shown by the agent.

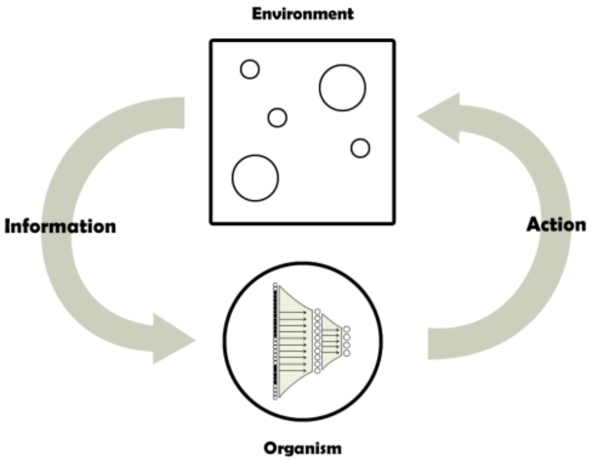

Figure 12 - Organism-Environment relationship

3.5. Conclusions

I described an artificial life simulation in which a simulated agent controlled by an evolved neural network shows size constancy abilities in solving a simple categorization task. Further analysis are required to better understand what happens inside the neural controller and to explain the agent behaviour in more detail. The robustness of the behavior must be tested in different environmental conditions, with different starting position and with different objects arrangement. It would be also interesting to understand what happen in the oscillating phase. An interesting hypothesis, is that the agent performs some kind of assessment of the expansion gradient which, since it must be comparable between the objects, is performed at the same distance from the objects and at a close distance to obtain best results.

The model proposed here and the previously mentioned works with real and simulated robots (Scheier, Pfeifer, & Kunyioshi, 1998; Nolfi & Floreano, 2000; Williams & Beer, 2010), beyond their differences and similarities, constitute a valuable contribution to the understanding of the size constancy problem. As Tom Zimke (2003) notes “instead of focusing on one experiment or a few experiments with a real robot, many questions are more suitably addressed through a large number of experiments allowing for more variations of agent morphologies, control architectures and/or environments”. However, I think that the artificial life methodology lacks a more structured research program, informed by the psychological literature and aimed at building models of increasing complexity where the simple sensory-motor strategies like the ones described here could evolve into more complex behaviours and cognitive processes.

4. Kinetic Size Constancy and self-motion

The Artificial Life model presented in the previous chapter, and similar model developed earlier in Evolutionary Robotics research, are proofs of concept of the idea that action and perception are tightly connected. In this chapter, I present an empirical work aimed at testing this idea on humans with a psychophysical experiment that involves kinetic size constancy. Some research on kinetic size constancy have been mentioned in section 2.2. In these experiments, motion was produced by the experimental apparatus and was therefore passively experienced by the participants. What happens if participants can actively move around, changing their position in space or changing stimulus position or orientation?

In the first part of the chapter, I briefly review some empirical works that have investigated the role of active motion in perception and have found that extra retinal information, like the efferent copy of motor commands, can improve performance in visual task with ambiguous configurations. The results of my experiment, described in the second part, partly confirm these results, but also show that some people rely much more on top down cognitive schemas.

4.1. Self-motion improves perception of ambiguous configuration

The relation between action and perception has started to gain growing interest and importance in the early 1990s as is shown for example in the works of Ballard (1991), Thompson (1992; 1995), Churchland, Ramachadran and Sejnowski (1994), Kelso (1995), Clark (1997; 1999), Jarvilehto (1998a, 1998b, 1999, 2000), O'Regan and Noe (2001; 2001; 2001), Noe (2004). As Creem-Regehr & Kunz show in a recent review (Creem-Regehr & Kunz, 2010) there are multiple approaches in considering the links between action and perception, which is a vast topic. Here I want to focus on some empirical studies in the psychological literature that showed how self-motion influences the interpretation of optic flow and consequently the perception of depth, size and structure from motion.

The optic flow (Ullman, 1979; Koenderink, 1986; Simpson, 1993) is the deformation of the retinal image produced by observer motion or object motion, and is a rich source of information about the spatial layout of the world. Lateral motion, in particular, produces the so called *motion parallax* that is the relative movement of images across the retina that is inversely proportional to object distance. Motion parallax has been first demonstrated to be an independent source of depth information by Rogers and Graham (1979) who used computer generated random-dot patterns to isolate optic flow information from other depth cues. They found that motion parallax due to either object motion or observer motion, produced consistent and unambiguous impression of depth, shape and relative order of surfaces in depth. These and other studies (Koenderink, 1986; Simpson, 1993) were conducted with the assumption that there is no difference between the interpretation of optic flow produced by the observer own movement or by object motion.

Recently, some empirical studies have questioned this assumption. They have compared actively moving observers with immobile observers and have produced results that support the hypothesis that optic flow is interpreted differently in the two conditions. The extra-retinal information derived from the feedbacks of motor commands seems to contribute to the perception of absolute distances or to the removal of ambiguities in the extraction of a 3D surface from optic flows.

Ono and Steinbach (1990) studied monocular stereopsis with and without head movements. They showed configurations of moving random dots in two experimental conditions. In one condition, participants were asked to move their head laterally and the stimulus motion was synchronized with head movements. In the other condition, participants did not move their head but the stimulus was the same. The random dots configuration was designed to create the illusion of two static planes at different depths. Participants were asked to indicate the amount of depth between the planes and to report whether the dots appeared to move. The condition with head movements produced a stronger impression of depth and planes were perceived to be static. In the no-head movement condition, the two planes were judged to be closer to each other and more often seemed to be moving.

Rogers and Rogers (1992) tried to find an explanation for the absence of ambiguity found in the two conditions of the original experiment of Rogers and Graham (1979). According to them, the random dots configuration used in that experiment where ambiguous if perceived passively. They hypothesized that other kind of information were available (for example optic flow information coming from the surrounding of the oscilloscope).

Dijkstra et al. (1995) conducted experiments in which they tested the performance of detection of curvature of 3D objects with three different movement conditions and two different sizes of the field of view. All movement conditions resulted in the same motion parallax on the optic array of the observer, hence providing identical information about the 3D shape of the object. The difference between the conditions was the amount of extra-retinal information available. In the subject-movement condition, the subject moved their head left and right and a simulated segment of a sphere or plane was shown. In the object-translation condition, the head of the subject was stationary and the stimulus translated left and right. In the object-rotation condition, the head of the subject was also stationary but the stimulus rotated in depth.

The performance for curvature detection in the three movement conditions was roughly constant for large-field stimuli but there was a great difference for small-field stimuli. Small-field stimuli gave a reasonably good performance for the subject-motion condition and a performance near chance level for the object-translation condition. Although the distinction between a flat or curved surface was made very clear in the object-rotation condition, ambiguity between convex and concave surfaces was present for the small-field stimuli.

Depth perception in relation to head movement was investigated in two studies by Peh et al. (2002) and Panerai et al. (2002). Peh et al. tested the ability of monocular human observer to scale absolute distance during sagittal head motion in the presence of pure optic flow information. They used computer-generated spheres covered with randomly distributed dots, placed at several distances and presented at eye-level. They compared the condition of self-motion (SM) versus object-motion (OM) using equivalent optic flow field. When the amplitude of head movement was relatively constant, subjects estimated absolute distance rather accurately in both the SM and OM conditions. However, when the amplitude changed on a trial-to-trial basis, subjects' performance deteriorated only in the OM condition. They found that distance judgment in OM condition correlated strongly with optic flow divergence, and that non-visual cues served as important factors for scaling distances in SM condition. Absolute distance also seemed to be better scaled with sagittal head movement when compared with lateral head translation. Results were confirmed in Panerai et al. in which it was also found that a ground floor improved the performance but not the visual field size.

Boxtel et al. (2003) investigated the perception of three-dimensional plane orientation perceived from an optic flow generated by the observer's active movement around a simulated stationary object, and compared the performance to that of an immobile observer receiving a replay of the same optic flow. They found that perception of plane orientation is more precise in the active than in the immobile case. In particular, in the case of the immobile observer, the presence of shear in optic flow drastically diminishes the precision of tilt perception, whereas in the active observer, this decrease in performance is greatly reduced. The difference between active and immobile observers appeared to be due to random rather than systematic errors.

Dyde and Harris (2008) have made some experiments to determine the amount by which a fixated object need to be moved in space in order to appear earth stationary to a linearly moving observer. Observers were oscillated sinusoidally either passively or under their own control, under lit and fully darkened conditions. The visual targets always needed to move (in space) in the same direction as the observer to be judged as earth stationary. They found that, paradoxically, in order to appear stable a target needed to move consistently in the same direction as the moving observer. The effect was stronger in the dark and passive conditions in which the targets needed to be moved to a greater extent. The authors explained this with the different amount of extra-retinal information available in the two conditions. That is, in the dark and passive condition the effect was stronger due to a lack of self-motion information.

All the researches mentioned above studied self-motion with participants moving their head or the entire body. Umemura and Watanabe (2009) have tried a different approach and experimental setup. They investigated whether the visual system could use a novel action–perception relationship mediated by a touch panel to resolve ambiguity in 2D optic flows. The stimulus was an optic flow produced by a dotted plane, which was translated and rotated in depth. The translation was synchronized with subject's hand movements on a touch panel. The optic flow was ambiguous because it could be interpreted as a combination of translation and rotation, as it actually was, or only as a rotation. Subjects were tested in a total of six sessions. In the first four sessions, the stimulus was synchronized with hand movement (active motion). In the fifth session, they passively saw the stimulus motion recorded in the active movement sessions (passive motion). In the last session, the movement of the stimulus was reversed. Brutally summarizing the results in few words, the outcome of the experiment indicated that subjects in the active motion condition were able to disambiguate the optic flow and correctly decomposed motion in a translation and rotation components, while in the passive condition they sometimes perceived only a rotation and sometimes a translation and rotation. The ability of decomposing the optic flow correctly was learned during the four active motion trials.

4.2. The role of self motion in Kinetic Size Constancy

Drawing inspiration from the above mentioned literature, I have devised an experiment to investigate the role of self-motion in size constancy with a dynamical experimental setup. The stimuli are two spheres in a three dimensional virtual environment displayed on a computer monitor, and the task assigned to participants is to indicate which of the two is bigger. Since the spheres are placed at different depth, the task involves the ability to scale angular size with distance, namely size constancy. The spheres are static but participants can move the virtual camera horizontally and in depth. By doing so they generate an optic flow that can provide information about depth. What make this task a dynamical one is that static depth cues have been drastically reduced so that the only way to obtain distance information is through motion and optic flow. There are two different experimental conditions. In the active motion conditions participants can actively move around and while accomplishing the size discrimination task. In the passive motion condition, they passively observe the optic flow generated by other participants. If, as the enactive approach suggests, perception is a sense making process that involves the circular interplay between action and perception, then we must expect that performance in the active condition should be significantly better than performance in the passive condition. This is the main hypothesis under investigation.

4.2.1. Participants

Forty participants (age=23-52, mean=38; 15 female, 25 male) took part in the experiment without being paid. All had normal or corrected-to-normal vision and were naïve with respect to the purpose of the experiment. Data from two participants were discarded after the short debriefing phase at the end of the experiment. One participant misunderstood the experimental task and consistently gave wrong responses. Another participant said that was too distracted by the fast moving images and was unable to give meaningful responses. All the remaining thirty-eight participants were tested in two experimental conditions (with balanced order).

4.2.2. Apparatus

The stimuli were created using the Unity3D game engine and displayed on a Dell Full HD 24 inches colour monitor with IPS technology. Participants viewed the display binocularly from a distance of about 60 cm. The adaptive psychophysical procedure was implemented in Matlab using the Palamedes Toolbox. The Unity3D application and the Matlab script were connected with TCP sockets communication through a TCP/IP broadcast server. All software was ran on an MSI GT72s 6QE laptop computer equipped with a NVIDIA GTX980M graphic card featuring the G-SYNC technology. Only the external Dell monitor was used during the experiments.

4.2.3. Stimuli

The stimuli consisted of two spheres placed in a 3D interactive scene where the camera could move to produce an optic flow (Figure 13). The spheres appeared suspended in the centre of a virtual "room" whose centre coincided with the origin of the 3D coordinate system. The room had a square prims shape with the following dimensions expressed in 3d units: length=120, width=40, height=40 (Figure 14). The diameter of one sphere was set to one and remained unchanged during all experiments (reference stimulus). The diameter of the other sphere (test stimulus) was controlled by the PSI adaptive method algorithm (see next) and could vary continuously from 1.0 to 2.0.

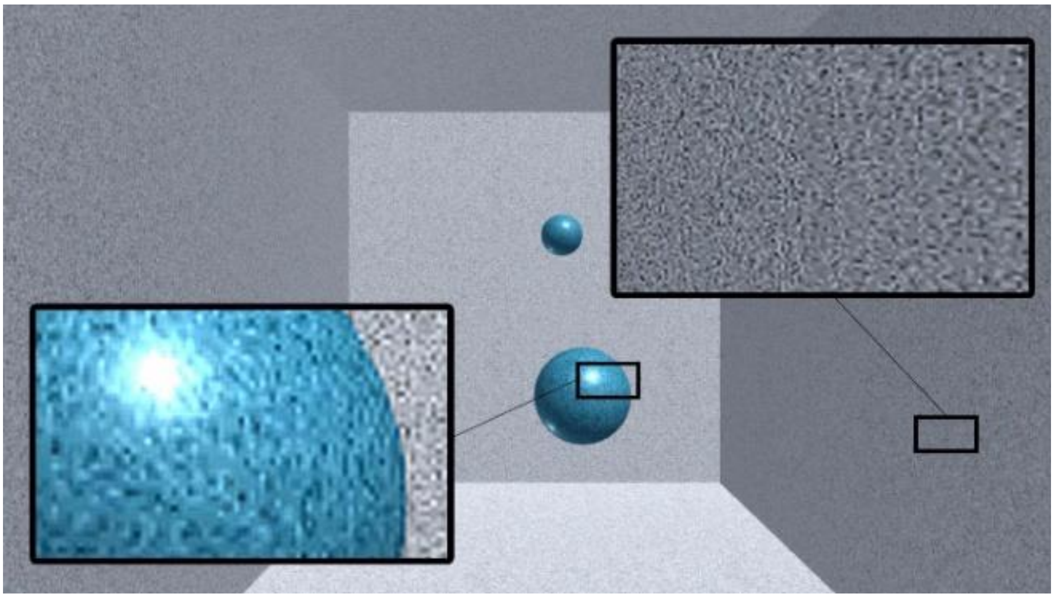

Figure 13 - Screenshot of the 3D scene showing the noisy grain texture utilized to enhance optic flow.

The positions of the spheres varied randomly from trial to trial along the vertical plane of symmetry. Their position was randomly drawn in the following set of coordinates (x,y,z): (0, 2, 3), (0, 2, -3), (0, -2, 3), (0, -2, -3). The test sphere was then positioned symmetrically with respect to the origin. This ensured that the two spheres were always kept at different distances and heights with respect to the camera.

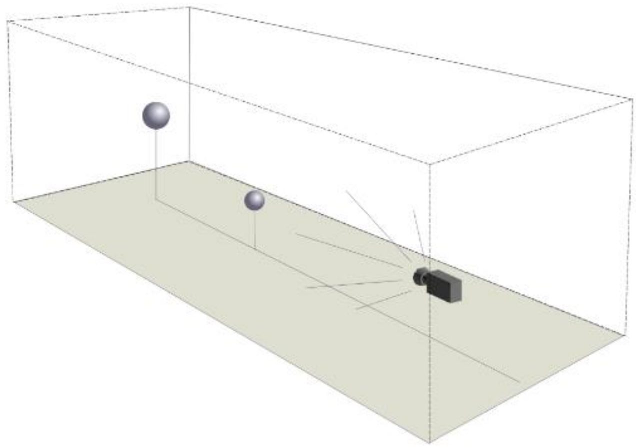

Figure 14 - Schematic representation of the 3D scene setup

The scene was rendered with daylight (parallel) illumination and without cast shadows. The stimuli were presented for 5 seconds during which participants could actively move the scene camera with the mouse (active motion condition) or passively see the

recorded motion from other participants (passive motion condition). The camera could not rotate but only translate on the horizontal plane of symmetry of the virtual room. The motion was constrained in order to keep the camera always inside the room and to avoid the two spheres going out of sight. Translation along the z-axis (depth) was limited in the range (-10,-35). Translation along the x axes was limited depending on the camera z position in a range varying from (-2.5, 2.5) to (-15, 15).
It is useful, for subsequent interpretation of participants' behaviour, to analyse how the angular size of the two sphere varied depending on their difference in size, depth order and distance from the camera. When the difference between the two spheres was greater than 0.84, the test sphere appeared always bigger (its angular size was greater than the reference sphere) independently of depth order and distance from the camera. In this range, the angular size was in accordance with physical size. When the difference was less than 0.19 the near sphere appeared always bigger than the far sphere independently of their physical size. When the difference was in the range between 0.19 and 0.84 the angular size had different behaviours depending on the depth order. When the test sphere was nearer (50 % of the time), it always appeared bigger. When the test sphere was farther, its angular size could be greater, smaller or equal to the reference sphere depending on the camera position. I will use the term "Point of Angular Size Equality (PASE)" to indicate the camera z position at which two spheres appears of the same size. If the camera z position was shorter than the PASE, the angular size of the test sphere was smaller than the reference sphere. If the camera z position was larger than the PASE the angular size of the test sphere was greater than the reference sphere and in accordance with its physical size. Figure 15 show how the PASE changes at different distance of the camera form the stimuli.

4.2.1. Task

The task was a two alternative forced choice task (2AFC task) where participants had to choose the bigger of the two spheres. As is clear from the above description, this type of task requires size constancy abilities because the spheres have different diameters and are located at different depths. The angular size must be combined with distance information to obtain the physical size. Moreover, participants were in a distance reduced-cue condition. Ocular cues were suppressed because they saw 2D flat images. Occlusion never happened because the two spheres were displaced vertically. Textures could not give any static cue to depth because the sphere were suspended and therefore were not in touch with any surface. Cast shadows were suppressed. The stimuli were not familiar object for which size can be easily estimated based on past experience. The only reliable source of depth information could come from self-motion and the optic flow.

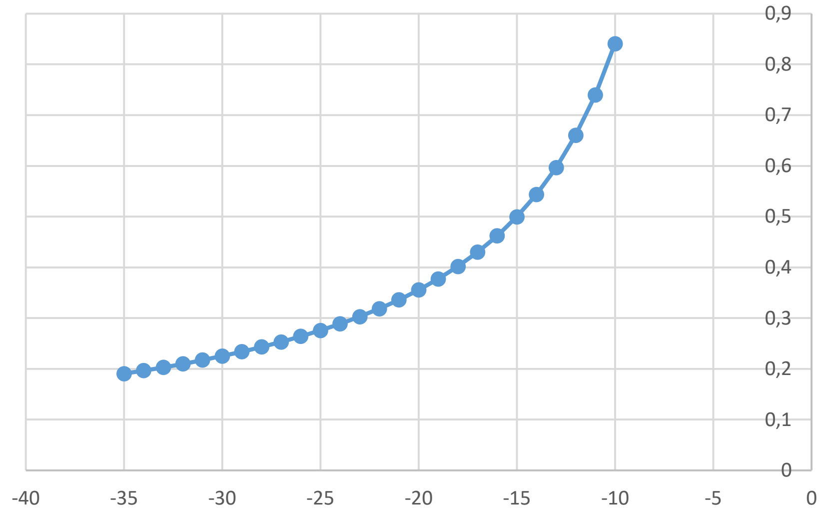

Figure 15 - Relationship between distance and size difference at the Point of Angular Size Equality (see text for an explanation).

4.2.2. Measures

The size discrimination threshold was measured using the PSI adaptive method during 30 trials in which the size of the test sphere was adjusted with respect to the reference sphere. The PSI method uses a Bayesian approach to estimate both the threshold and the slope of a psychometric function simultaneously, using an adaptive algorithm that minimizes the uncertainty about the estimated parameters. Other adaptive methods can only estimate thresholds and require prior assumptions about the slope. Using incorrect slope assumptions could yield incorrect estimates of the threshold. Therefore, this method is particularly useful in situations where the slope is not known or where the slope can vary in different conditions. The PSI method was developed and tested specifically for two-alternative forced-choice experiments.

The PSI algorithm was implemented in Matlab starting from an example script of the Palamedes Toolbox. The assumed psychometric function was a cumulative normal distribution. The stimulus interval was set in the range (0.01, 1.99). The prior alpha and beta range were set respectively in the intervals (0.1, 1.9) and (0.5, 10). The guess rate was set to 0.5. The lapse rate at 0.02.

The PSI algorithm is quite complex but essentially what it does is to adjust the stimulus size based on participant answers until correct responses converge to the threshold. A correct response usually produces a decrease in stimulus size. On the contrary, an incorrect response produce an increase in stimulus size. This is particularly true at the beginning of an experiment. In the size discrimination task proposed here the stimulus corresponded to the difference in size between the two spheres. An example of stimulus adjustment along the 30 trials is shown in Figure 16. The stimulus was initially set by the algorithm to a value of 1.14 which means that the test sphere was more than double the size of the reference sphere. Then it was decreased due to a series of correct responses. At the 8th trial the stimulus level raised due to an incorrect response. And the same happened at the 10th trial. In this case the final estimated threshold was 0.4478.

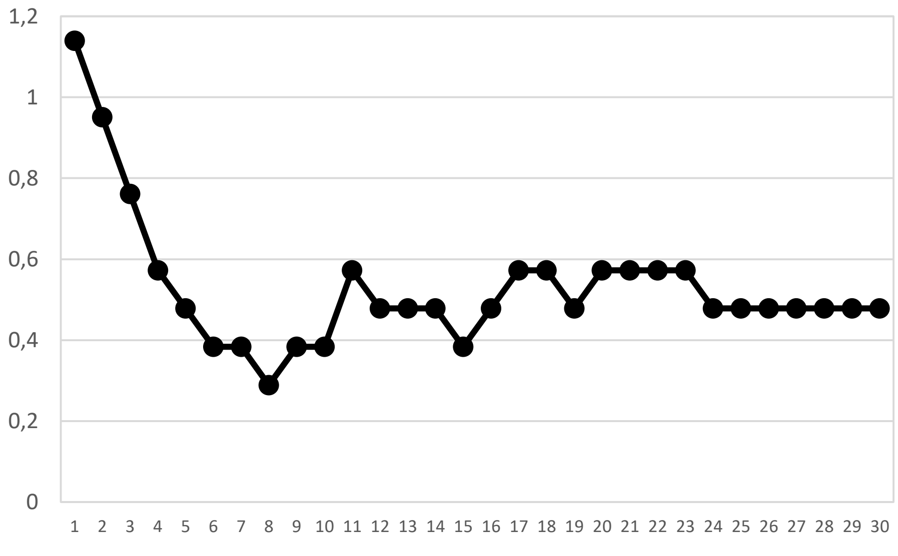

Figure 16 - Adjustment of the stimulus size along the 30 trials with PSI adaptive method

4.2.3. Procedure

Participants sit in front of the display that was placed at eye level. An optical mouse was placed on the right or left side of the screen depending on participant handedness. A first example trial was used to explain the task and to give participants instruction on how to perform the judgments. As it is know from the size constancy literature instruction is the most powerful factor in affecting experimental results. The four main type of instructions given in size constancy tasks are the following: objective, perspective, projective and apparent. In this experiment, participants were asked to explicitly take in consideration distance to scale apparent size (perspective instructions). Before starting the actual experiment, they were allowed to familiarize with the task and 3D environment in a series of free trials until they felt comfortable. All 38 participants were tested in two experimental conditions in a repeated measure design. In the Active Motion Condition (AMC), they actively controlled the scene camera using the mouse. In the Passive Motion Condition (PMC), they passively saw the camera motion recorded from other participants. The order in which the two condition occurred was balanced so that half of the participant started with the AMC and the other half started with the PMC.

Each condition consisted of 30 trials that could be started by clicking on a small red button in the lower part of the screen. The virtual room with the two spheres appeared and the participants had 5 seconds to move the camera with the mouse (or passively see it moving) trying to assess the spheres sizes. After five seconds, the motion stopped and a message on the screen asked participants to click on the sphere that they had perceived to be the bigger during the camera motion. No feedback was given for correct or wrong responses. After the sphere selection, a new trial was presented and the procedure continued for all 30 trials. At the end of each experimental condition, a message on the screen informed participants that the experimental phase was concluded. Participants were then allowed to have a small break. The second part of the experiment started with a brief explanation of the task since it was a little different from the first condition. Participants were allowed again to familiarize with the new version of the experiment until they were ready to start.

The experiment was concluded by a short debriefing phase. Participants were asked, in particular, if one of the two conditions was more difficult than the other and what strategy they used in the active motion condition.

4.2.4. Results and discussion

Before analysing numeric data, it is interesting to summarize the verbal feedbacks given by participants at the end of the experiment, and the motion strategy as they result from the motion tracking data.

With the exception of two people, all described the passive motion condition as more difficult because they did not decide what movements to do, and sometimes were frustrated by seeing odd movements performed by other participants in the recorded motion. Two people, on the contrary, found the passive motion condition as easier because allowed them to see the stimuli from useful perspectives, which they did not consider their own. All participants reported that in the active motion condition their first goal was to determine the depth order of the two spheres. This information was then combined with apparent size to achieve objective size and be able to judge which of the two spheres was bigger. Despite this general agreed strategy, the tactics varied across participants. Most of them reported that the best way to determine the depth order was to move laterally in an attempt to get a sideview of the stimuli. Other found more useful to get close to the sphere and move back and forth. A minor part of the participants said that they tried to rely on perspective information from a static lateral viewpoint. All participants noticed that trials were increasingly difficult due to the reduced size difference. Some participants, interestingly, had the impression that one of the spheres was moving despite the fact that in the experimental instructions they were described as static.

Motion tracking data are more diversified than verbal reports. Some of the motion trajectories are in accordance with what participants said. However, the most part are of difficult interpretation. Each person exhibited a unique motion style that was rather consistent and recognizable across the thirty trials.

Figure 17 shows four examples of motion trajectories from different participants, some of which are particularly neat and clearly interpretable. The camera motion always starts at (0,-30). The top left graph shows an example of back and forth motion. The camera moves straight forward and get close as close as possible to the stimuli. Then it go back and forth a few times following an impressive straight path. The top right graphs shows an example of lateral motion. The camera moves first on the right of about seven units, then on the left of about ten units. After a short oscillation it moves back towards the centre. The bottom left figure shows an example of trajectory from a participants that reported the use of a static perspective tactic. The camera is moved on the far left position and then stopped there. From this position the spheres appears in a perspective view. On the bottom right a more complex and less easily interpretable trajectory.

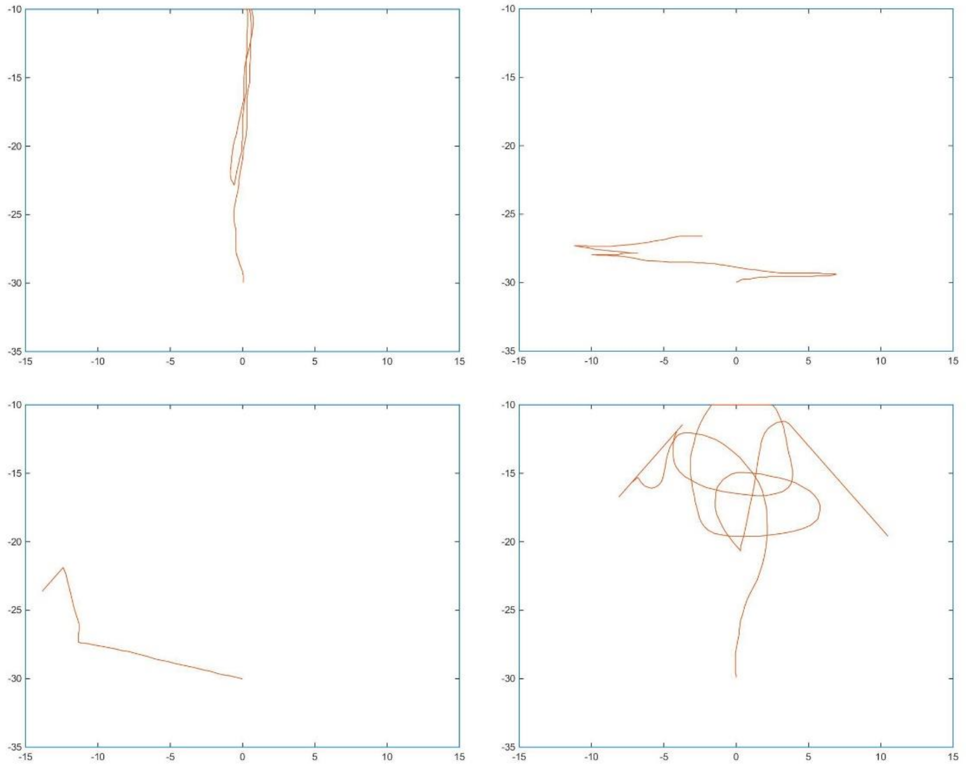

Figure 17 - Examples motion trajectories from different participants

Figure 18 shows the trajectory of a single participant in four different trials. The motion follows a characteristic y shape that reveals a peculiar motion strategy consisting in approaching the stimuli from the right side and then going from right to left with an arc trajectory. This is an example of how the motion strategy was consistent for each participant across different trials.

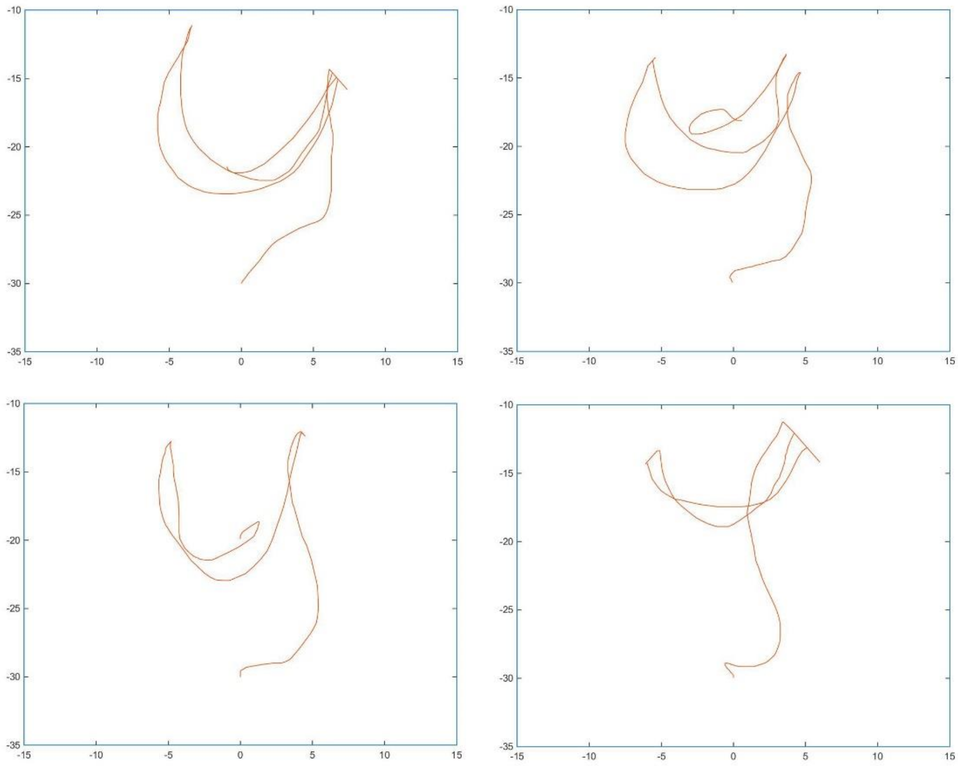

Figure 18 – Motion trajectories of a single participant in four different trials

The main goal of the experiment was to compare the differential thresholds in the two experimental conditions (AMC, PMC). Before applying any statistical test, measures have been analysed as frequency distribution. Figure 19 shows the frequency distributions of all measures and a comparison for the two conditions separately. Distributions in all graphs show a multimodal shape with three peaks at around 0.25, 0.45 and 0.85. If we combine what we know about the PSI adaptive algorithm and the angular size of the spheres we can hypothesize that these three values correspond to three different perceptual approaches used by participants during the size discrimination task, which are associated with three different performance levels.

First let us consider what happens if one adopts an apparent (angular) size approach in the size discrimination task. Let us assume that the camera is uniformly moved in depth without any preferences for the rear or front positions. In the stimulus range (0.84, 1.14) the angular size is in accordance with physical size, so the apparent size approach will give correct responses.

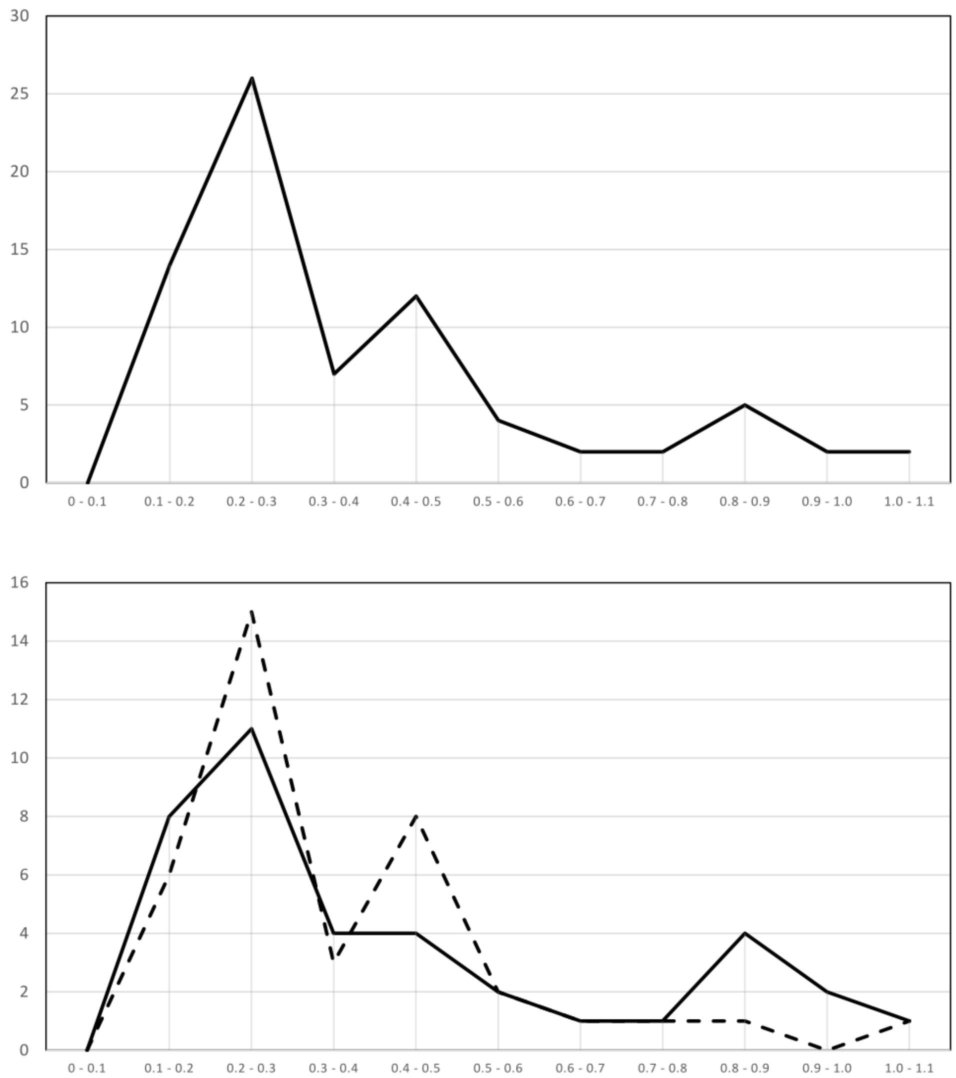

Figure 19 - Frequency distributions of the differential thresholds. Top: frequency distribution of all the 78 measures (both conditions). Bottom: comparison between the frequency distributions in the two conditions

The PSI algorithm will progressively lower the stimulus level down to 0.84. In the range (0.19, 0.84), the angular size is in accordance with physical size only if the camera z position is behind the PASE (Point of Angular Size Equality). This happens quite often when the size difference is little below 0.84, because the PASE position is quite ahead and most of the time the camera position falls behind it. On the contrary, when the stimulus level is low, the camera position will fall in front of the PASE and the physical size will not be in accordance with angular size. Apparent size responses will be incorrect most of the time. When the stimulus level is in the middle of the interval, the physical/angular size accordance will only happen 50% of the time. This will also be the proportion of correct responses if the apparent size approach is employed. Given these considerations, the second peak of the frequency distribution appears compatible with the performance of an observer that relies on apparent size.

The third peak of the frequency distribution shows a performance that is worse compared to the apparent size approach. In the range (0.84, 1.14) behaviour is probably driven by the apparent size approach until the stimulus level reaches the value of 0.84. However, as the stimulus level decreases, behaviour starts to go in the opposite direction. If we look at the recorded response, we see that spheres with smaller angular size are frequently judged bigger than spheres with larger angular size, and this leads to a series of wrong responses that makes the estimated differential threshold settle at around 8.5. There are several hypothesis to explain this behavior. One is that participants are subjected to an overconstancy phenomenon. As we have seen, this is a well known phenomenon studied in the classical literature that makes distant objects to appear bigger than their real physical size and is common among adults. This hypothesis is supported by the fact that some participants within this high threshold performance group mentioned perspective as one of the cue they used to judge sphere size, and, as Carlson (1962) showed, perspective instructions are frequently associated with higher level of overconstancy. Another hypothesis comes form researches on distance perception in virtual environments (for a review see Interrante, Ries, & Anderson, 2006), which found that distances in these conditions are perceived as compressed. In the case of my experiment, this means that the farthest sphere is systematically perceived as nearer than it is, and therefore, in relation to the same angular size, it appears bigger.

The first peak in the frequency distribution is characterized by a high performance with a low differential threshold. This means that participants were able to discriminate between spheres that were very similar in size. For such small size difference, the stimulus configuration does not give any visual hint because physical size is not in accordance with angular size or depth order. Judgments, in this case, can only rely on the accurate perception of the physical size.

To perform the statistical analysis, participants were divided in three groups with a mixture Gaussian model applied to the frequency distribution. Figure 20 shows the comparison of the performances of the three groups in the two experimental conditions. A paired t-test was used to determine if there was a difference in the two conditions in each of the three groups. In the low threshold group the performance was better in the active motion condition (one tail $t(21)=-4.396$, $p<0.001$). In the middle threshold group there was no difference between the two conditions ($t(6)=0.995$, $p=0.358$). In the high threshold group the performance was better in the passive motion condition (one tail $t(8)=2.826$, $p=0.011$).

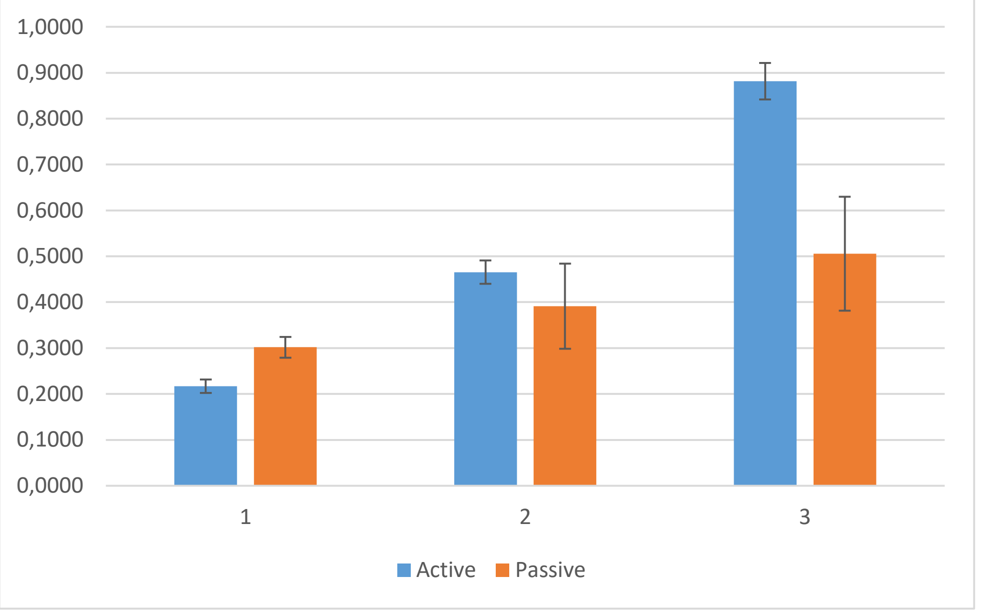

Figure 20 - Comparison between the performances (differential thresholds) in the active and passive motion conditions in the three performance groups (1=low threshold, 2=middle threshold, 3=high threshold).

These results are coherent with the three different perceptual strategies identified. As hypothesized before, the low threshold performance can be explained by an active motion strategy that is utilized to extract depth information from optic flow. In the passive motion condition, the performance decreases because participants cannot control camera movements and the optic flow follows unexpected motion patterns. The middle threshold performance is mainly based on apparent size and therefore is less dependent on a specific optic flow. This is why there is no difference in the two conditions for middle threshold performers. The high threshold performance derives from a static perspective attitude. In the passive motion conditions, participants are unable to apply their perspective strategy and their performance improves to the level of an apparent size judgment. It is interesting to notice how the passive motion condition flatten performances with respect to the active motion condition. Moreover, in this condition the performance is subjected to more variability.

To summarize this results, we can say that participants showed three different levels of performances that corresponds to three different perceptual strategies. The best performance was shown by the group of participants (58%, mean differential threshold=0.22) that were able to exploit optic flow information to assess the spheres sizes, and in this cases self motion improved size perception. A middle performance group (18%, mean differential threshold=0.47) reported angular size judgments, and their performance was the same in the active and passive motion condition. The low performance group (24%, mean differential threshold=0.89) gave a better performance in the passive motion condition. Probably, they have been misled by the perspective appearance of the virtual environment that led them to apply top-down perspective schemes that were not based on actual cues (which were absent in the scene). This is consistent with the two-process theory of response to size and distance elaborated by Gogel and Da Silva (1987). These authors distinguish between primary and secondary processes that operate in the visual processing of size and distance. The primary process uses raw sensory information contained in the immediate visual stimulus. It does not require a memory of prior spatial extents, and it invariably results in perceptions. An example of the primary process is the perception of size (for a given size on the retina) resulting from a perception of distance as determined by oculomotor cues and binocular disparity. The secondary process is a higher cognitive process that judges size based on previous knowledge or expectations and can override the primary process.

4.3. Conclusion

The results of the experiment suggest that self-motion plays an important role when static depth cues are suppressed and depth information come from optic flow. This is consistent with the results of similar studies that I have reviewed in section 4.1 that investigated the relation between action and perception and in particular the role of self-motion in perception.

However, it is also interesting the fact that 41% of the participants were unable to exploit an effective motion strategy and, in some cases, explicitly reported that they ignored motion as a source of information about depth order and distance. Further experiments are needed to understand what exactely trigger different perceptual strategy. One hypothesis is that they can be attributed to individual difference for example in cognitive syle. Another hypothesis is that there have been differences in the interpretation of experimental instrucions, which, as we have seen, is a powerful factor influencing the performance in size constancy experiemnts. It would be interesting to perform the same experiment in an immersive virtual environment with the availability of binocular depth cues and different types of self motion like head movements.

On a more general level these results confirm the hypothesis of two visual systems, with a “vision for action” system and a “vision for perception” system (Milner & Goodale, 2006). Functionally, the first one relies on fast, unbiased, egocentric processing of the spatial information, whereas the second one is slower, subserves the formation of spatial representations in memory, and may use nonegocentric reference frames.

5. General Conclusions

Size constancy is undoubtedly a complex subject that has intricate links with many aspects of cognition and behaviour. As highlighted many times through this work, the most part of size constancy experiments have been performed in static perceptual conditions. While not diminishing the importance of these works, I argue for a more balanced consideration of the dynamical, embodied and situated aspects of this phenomenon. To this purpose, I propose to refer to the theoretical framework provided by the Enactive Approach to cognition (Valera, Thompson, & Rosch, 1991; Rohde, 2010) that suggests a broader perspective in studying cognition including principles like autonomy, emergence, embodiment and situatedness.

Many of the key principles that the enactive approach emphasizes are not easy to be investigated, especially in humans, and with a classical experimental approach. However, as I have suggested with the Artificial Life model presented in chapter 3, their foundational aspects can be explored and can generate useful questions and hypothesis. These kind of models, in conjunction with comparative studies as the ones mentioned in section 2.5, could help to understand where size constancy "comes from". For example, the presence of basic size constancy abilities in lower vertebrates, suggests that it could have evolved from basic cognitive capabilities aimed at an effective interaction with the environment. More in general, with their simple minimal models, the evolutionary robotics and artificial life techniques could also generate new ideas, concepts, mechanisms, hypothesis about the key principles of the enactive approach like embodiment, emergence, autonomy and situatedness.

The enactive approach can also be applied to the study of size constancy in human. This is what I have tried to do with experiment presented in chapter 4. In this case, the goal was to investigate how much size constancy depend on a circular interaction between the observer and the environment through perception and self-motion. Results partially confirms the view that perception is not an off-line elaboration of a static visual input, and that the extraction of size and depth information from optic flow relies on the dynamical interaction between sensory stimulation and motor commands.

However, things in humans are much more complex. The same experiment shows that, in some circumstances, the visual input is interpreted with higher order cognitive schemes. This is in accordance with a dual modes theory of perception that is supported both biologically (Milner & Goodale, 2006) and experimentally (Gogel & Silva, 1987).

Anyway, the main purpose of my work is not to support one theory over the other. What I have tried to do is to highlight the fact that employing different methodologies can give a more complete picture of a problem. And to do so, they must be applied with an integrated approach and need to be reciprocally informed. The three Evolutionary Robotic models on size constancy that I have cited (Scheier, Pfeifer, & Kunyioshi, 1998; Nolfi & Marocco, 2000; Williams & Beer, 2010) have been built without any plan to find links with the psychological literature, neither the empirical nor the comparative one. It seems they have been carried out without a road map of the size constancy problem, which the psychological literature can provide. Just to give few examples, it would be interesting to build an Artificial Life or Evolutionary Robotics model to explore size constancy in presence of multiple depth cues. Would we obtains results similar to the classical experiment of Holway and Boring (1941)? Would an artificial system at some point develop a static size constancy mechanism allowing it to judge size without moving too much? Then, how much would a double-eyes vision system with convergence improve size constancy? These and many other questions could be the base for a multi-year research program.

Psychology, on the other hand, has focused too much on studying size constancy with static displays. The few works on Kinetic Size constancy (see section 2.2) has focused mainly on forward and backward movements. Research on motion parallax has mainly focused on distance perception and not directly on size constancy. It is true that "A rich apprehension of the surrounding scene can be gained from a static view" (Gillam, 1995), but our knowledge about the contribution of motion in spatial perception is currently very limited. Moreover, we can hypothesize that some of those static indexes can be acquired by a process of learning through motion.

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