Human and artificial strategies for depth discrimination with sensory substitution devices

Dissertation for the Evolutionary and Adaptive System MSc

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Abstract

This work reports on a set of experiments designed to clarify the importance of embodied action in the perception of external spatiality. By making use of the Enactive Torch - a custom-built minimalist distance-to-tactile perceptual supplementation device - minimally trained participants can locate objects placed in front of them, by engaging in active exploration. Constraining the available exploratory movements induces an experimental set-up in which a constitutive relationship between degrees of freedom and perception of depth is clearly identifiable.

Many theories attempt to capture vision-substitution mechanisms and how they take place in the brain; some such mechanisms are described and related to the results of the experiments presented. Contextually, I discuss possibilities offered to the scientific community by minimalist devices, propose new experiments to further investigate the role of embodied action in the perception of spatiality and show how a computer program can evolve strategies to explore the scenario used for the experiment.

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Contents

Chapter 1

Introduction

The senses deceive from time to time,
and it is prudent never to trust wholly
those who have deceived us even once.
René Descartes

Purpose of this work is to experimentally investigate minimal strategies for non-visual spatial exploration in minimally trained subjects. The Enactive Torch, a tactile-to-vision substitution device, is used as means to acquire spatial awareness of a strictly controlled bi-dimensional space.

Conceptually, our hypothesis acknowledges the brain's innate ability to combine heterogeneous sensory input to portray the reality we experience in a manner that is the most advantageous for its comprehension. As a consequence, the brain develops conscious and unconscious strategies apt to determine the location of an object relative to the user's "point of view". Some such strategies are described and compared with respect to their accuracy.

Experimental results show that participants can indeed develop a sense of depth while experiencing a simple bi-dimensional "world" via a binary tactile feedback device. By constraining the degrees of freedom (DoF) available in such an "enacted space" we show also that two DoFs are sufficient for the task at hand.

Furthermore, this experiment shows that the Enactive Torch is a valid tool for research in the field of sensory substitution, especially considering how important second-hand approaches are in the study of perception. Researchers can experience the experiment themselves without having to resort to expensive or overly complex equipment. This can lead the scientific debate on enactive perception out of pure philosophical speculation and into quantitative studies with greater chances of objectivity.

Chapter 2 presents the theoretical background of the problem at hand; chapter 3 presents the experimental set-up and details the protocol used; chapter 4 discusses results and provides an in-depth analysis of them. Chapter 5 describes a computer program designed to evolve strategies for the exploration of an environment similar to that used for the experiments, whereas chapter 6 expands on the research presented and describes new experiments in line with the current theoretical framework. Chapter 7 concludes this work.

A paper based on this work was submitted to the ENACTIVE 08 conference under the title "On the Role of Bodily Degrees of Freedom for the Active Constitution of External Spatiality and Depth". At the moment of writing it is not known whether the paper has been accepted for publication.

Chapter 2

Action, Enaction and Perception

This work aims at investigating strategies for spatial exploration using a tactile-to-vision substitution device. The basic assumption is consistent with the *enactive view*: that perception is a guided form of action in a defined space. Participants of the experiment are exposed to a novel environment via a device providing tactile stimuli meant to temporarily replace their sense of sight.

This Chapter introduces the concept of enaction and describes the "enactive approach" to perception; with respect to the nature of vision and the issue of "what is to see" I briefly review the philosophical and empirical investigations that attempted to answer *Molyneux's Question* since the XVIII century. The last part of this chapter is devoted to delineating the current state of research in tactile-vision substitution systems, with particular emphasis on the work by Back-y-Rita; an outline of phenomenological issues related to vision, perception and the study of pertinent empirical data concludes this part.

2.1 Enaction and Perception

In [20] Varela, Thompson and Rosch defined Perception as "perceptually guided action" and cognitive structures as emerging from "the recurrent sensorimotor patterns that enable action to be perceptually guided". Noë in [15] also defines perception as "not something that happens to us, or in us. It is something we do.".

The enactive view emphasises the importance of *action* as a direct cause of *perception*. Even though we are exposed to the common knowledge of the brain as a computing machine passively connected to streams of sensory inputs, according to the enactive approach the key element that enables us to be aware of what happens around us lies precisely in the closed loop between our senses, our brain and the action undertaken by our body.

The relevance of action in acquiring the ability to meaningfully perceive is manifest even at early stages of biological development: in [10] Held and Hein show how being exposed to passive movement does not necessarily lead to sensorimotor awareness and motor abilities.

In recent years, a consensus has emerged within the cognitive science community that the body shapes the mind, in particular with respect to embodied action being necessary for perception. At present, further comprehension of the role of the body is required to make progress in understanding the mind. Nevertheless, this consensus reached various stages of acknowledgement; the details are still under debate.

The enactive approach to perception leads to a novel definition of "what is to see"; in particular we could consider sensations as conceptually different from perceptions. An example is the "rubber hand illusion" (see [4] and [1]) in which subjects perceive a rubber hand as their own hand when visual and tactile stimuli occur simultaneously on the limb.

2.2 Molyneux's Question

In 1694 William Molyneux, in a letter to philosopher John Locke, posed the following question:

> 'Suppose a man born blind, and now adult, and taught by his touch to distinguish between a cube and a sphere of the same metal, and nighly of the same bigness, so as to tell, when he felt one and the other, which is the cube, which is the sphere. Suppose then the cube and sphere placed on a table, and the blind man to be made to see; *quaere*, Whether by his sight, before he touched them, he could now distinguish and tell which is the globe, and which the cube?' (as cited by [6]).

Since then, philosophers and researchers have tried to answer Molyneux's question, examining it from several points of view. Different interpretations of the original question led to diverse approaches to the answer: did Molyneux ask whether the blind man is able to apply *spatial* concepts to his newly acquired sense of sight? Would Molyneux's Patient (as referred to in [9]) be able to recognise objects placed at a *distance*? (See Diderot's interpretation, as referred in [6]).

Evans in [6] also stresses the fact that the blind man already has formed the concepts of squares and circles - and the question is whether he can extend them to the objects in front of him.

Negative Answers Berkeley - and others that subsequently answered negatively - based their response on their belief that the blind man would have no spatial concepts at all (as referred in [15]). Von Senden also stated that 'Since nothing is given simultaneously to his senses as spatial, it must be mentally strung together in time [...] A spatial line must be replaced by a temporal sequence' (cited in [6]); this remark has some empirical validation in the experiment described in Chapter 3, in which some participants used time as a reference to determine the size of an object during a blindfolded exploration of a novel environment.

Positive Answers Leibniz was the first to argue in favour of a positive answer to Molyneux's question; he hypothesised that, by using logic and reasoning, the blind man would be able to tell the two objects apart. The enactive view also requires a positive answer to the Question for similar reasons (see Noë in [15]) - mainly, that the ability to represent spatial properties is derived both by sight and touch. The blind man, thus, must be able to recognise the two objects by sight on the basis of his tactile experience.

Neurophysiological Approaches Gallagher in [9] answers the question with a novel approach, on the basis of empirical and neurophysiological data. According to recent results in the field of Neuronal Development, neurons degenerate in animals in which a vision impairment has occurred within a critical period. Therefore, a Molyneux Patient, if born blind, would not have neural structures apt to recognize object, should he suddenly be given sight. His vision would 'be limited and quite different, not only from the normal adult, but also from the newborn infant'. Degenaar also suggests that Molyneux's question cannot be answered 'because congenitally blind people cannot be made to see after their critical period of development has passed' (as cited in [9]). However, Gallagher also remarks that perception is already intermodal from birth, i.e. during *in utero* development the senses already build their own means of communication.

This last approach is in slight contrast with the experiment carried out in [5], where a blind subject was provided with a brain implant capable of receiving visual stimuli from a video camera; the subject could perform basic tasks such as spatial navigation and object grasping. However, this last person has lost sight in his adulthood (at 36) and the electrode was implanted at age 44 - thus one can argue that the neural pathways and structures for vision were already in place, albeit possibly degraded.

2.3 Tactile-Vision Substitution Systems

In 1969, Bach-y-Rita employed a tactile-vision substitution system as "a practical aid for the blind and as a means of studying the processing of afferent information in the central nervous system" [2]; use of an array of stimulators allowed several blind subjects to perceive the world as if through a camera. This study opened a vivid debate about the nature of the phenomenological aspects of perception with sensory substitution devices (also known as "perceptual supplementation" devices for reasons given in [12]).

In the past half a century several research groups have conducted studies in tactile-vision sensory substitution. For a review of some noteworthy studies see [21]. In addition to employing the skin as a conductor for external stimuli - meant to replace visual information - researchers have also employed the tongue: its sheltered environment within the mouth contributes to an enhanced sensitivity ([3]).

Lenay and Steiner in [13] used a minimal Enactive Interface to investigate aspects of perceptual awareness, addressing in particular the issue of how such aspects relate to inner/outer spatial localisation. The authors show how *perception happens in the enacted space*, i.e. where the object is located; hence, cognitive activity is to be thought of as equally localised in brain, body, environment and in their mutual interactions.

2.4 Phenomenology and Other Issues

How to best interpret and characterise the perceptual experience reported by participants in tactile-to-vision substitution experiments? The use of third-person methodologies could lead to a debate based purely on interpretation of the verbal reports; such interpretations can be (and have been) contradictory and so far have led to lengthy speculations. In [8] Froese and Spiers address this issue by arguing that a solution 'requires the development of a phenomenological pragmatics', or a research program able to overcome third-person approaches. Furthermore, the authors emphasise the importance for the researchers themselves to become skillful in the use of the devices.

Petitmengin in [18] provides a methodology to interview an untrained subject describing a subjective experience. The experiments carried out for this work follow her guidelines (see Appendix A) in directing the subject's response towards a deeper understanding of the experience and in reporting it in greater detail.

Chapter 3

The Experiment

The experiment upon which this work focuses has three main purposes:

- to measure to what extent participants can perceive the position of a target in a novel environment with strictly controlled conditions;
- to test the validity of the Enactive Torch - a tactile vision substitution device - as a tool to investigate enactive spatial perception with minimal training;
- to explore the strategies emerging during the exploration of a simple environment, as a result of constraining the available degrees of freedom.

Furthermore, results can give rise to insightful speculations about the inner workings of perception within an enactive perspective.

In particular, our goal is showing that the ET is sufficiently powerful to allow for effective spatial exploration. We operate under the assumption that "vision" (spatial perception included) is an exploratory activity through sensorimotor *contingencies* (see [16]) and not a simple activation of internal representations of the outside world.

In order to replicate the results presented by Lenay and Steiner with a novel perceptual supplementation device, we combined the minimal interface of the Enactive Torch with a controlled environment, allowing participants in the study to explore the experimental set-up with one and two degrees of freedom (DoFs). The experiment is, therefore, organised in two separate tasks: the first involves displacing the Enactive Torch along a fixed axis on the horizontal plane (one DoF), whereas the second also employs rotation of the Torch about its centre on the same plane (two DoFs); the additional degree of freedom in the latter task provides a basis to involve the notion of depth.

We refer to DoFs in the experimental set-up as bodily degrees of freedom, although participants are not physically constrained to making use of only a part of their bodies. In this context, the term "bodily" is intended in relation to the richness of perceptual supplementation: the number of DoFs is equivalent to the degrees of freedom of a physical apparatus capable of detecting the same information, had nature endowed participants with one.

3.1 The Enactive Torch

The Enactive Torch (ET) has been designed by Froese and Spiers [8] as a cheap, non-intrusive and easy to build device such that it has the potential of becoming widely distributed to the research community, as well as being simple enough to use as to only require minimal training time.

From its conception the ET has served both as a tool to support the philosophical and scientific investigation of perception and as means to push the debate on perception beyond purely speculative accounts of third-person methodologies - thus opening a further path towards quantitative approaches. In addition, the ET allows investigation into sensory substitution mechanisms without having to resort to expensive and complex equipment.

Figure 3.1 displays a prototype of the device; its main body contains the power source (batteries) and the circuitry; the handle is equipped with an ultrasonic sensor mounted on one end, a small servo-motor with a rotating disc and a vibro-tactile actuator; the vibro-motor can generate a set of vibration patterns of variable intensity that can be felt by gripping the handle. In its normal mode of operation, the strength of vibration/angular displacement of the disc is proportional to the distance to the closest object in the sensor's range.

In this work, the servo-motor is inactive and the ET is employed in "binary mode", i.e. the strength of response can only assume two values according to whether or not an object is present in the Torch's field of perception. The maximum range in this mode of operation is limited to approximately 60 cm; objects are detected if localised within a cone of aperture ca. 30°.

Figure 3.1: A recent prototype of the Enactive Torch.

3.1.1 The Philosophy Behind the Enactive Torch

The first Enactive Torch prototype (named the Haptic Torch) was designed as an engineering project to build a non-intrusive navigation aid for visually impaired persons. It did not include a vibro-motor mechanism and had only a small rotating device to be placed under the thumb; the device encoded distance information, more precisely the distance from the nearest surface located in front of the Torch. The other novel element of the device was the presence of a single sensor, chosen to keep the information easily understandable to the user - even though the majority of navigation aids employ several sensors [personal communication with A. Spiers, Aug. 2008].

The potential applications of the Torch as a tool in the investigation of perception became clear afterwards. Within the debate about the effectiveness of second- and third-person methodological approaches in the study of enactive perception, in [8] it was first made clear how this device could aid researchers due to its ease of use, minimal training required and affordable cost.

3.2 Methods and Materials

The experimental set-up (see Figure 3.3) consists of a sliding platform placed over a 160 cm long rail; the platform can rotate and slide along the rail. Objects are placed in the test-space; the Enactive Torch is mounted on the platform, thus being constrained to motion in the horizontal plane. Use of the rotational DoF is permitted only for certain tasks. A picture of an experiment is shown as Figure 3.2.

In this set-up, objects are classified according to size in small, medium-sized and large; likewise, distances are classified as near (8 cm), medium (16 cm) and far (42 cm) with respect to the rail. There are one small and two medium-sized cylindrical objects, whereas only one large flat object ("wall") is present.

The conical shape of the sensor's receptive field gives rise to a counter-

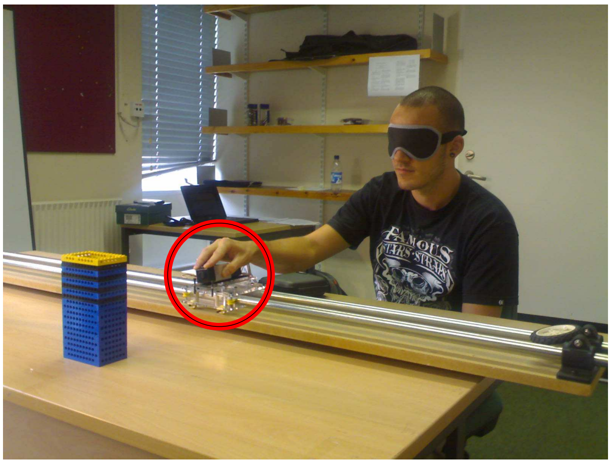

Figure 3.2: A participant during a training task. The red circle indicates the Torch mounted over the platform.

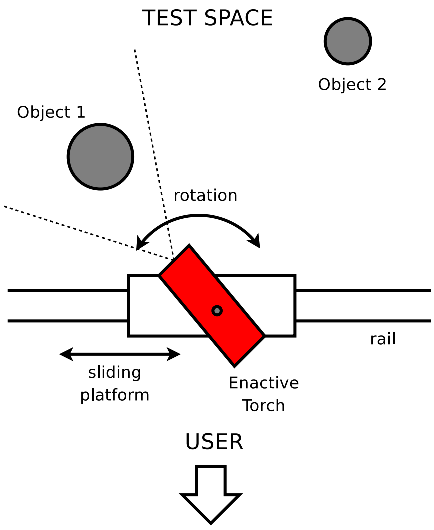

Figure 3.3: Experimental set-up; the user (indicated here by the large arrow) can perceive the presence of an object within the Torch's range by sliding and rotating the platform on top of which the Enactive Torch is mounted.

intuitive "inverse shadow" effect: the farther the object, the larger it appears (see Figure 3.4). To prevent users from perceiving distance as a simple function of apparent size, participants have been provided with an experimental situation that violates the regularity of the inverse shadow effect. To this purpose, the size of the the large flat object ("wall") has been chosen such that, when placed at a near distance, it appears as large as a small object placed far. Moreover, the wall is flat to discourage participants from paying attention to its depth, encouraging them instead to mark the object only by its distinguishing shape (during the distance-evaluation task explained in the next section).

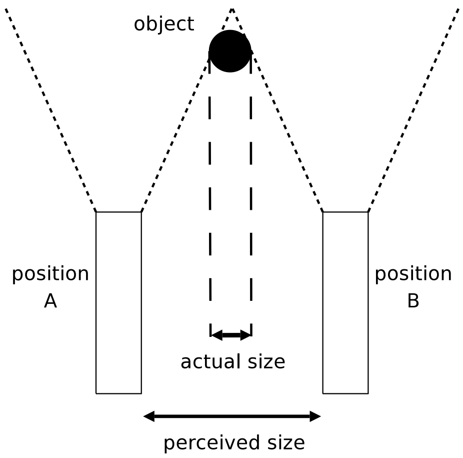

Figure 3.4: The *inverse shadow* effect: assuming the device is moving left-to right, the user will start perceiving the object at position A and stop perceiving it at position B. The object's apparent size is bigger than its actual size.

Sixteen participants volunteered to take part in this study, mostly amongst researchers in the fields of Informatics and Psychology. Participant mean age is 31.66 with standard deviation 12.77; there are two outliers (age 65 and 45). In the pool of participants, 43.75% are women, 86.67% declare themselves right-handed and 31.25% are non-native speakers of English. Two of the participants were already familiar with the ET device; however, the experimental tasks were novel to them.

3.3 Experimental Protocol

In order to determine how participants perceive spatial location, the experiment has been divided into two tasks, in accordance with the number of allowed degrees of freedom: the first one involves displacing the Enactive Torch along a fixed axis on the horizontal plane (one DoF), whereas the second employs rotation of the Torch about its centre on the same plane (two DoFs).

The experimental tasks also comprise subtasks; an asterisk marks subtasks used in the training phase. Further experimental parameters are gathered in Table 3.1.

1. Task 1 (sliding only, 1 DoF):
   (a) * count the number of items in the test space
   (b) * determine which object is larger
   (c) determine the centre of the object
2. Task 2 (sliding and rotation, 2 DoFs):
   (a) * determine near/far object
   (b) evaluate distance

The number of trials per (training) task ranges three to five, depending on the participant's confidence and on the percentage of correct answers. Participant are blindfolded when carrying out tasks and have been allowed to visually check their answers after each training trial; visual inspection of the test-space was not allowed in Tasks (1c) and (2b), to avoid implicit training. The visual inspection process allowed subjects to acquire a good ability with the ET within minutes from first use.

In Task 1c, participants were asked to explore the target space and point the ET at the (perceived) centre of the object; the experimenter then records the answer, replaces the object and starts the subsequent trial. The process is identical for task 2b , in which subjects are asked to classify the object's distance (either "near" or "far"; no object were placed at the "medium distance" marker for this task); the experimenter would record the answer, replace the object and ask the participant to perform another trial. Both tasks are carried out without any verbal feedback from the experimenter.

Since the ET operates in binary mode, the response is not related to the distance between the device and target objects; hence, the expected minimum number of DoF for which perception of *depth* can emerge is two. Experimental results confirm this hypothesis; see also section 3.4 for further investigation into this matter.

While carrying out the experiments, measures have been taken to minimize contextual clues - such as the noise produced by placing objects in the test-space - that could potentially be exploited by participants to answer successfully by means other than those intended.

During the training phase (visual inspection was allowed), at least one trial involved the wall and a small object placed at different distances. In this manner participants have been provided with negative evidence for the inverse shadow effect; participants reported feeling the need to develop a better strategy in order to overcome this apparent difficulty.

Subjects could reach both ends of the rail by extending their arm and,

task	no. objs	obj. size	obj. distance
1a	2-4	any	any
1b	2	different	same
1c	1	any	any
2a	2	different	different
2b	1	any	any

Table 3.1: Experimental parameters; a value of "any" in the third column means that objects could have either different or same sizes; a value of "any" in the fourth column means that objects were placed at a random distance among near, medium distance and far.

if needed, sliding their chair laterally.

3.4 Pilot Studies

During early phases of the experiment a small number of subjects have been tested on their ability to perceive distance by using only one degree of freedom. Such evaluation occurred in tasks (1a) and (1b), i.e. by reporting the number of perceived objects and their apparent size. Once proficiency in using the Torch has been achieved, subjects have been asked to report, along with the perceived size, also their estimate on object distance from the Torch.

All subjects but one admitted guessing on the perceived distance; in particular, one participant explicitly remarked that it is not possible to correctly tell the distance with only a binary input and a single degree of freedom, also considering that the distance/size relationship does not hold at all times due to the presence of the large wall-like object.

Anomalies When asked to evaluate distance, a participant spotted and exploited a particular feature of the ultrasonic sensor: when moving the Torch near the edge of an object, he noticed an inconsistent vibration pattern. If the object is close, the Torch starts vibrating immediately, whereas with farther objects vibration goes through a very brief discontinuity – thus giving the subject another bit of information and allowing him to judge the object's distance with very high accuracy.

This subject's reliance on the anomaly implies that his performance would depend on data that was not intended to be available; thus, he was not allowed to take part in the remaining parts of the experiment. No other participant detected this feature; inspection of their techniques to evaluate object distance shows a heavy reliance on triangulation and other methods that depend on exploitation of both degrees of freedom available. Further proof that other participants have not relied on the anomaly lies in the anomaly occurring only for extremely slow motion of the Torch in the neighbourhood of an edge - a behaviour that no other participant exhibited and maintained during the remaining tests.

3.4.1 Early Hypotheses and Different Approaches

This section briefly describes two alternative approaches to the experiment and the reasons for their dismissal. Section 6.1 will elaborate on the shortcomings encountered while exploring those alternative approaches and the current set-up and propose further improvements.

Navigation in a Larger Environment

One of the first experiment designed in order to investigate the validity of the Enactive Torch as a tool involved spatial perception coupled with a complete set of body movement.

Experimental set-up The experimental set-up for this investigation consisted of an empty room where the participant could move freely. After an initial training session an object was placed in the room and a blindfolded user was asked to:

1. recognise a familiar object (chair, ball, door, etc.);
2. interact with it (walk around, grab, exit through door);
3. describe its location relative to the starting position or other objects;

Purpose of experiment This experiment had two main objectives: to show the minimal training requirements for using the Enactive Torch; and to find common patterns in the Torch's movement (amplitude, frequency, direction, etc.) during the object recognition task. A secondary objective involved investigating the use of landmarks and episodic memory to determine egocentric position.

The training sessions were designed to be either null (thus leaving the subject free to correlate the tactile feedback with the external environment) or limited to a few minutes of free movement with open eyes. The object recognition task involved acquiring data from the Torch's accelerometers and comparing it to the complexity of the object itself and the vector of approach.

Difficulties The issues encountered with this experiment could be grouped in two main families: ethical issues and practical issues. Among the first group stands out the danger of having a blindfolded user walk around in a room with obstacles; a careless user could hurt him/herself easily (by topping over the chair or another low object). To avoid this problem the experimenter could guide the user or warn him/her of an impending danger; this solution, however, leads to a lack of trust in the experimenter-participant mutual relationship which in turn leads to unexpected behaviour from the subject. The experimenter's voice could also be used as a form of landmark (even though a radio transmitter could be used instead).

Among the practical issues encountered one of the most prominent was the choice of objects to be used: they had to be simple enough to be recognised by using the Enactive Torch (with minimal training) and at the same time complex enough to allow uncertainty and to encourage the user to explore new techniques of "seeing". However, there are too many objects we are "familiar with" in our daily life; telling the users in advance what kind of object they were expected to find biased highly their choice of strategy and the accuracy of their answer. Most test subjects exploited known characteristics of the expected objects (shapes, number of sharp corners, etc.) to be able to tell their nature with the smallest effort.

This last set of difficulties put the whole experiment at risk of being just a measurement of a single person's ability to recognise a shape (involving memory, creativity, familiarity with the object - all aspects that are extremely difficult to control as experimental conditions) and not of the capabilities of the Torch itself as a scientific tool. Therefore it has been opted to investigate first a minimal (and highly controllable) set of environmental conditions.

Restraining the Participant's degrees of freedom

Given the requirement for a minimal setting, and in order to show the validity of the Torch as a tool to study enactive perception, the work of Lenay and Steiner ([13]) has been taken as a model. A similar experiment was designed to replicate their results in a stricter set of conditions; the one-dimensional landscape was kept as a source of feedback, and the participants' movement were restrained.

Experimental set-up This experimental set-up consisted in a room where the participant was meant to be taken blindfolded. The Torch was held in the subject's hand but her arm's movement were impaired by a restraining device apt to limit the degrees of freedom of the joints. Once in the room the subject had to locate some vertical objects (poles) around her by moving the Torch on the horizontal plane. Subsequently a further degree of freedom was allowed to the participant (movement of the wrist), and more explorations of the surrounding space were requested. The user was then asked to estimate the distance of the vertical objects with respect to her current location by combining the wrist's displacement and the arm's rotation.

Purpose of the Experiment The purpose of the experiment was to show how two degrees of freedom are sufficient for a successful exploration of a bi-dimensional space in the enactive domain. As for the current experiment, the Torch was meant to be used in binary mode, thus giving a feedback only if an object was detected within range.

Difficulties The major issues in setting up this experiment concerned the restraining of the bodily degrees of freedom. Even by having the subject sitting on a chair, minor dislocations of the shoulder or of the hips gave enough information to do a very rough triangulation on the pole's position without moving the wrist.

Furthermore, the arm-restraining device turned out to be difficult to adapt to the various participants; arms of different length and size made this device either too long or too short to keep the arm's available movements under control. Asking the users not to move their wrist or shoulder in any way was not considered as a viable option for a proper controlled environment.

On a side note, the current Enactive Torch prototype has been programmed to have a small sensory range (around 60 cm) when in binary mode; this also impacted the choice of the experimental set-up to be limited roughly to the depth of a common work surface.

3.4.2 Improvements to the Experimental Set-Up

During the performed experimental runs several improvements have been noted; their importance was not considered vital for the successful outcome of the tests and they are reported here as a guideline for future replications of this work.

Acceleration and Movement The current Enactive Torch prototype has a 3-axis accelerometer built in; its purpose was to be an aid in measuring the magnitude and the frequency of the Torch's movement in space. By doing a simple numerical integration it would have been possible also to measure the Torch current position relative to the starting point.

Due to the tight constraints of the experimental set-up and the use of the vibro-motor as a form of tactile feedback no recordings were possible:

- the movement of the Torch was limited to the horizontal plane; moreover, the short length of the rail induced most participants to give little acceleration to the device, thus rendering the accelerometers useless given their poor sensitivity to small scale accelerations;

- the vibration of the motor resonated on the Torch platform and the rail, causing severe interference in the data recorded by the accelerometer. Adding a damping support would have allowed too much movement on the Torch, especially on the horizontal plane, when it was not allowed.

The best way to record movement probably would be a pointing device (i.e. a Laser light or a bright colour painted on the device) tracked on a surface just in front of the torch or by a head-mounted camera; this data would give a very good distance estimate between the Torch and the pointed object, especially during the tests which involved rotating the torch on the horizontal plane.

Another solution could involve the use of an odometer mounted on the torch platform; coupling this device with a known starting point and known locations of the targets will give enough information to track the Torch's movement with a satisfiable accuracy.

Using the servo-motor Even though the current Torch prototype is equipped with both a vibro-motor and a servo-motor, the latter one has not been used for the experiments. Due to its placement on the a side of the Torch, its usage would have affected some strategies (see section 4.2.4) where some users used both hands to perform certain tasks. The servo-motor requires a finger to be in the same position for the entire test.

Given the issues experienced with the recording of the accelerometer data, however, the use of the vibro-motor could be exploited by compromising on its location: further experiments might be carried on by removing the disc from the handle and handing it to the participant who would be free to hold it in the most comfortable way.

Torch Range and Sensitivity Angle The ultrasonic sensor range posed a significant challenge to the successful run of the experiment: as described in previous sections the sensor has a cone of sensitivity which caused the "inverse shadow" effect. Furthermore, this cone affected the available working area: if the Torch is placed on the same level of the target object it would "pick up" the table itself, thus voiding any feedback.

To overcome this issue the height of the platform was increased by mounting the rail over a higher surface. Moreover, the depth of the working area had to be limited to ca. 60 cm. A solution would involve narrowing the sensitivity of the ultrasonic sensor to a sharper angle when the Torch is used in binary mode; this would reduce also the impact of the "inverse shadow" effect, limiting as well the probability that a user would exploit the size/distance relationship to predict the distance of the object.

Chapter 4

Results and Discussion

The following table restates each task followed by a brief description; an asterisk marks subtasks used in the training phase.

task	training task?	description
1a	*	count the number of items in the test space
1b	*	determine which object is larger
1c		determine the centre of the object
2a	*	determine near/far object
2b		evaluate distance

4.1 Results

Task (1c) was achieved successfully by all subjects in every trial with a remarkable degree of accuracy in identifying the centre of the target object. Reported centres generally differ by no more than 1 cm from actual centres. Since the ultrasonic sensor is slightly inconsistent across object shapes and textures, an error of 1 cm is a reasonable upper bound on performance; it has not been considered necessary to look for greater accuracy.

The only exceptions to the 1-cm upper bound occurred in two trials,

participants	correct answers	std. dev
all	81.25%	0.2627%
with strategy	88.1%	0.1597%

Table 4.1: Results of Task (2b); the figures in the first row are comprehensive of two subjects who reported not having developed a strategy and simply guessing the distance.

with subjects "missing" the correct center respectively by −2 cm and +3 cm. This situation was in all likelihood originated by an unlucky combination of shape, texture and speed of movement with a glitch in the ultrasonic sensor: vibration ceased while the object was still in the sensor's range. Subjects reasonably assumed an incorrect size and reported the expected center; the same participants reported within the 1-cm bound in all other trials.

Table 4.1 shows the figures for Task (2b). Participants correctly classified distance as near or far in 81.25% of the cases (standard deviation is 0.2627). Participants who report using a strategy correctly classify distance in 88.1% of the cases (standard deviation is 0.1597).

4.2 Discussion

Most participants reported consciously attempting to generate a strategy to carry out the task at hand, in particular with respect to the more elaborate tasks (2a) and (2b). Reported strategies can be categorized as *cognitive*, *intuitive* or *unknown*. The cognitive category consists of all approaches that are based on explicit geometric/analytical thinking; once a strategy has been developed, the participant tries to carry it out, as if performing the steps specified by an algorithm. The intuitive category serves to capture approaches that rely on intuitive feelings or on pre-reflective bodily skills; in

strategy group	subjects	correct ans.	std. dev
cognitive	11 (68.75%)	90.91%	0.1485
intuitive	3 (18.75%)	77.78%	0.1571
unknown	2 (12.5%)	33.34%	0.33

Table 4.2: Results of Task (2b) for different strategies. The first column shows the number of subjects who belong to each category

a sense, participants are exploiting their bodies as natural enactive learning machines, in a manner much akin to training neural networks. The last group (unknown strategies) accounts for participants that did not report on their strategy (if any was developed).

In the cognitive group, some participants chose to elaborate a strategy before starting Task (2a), whereas others preferred to attempt the task at least once before developing a strategy that would fit their perceptions.

Table 4.2 shows the results for each group related to Task (2b).

This spread of strategies indicates that the perception of space and depth is not necessarily constituted by cognitive inference, although cognitive inference remains a possible strategy. Further phenomenological research is needed to specifically evaluate the range of strategies, identify the most advantageous (if any) and evaluate the impact of the chosen strategy on factors such as speed of response and confidence in the correctness of the answer.

4.2.1 Cognitive strategies with one DoF

When the ET was limited to only sliding along the rail, the sole strategy reported is based on a constant speed of the platform, coupled with a rough estimate of the time required for the Torch to "traverse" the object. Although only four participants explicitly reported having adopted this method, it has been observed in others as well.

With respect to body movement/awareness, it is interesting to note that all participants tried to minimize the number of moving parts: three subjects were observed to only move the arm and keep the rest of the body still, whereas three others kept the arm fixed in position and moved the body instead (by sliding their chair laterally). One participant reported using the elbow as a marker for the location of an object's earliest detection; the marker was later exploited to yield an estimate of the object's size, as per Task 1b.

4.2.2 Cognitive strategies with two DoFs

The extra degree of freedom in Tasks (2a) and (2b) lends to a broader range of more elaborate strategies, in comparison to the approaches developed for the previous tasks. The most frequent strategy (observed in seven participants) consisted in pointing the ET at the centre of the target object and rotating it in both directions until the object was out of the sensor's range. This behaviour not only proved successful, but also actively exploited the experience acquired during Task 1c, even though subjects were not allowed to verify the correctness of their approach by visual inspection.

Another approach relied on the inverse shadow effect to give a rough estimate of distance as a function of perceived size; even though all subjects were aware that the regularity holds only for same-shape objects, four participants reported using it as an initial estimate, switching then to rotation as a method to validate their guess. In particular, by rotating the ET, participants were able to detect if the target was the wall - if not so, then the inverse shadow effect can be thought to approximatively hold. When the target object was the wall, the task took significantly longer to complete, albeit consistently with the correct answer ("it is a near object").

An interesting example of strategy-switching comes from a participant whose approach in Task (2a) consisted in positioning the ET approximatively halfway between objects and rotating the handle until the target object was out of range. The extent of rotation was used as an inverse correlate of distance. However, since Task (2b) is a single-object task, this approach could not be applied and the participant switched to a different approach, which consisted in sliding the Torch in one direction until it reached the end of the object; at this point the Torch would be slid and rotated in the opposite direction, tracing out tangents to the object. The rate of decrease of the angle was used to determine the object's distance.

Only one participant devised a strategy based on landmarks for Task (2b). The end of the rail can be reached by stretching out the free arm and serves as the reference point; the ET is then rotated, up to a 90° angle, until the device detects the object. The landmark can then be exploited to deduce an estimate of the object's position. This strategy involves sliding the ET "backwards" on the rail while rotating the handle towards the landmark and adjusting the angle until the target is no longer in the sensor's range. If empty space is detected between the object and the rail, the object was reported as being "far".

4.2.3 Intuitive strategies

A small number of participants reported using "feelings" and not elaborating an explicit strategy for the required task. Table 4.3 details the number of subjects revealing this behaviour.

When asked to elaborate on this, three subject explicitly reported finding it difficult to move the device at a constant speed (Tasks 1b and 1c) and

tasks	subjects
(1b) and (1c)	3
(2a) and (2b)	3

Table 4.3: Number of subjects explicitly reporting using an intuitive strategy for a set of tasks. Note that only one participant used such strategy across all tasks.

having to rely on "sensations" to estimate the size of objects (one of them reported using an "imaginary space" to measure them). With respect to Tasks (2a and 2b), three subjects explicitly stated not being able to find a correct strategy for the distance estimate and deciding to rely on senses and perceptions rather than on analytical thinking.

4.2.4 Further Remarks

Two participants used both hands for all tasks, even though they had been instructed to place only their preferred hand on the handle; one hand was used to guide the platform along the rail, while the other hand was firmly placed on the handle and controlled rotation. One of these participants reported having difficulties with stereopsis in everyday life and encountered difficulties in Task (2b) because of "the lack of references". Movements were extremely slow and the subject strove to explore new strategies that could lead to the right answer.

Two other participants used the right or the left hand, depending on the positioning of the ET relative to the body. Although not ambidexterous, these participants decided to use their non-preferred hand on the grounds that "it felt more natural".

Participants' reports include some salient observations that do not directly pertain to strategies but can be useful in assessing which cognitive and perceptive traits are connected to enactive exploration with the ET:

1. Three subjects report that spatial exploration with two DoFs felt like being able to see around the object.

2. One participant described spatial exploration with two DoFs as "projecting my consciousness forward"

3. Five participants repeatedly experienced surprise during visual inspection of the test-space, for the sharp contrast between perceived size and actual size of the objects. It took a few trials before subjects were able to internalize the inverse shadow effect and complete the remaining tasks normally.

4.3 Conclusions

In [16], the act of "seeing" is considered as "the ability to modify sensory impressions in certain law-obeying ways". The present work treats the notion of sight as inclusive of spatial awareness, as perceived through a distance-to-tactile perceptual supplementation device.

Our experiment supports the idea that enaction is a fundamental mechanism in spatial perception; with respect to use of perceptual supplementation devices in investigating spatial cognition, it has been shown that the Enactive Torch is a viable choice for experimental methods; the ET has proven advantageous by virtue of its simplicity and ease of use, in addition to requiring minimal training time. Furthermore, this experiment verified that spatial awareness and perception of depth are in direct relationship with bodily degrees of freedom.

Chapter 5

Simulation

This chapter describes the structure of a computer program designed to evolve exploratory strategies for a virtual environment similar to the one described in chapter 3. The purpose of this program is to provide an evaluation mechanism to compare such strategies.. The source code is listed in Appendix B.

The program consists of three main components, each representing a different aspect of the experimental set-up:

- the environment;
- the strategies;
- the mechanisms to implement the evolution of strategies;

Each strategy is evaluated by applying it to randomly-generated scenarios. Data collected is passed as input to an artificial neural network (ANN), which is trained to predict the centre of the nearest object. Subsequently, the strategy is applied to new scenarios and the ANN is tested on the new data set; the performance accuracy determines the strategy's fitness.

A genetic algorithm evolves and compares different strategies over several generations. Better strategies survive, whereas strategies performing worse (on average) are discarded and eventually mutated to produce new offspring.

5.1 Environment

In order to recreate conditions similar to those experienced by participants in the experiment, the Environment (called "scenario" in the program) is defined by:

1. a limited space;
2. a "sensor", with an angle of reception and sliding/rotational capabilities
3. two "objects" of different size, distributed evenly in the area in front of the sensor;

Each object is placed either "near" or "far" from the sensor. New environments are generated for each trial; the objects are guaranteed not to overlap.

5.2 Strategies

A "strategy" is a collection of "actions" and "conditions". Possible actions are:

- move left;
- move right;
- rotate left;

- rotate right;
- jump left;
- jump right;

whereas conditions are:

- the sensor's status becomes 'on' (i.e. an object is currently within the reception angle);
- the sensor's status becomes 'off';

Each action changes the sensor's position (or rotation) by a fixed amount in the requested direction until a particular condition becomes true. The "jump" actions are used to support a form of landmarking: they do not require any condition, but move/rotate the sensor passively.

Strategies can have different lengths; the program allows the user to specify an initial and a maximum strategy length.

5.2.1 Evaluating Strategies

The evaluation process of a strategy includes a training phase and a testing phase. Training proceeds as follows:

1. a new, random scenario is generated;
2. the strategy is parsed: each action is applied to the current values of sensor position/rotation, until a specific condition is met;
3. for each step of the strategy (namely, the action/condition couple) three values are stored: sensor position, rotation and status;
4. once the strategy has been entirely parsed, the stored data is passed as input to an artificial neural network;

5. the ANN is trained (with the backpropagation algorithm) to compute as output a value as close as possible to the centre of the nearest object (known *a priori*);

Every ANN undergoes several training phases, each one comprising of a new scenario. After a user-specified number of training iterations, the network is tested with a procedure similar to the training one; the only difference consists in the absence of network training, to be replaced by network *testing*. Mainly, the ANN is executed only once, and the output value is compared to the expected value (the centre of the nearest object).

The testing phase is repeated several times (according to a parameter specified when running the program) and the average correctness of the network is the *fitness* of the strategy (although technically it is an *error measure*).

5.3 Genetic Algorithm

The genetic algorithm evaluates two strategies by comparing their fitness: the "winner" is kept while the "loser" is either mutated or cross-bred with the winner.

The mutation procedure either changes a "gene" in the loser's genotype (the strategy, being a collection of symbols, is fit to serve as a genotype) or adds/remove a gene. In the former case, either an action or a condition is changed to a different value; in the latter case, a random action and the corresponding condition are removed or added from the genotype. It must be noted that the adding procedure does not necessarily add an action/condition couple at the end of the string, but could add it at any location.

The cross-breeding procedure takes a gene (an action/condition couple) from the "winning" strategy and copies it into any place of the "loser's" genotype, either overwriting part of the "loser's" strategy or appending it to its end.

Every newly generated individual is stored in a hash database to avoid repeating the time-consuming evaluation of its fitness.

5.4 Results and Analysis

A sample run of the program yields the following strategy:

`412161624200000`

Decoded as follows:

- `41` rotate rightwards until an object "disappears"
- `21` move rightwards until an object "disappears"
- `61` jump right
- `62` jump right
- `42` rotate right until an object "appears" or until the end of the track is reached

Initial parameters were:

- maximum population size: 500000 individuals
- maximum number of generations: 100000 (runs of the genetic algorithm)
- maximum number of *epochs*: 5000 (trials for the ANN training)
- minimum error of the ANN: 0.001
- maximum strategy length: 8 action/conditions couples

- initial strategy length: 5
- number of training phases: 100
- number of testing phases: 100

The evolved strategy had a fitness of 0.018046 - on average, its predictions of the centre of the nearest object are accurate with an error of 2%. Moreover, the strategy does not extend to the maximum genotype length available: in fact, longer strategies were less effective in predicting the nearest object.

This evolved strategy, albeit perhaps slightly counterintuitive, shares salient features with strategies developed by human participants: it is relatively short and accurate; uses every possible action available with respect to a certain degree of freedom; introduces and exploits the concept of "jumps" to better explore the environment; it requires a certain number of evolutionary steps to emerge, similar to the minimal training required by the participants in the experiment (the strategy appeared around the 6500th generation and survived beyond the 32000th generation, when the program was interrupted).

5.5 Conclusions and Future Work

Evolving strategies shows how it is effectively possible to explore a bi-dimensional space using two degrees of freedom in order to determine the distance of an object. The evolution of a successful artificial strategy for depth discrimination effectively shows that it is possible to explore a 2D space and discriminate the distance of an object, using a supplementation device with two degrees of freedom. The best evolved strategies can be compared with those developed by participants in the experiment: if quantitative data were to be recorded, a human-developed strategy can be encoded as an artificial genotype and evaluated along with evolved strategies.

Furthermore, by adding some form of Gaussian noise to the simulation, it would be possible to determine the minimum sensor performance required for such task - for both humans and computers alike.

Artificially evolved strategies can also be employed to study the *enactive* requirements of human perception: for example, a good artificial strategy might produce data which, when provided to a trained subject through a feedback device, might not be sufficient to understand the position of the nearest object - although the strategy has been proven to be *logically* adequate for the task. This would underline the importance of enactive - as opposed to passive - perception and provide means of studying this peculiar brain's mechanism.

Chapter 6

Future Work

The following sections address future investigations and propose guidelines based on the analysis of the experiment presented in Chapter 3 and on the philosophical and practical questions raised in Chapter 2. Section 6.1 presents an assessment of the shortcomings in the current experimental set-up and shows how improvements on its weak points can allow tackling new and relevant scientific questions. Section 6.2 expands further on such questions and presents new experiments - capable of targeting different aspects of the same issue (i.e. sensory adaptation, plasticity involved in complex tasks, etc.).

6.1 Improvements

Investigating strategies

As stated in section 4.2, it could be profitable for further research to specifically evaluate individual strategies, by resorting to quantitative comparison of experimental data and by relating the results to qualitative data, as reported by participants.

An interesting approach could correlate a detailed record of the device's movements (speed, frequency of motion inversions, angular displacement) with the degree of confidence reported by the participant in the correctness of her answers. In such a manner, a possibility opens up to measure both implicit and explicit strategies, so as to relate their effectiveness across participants. Furthermore, this approach has the potential to shed light on the nature of the strategies labelled as "intuitive strategies" (described in Section 4.2.3) and possibly assist in further classifying them.

Stereoscopic Enactive Perception

One subject of the experiment reported curiosity regarding a hypothetical use of two tactile devices employed simultaneously. An improvement on the current experimental set-up could employ two Enactive Torches to gather data on degree of confidence and strategies pertaining to a "stereoscopic" tactile-to-vision substitution system. Such experiments could show how the brain adapts to a richer enactive experience.

A key feature here lies in the partial redundancy of the sensory inputs (for example, when both devices point towards the same object) as opposed to an augmented perception (which occurs if the granularity of the sensor is improved).

New Objects

In the experiment presented in this thesis, the variety of objects involved has been rather limited, in order to minimize the duration of the training phase. Had minimal training not been a requirement for participation in the actual experiment, trials could have been carried out with a richer set of object types - in particular, with object types not encountered in the training phases.

Introducing novelty in objects types can lead to better exploration of the size-distance relationship; users can be tested for their ability to recognise a new "shape" and to relate it to other object types.

6.2 New Experiments

Sensory Field Inversion

Thanks to advances in computer technology, in recent years it has been possible to replicate early studies in Sensory Field Inversion. For example, in [17] simple robots are trained to follow a specific environmental clue. Once stability has been achieved, the robot's sensors are inverted. Results show that adaptation takes place spontaneously and in a relatively short time.

Early studies involved experimenting with subjects wearing specially-crafted goggles, to induce left- and right- vision inversion or distortion in visual features; see for example [11].

Further investigations in this area can be pursued by using the Enactive Torch in a new modality. Participants can be trained using the Torch in "full mode", i.e. with a vibration pattern directly proportional to the distance of the nearest object in front of the sensor. After training, the Torch can be switched to a vibration pattern inversely proportional to the distance, thus effectively implementing sensory field inversion.

A quantitative study can also be accomplished by measuring the Torch movements in space (using accelerometer data) and the subject's location within the environment. Implicit training can be achieved not only by visual inspection (the participant is allowed to see the environment after each trial) but also by tactile inspection (the subject can reach out and touch the objects with the free hand). Both methods allow investigating adaptation to sensory field inversion.

Additional Degrees of Freedom

A further experimental investigation could involve navigation in a larger environment without any constraints on the bodily degrees of freedom. As described in Section 3.4.1, a user in this setting moves freely in an unexplored space; the Torch's orientation and spatial location over time can be related to measures of subject confidence. Such an approach can assess the minimal training required in order to accomplish basic tasks of navigation and interaction.

Variants worth pursuing are:

Object retrieval A participant is asked to locate a certain large object (e.g. a table, a chair) and retrieve a smaller object placed on top of it; on the way towards the object the user can use the free hand to help locating obstacles and determine their distance (training phase); on the way back the hand is busy holding the small object, thus the user is forced to rely on memory and focus attention on the data flow coming from the device.

Recognition of shape and size A participant is asked to draw pictures of objects after having explored them with the Torch. Recorded data is aimed at assisting in classifying strategies, which can be compared with strategies evolved by artificial organisms or inspire new methods for navigation and object recognition for simple robots.

Social Interaction A simple version of this experiment consists in a room with three persons. Two are blindfolded and given an enactive device; their task is to locate the other Torch user. This experiment measures the amount of social interaction required to recognise a partner exhibiting similar behaviour.

In all experiments care must be taken in order to avoid intervening experimental condition (auditory clues, physical harm, etc.) that can impact results or their reliability.

Chapter 7

Conclusions

This work has shown how the Enactive Torch, a minimal tactile-to-vision substitution device, is a valuable tool in the context of constrained spatial exploration of a novel environment by minimally trained participants.

Experiments on spatial perception with sensory substitution devices (Chapter 3) show that human subjects approach depth discrimination tasks by resorting to a strategy; participants developed either *cognitive-* (based on reasoning) or *intuitive* strategies. Effectiveness of both approaches was measured, with the former yielding better performance (90.91% vs. 77.78%).

Artificial strategies have been evolved by a computer simulation working in a scenario similar to the experimental set-up; some such strategies have been shown to be also effective for spatial exploration, in particular with respect to object localisation and depth discrimination. Artificial strategies of the type implemented here serve as means of comparison for human cognitive strategies, which can be likened in some respect to algorithms as encoding explicit procedural knowledge.

The experiment emphasised the importance of *enactive* perception as a fundamental mechanism of spatial awareness, thus showing how the Enactive

Torch is a valid tool for research in the field of sensory substitution. This work also underlines the importance of first-hand approaches in the study of perception.

Lastly, this experiment verified that spatial awareness and perception of depth are in direct relationship with bodily degrees of freedom (intended here as the degrees of freedom of the Enactive Torch itself).

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Appendix A

Interview session

This appendix is a transcript of an experimental session. Text in square brackets provides contextual information, in case it not be discernible from the original tape (i.e. action being taken, etc.).

Experimenter: Hello and welcome to the experiment. The purpose of this experiment is to study how people can perceive objects in space using this device, which we call the Enactive Torch. Your session will be recorded, if you agree.

Subject: That's ok.

Experimenter: Good. A couple of things first: this is what we call the Enactive Torch. The device will give you a vibrating feedback every time an object is placed in front of it. Its sensor has an angle of perception - which means that an object which is closer feels smaller than an object which is far away because of this angle. If you want to try it first...

Subject: I see [tries the Torch]

Experimenter: The second thing is a Tail Effect, which means that when you move the Torch in front of an object it might start vibrating earlier with some sort of non-constant vibration, giving little 'peaks' of vibration and might stop vibrating for a few moments. This tail effect depends on the speed, the texture, sometimes on different angle of approach. The instrument is not really precise sometimes; objects might disappear briefly. This is just to give you an idea of what might happen during the experiment.

Subject: Ok.

Experimenter: You will be blindfolded if that's ok with you. You can take a break any time; if you have questions do not hesitate to ask; if you also want to think out loud, please do so.

Subject: Ok.

Experimenter: As a first exercise, I'm going to ask you to count the number of objects on the table, by moving the Torch. If you can blindfold yourself, I'm going to put some objects and ask you to count them. Tell me when you're ready.

Subject: [puts the blindfold on] I'm ready.

Experimenter: Ok, you can start.

Subject: [moves the Torch] here is one.. possibly one very long object... seems to be a slight gap there, and another object there. There's a gap now.. another object here.. there's possibly a gap there also.. one, two, three objects... [goes back and forth] .. four.. [thinks about it a little]

Experimenter: You can change hand if it's uncomfortable

Subject: Ok. Here's one.. two.. [moves the Torch slowly] I suspect what I'm feeling here it's not multiple object but just some sort of interference with some thing... Yes, I'm not really sure, possibly six

Experimenter: Ok, do you want to check?

Subject: Sure. [removes the blindfold, sees only three objects] I see now. Right.

Experimenter: This is what I meant before. For example here [points to an object] you said that there might be some kind of interference, and in fact it is a single object. If you want to try it again...

Subject: Right, just on the edges it feels like there are some more...

Experimenter: Also, here in the middle the Torch stopped vibrating for a bit; perhaps the texture of the object, or the sensitivity of the sensor

Subject: That's interesting.. Actually using sight is quite helpful for understanding what this thing is telling me

Experimenter: Yes, this is all part of the training phase; you can check the results after each test. Shall we do one more?

Subject: Yes. [puts the blindfold on]

Experimenter: [positions objects on the table] Same thing as before: multiple objects will be on the table, you just have to tell me how many you think there are. Start any time you are ready...

Subject: [moves the Torch around] I can sense one here... another there, if it's not your hand.

Experimenter: No, it was not me.

Subject: Ok, I'll say two. [removes the blindfold]

Experimenter: Correct. Any remarks, any feelings...?

Subject: Yes. Surely the angle you mentioned before is confusing, it feels like the objects are very very big...

Experimenter: Yes, this angle-thing is confusing and somewhat counter-intuitive. Let's do one more..?

Subject: Ok. [puts the blindfold]

Experimenter: [quiet]

Subject: Two objects.

Experimenter: Ok, do you want to check?

Subject: [removes the blindfold] Yes, I see. That's really interesting, you can feel it significantly different from the other objects. [refers to the large wall-like object]

Experimenter: Exactly, this is the reason for having this flat large object; it will not give you any idea about a relation between size and distance

Subject: Ok.

Experimenter: Good. We are moving now to a new section of the experiment, in which I will put just two objects on the table. Both of them will be at the same distance, and might have different sizes. Your task will be to tell me which one you think it bigger or smaller, or if they both feel the same.

Subject: Ok. [puts the blindfold on]

Experimenter: There we go. You can start.

Subject: Here's one.. that's a quite small-feeling.. [moves to the other object] feels relatively the same size, actually. I'd say they are equal

Experimenter: Ok. Do you want to check?

Subject: [removes blindfold] It was right.

Experimenter: Yes. Please remember that we are still in the training phase, so it does not matter much - the correctness; it is meant more to make you feel comfortable with the Torch. Would you like to add anything?

Subject: No.

Experimenter: Ok. Let's do another trial. Same task as before, two objects.

Subject: [puts the blindfold on] This one has a smaller feel in terms of vibration, so intuitively it feels further away, but I think you said it's the opposite fact...

Experimenter: Also, they are at the same distance in this task

Subject: Oh, ok. So this one is smaller. [the two objects have practically the same size, although one is circular and one is rectangular]

Experimenter: Ok. Do you want to check?

Subject: Ok. [removes blindfold] Oh, I see

Experimenter: Yes, there is no difference between them, when moving the torch in front. Let's do one more...?

Subject: Ok. [puts blindfold] This one feels slightly longer. [the two objects were far away and had different sizes; the subject points to the larger object declaring that it is smaller]

Experimenter: Ok. You can check.

Subject: [removes blindfold] Oh. I see.

Experimenter: Do not worry. At this distance objects might feel larger, especially when they have sharp edges. Probably the sensor picks up the edges, also biased by the movement.

Subject: Ok.

Experimenter: Do you want to add anything?

Subject: No, I don't have much to say.

Experimenter: Ok, let's do one more

Subject: [puts blindfold on]

Experimenter: Ok, you can start

Subject: This one is bigger

Experimenter: Would you say much bigger or slightly bigger?

Subject: I'd say not much bigger but definitively bigger. Perhaps four times the size...?

Experimenter: Ok, you can check.

Subject: [removes blindfold]

Experimenter: Good. If you don't have any further remarks... we are going to move to the next task, for which you will not be allowed to check your results. I'm going to put just one object on the table, and you'll have to find its centre. Which means you'll have to find the object and, when you think the Torch its located in its centre,you'll tell me. I will check it, remove the object from the table, put a new one, and tell you to start again.

Subject: Ok.

[no verbal communication takes place for this task; the subject located the centre of the object in two trials out of three]

Experimenter: Ok, we're done. Do you want to check this last one?

Subject: Ok.

Experimenter: It was very accurate.

Subject: Yes, that's interesting.

Experimenter: What is interesting? Please tell me

Subject: Well, a couple of things. First, when I'm moving, I'm getting vibrations from this - which is interfering a little bit. But, I do find the opposite/intuitive thing quite weird, I find it very hard to adjust to it. That one felt like a very slim object but you have to reverse what you think...

Experimenter: Yes, in fact it is interesting to see how people develop strategies around this, and adapt their [interrupted]

Subject: yes, what I'm feeling is a very slim object, so I have to mentally say to myself: "no, it's not like that"

Experimenter: I understand. Now, if you are OK we can move to the next section of the experiment, which introduces rotational capabilities.

Subject: Sure.

Experimenter: Good. Now I'm going to put two objects on the table: they can be of any combination of size and distance, but there will be just two objects. I'm going then to ask you to tell me which one you think is closer, or if they are at the same distance.

Subject: Ok.

Experimenter: Feel free to explore the space as much as you want and to tell me at some point "ok, I think the left one is closer, or the right one..."

Subject: Ok. [puts the blindfold on]

Experimenter: Ok, you can start.

Subject: So, intuitively this feels very very big and that feels very very small. But I suspect what that means is that this one is further away.

Experimenter: Do you want to check?

Subject: [removes blindfold]

Experimenter: So, I take that you were using the size/distance relationship, right? What about the rotation?

Subject: Well, ok. I was doing two things: first scanning like this, in ways I was used to previously, to get a sense about how they relate to previous objects, and then trying to find the edges by rotating, to get an idea of some sort of triangulation.

Experimenter: Sure. One more now, please

Subject: Ok [puts blindfold on] ... I find this one harder to tell the difference between the two objects... I think they are kind of similar... Again, I'm getting confused by what I intuitively feel and what I know about their [unrecognizable word]. It feels to me, naturally speaking, that the one on my right is further away and the one on my left is closer but I have to think that's actually the opposite case. My answer is that the one on my right is closer. [the final answer is not correct]

Experimenter: Ok. Do you want to check?

Subject: [removes blindfold] Oh. I was confused then. I really was. I wonder if this happened when I was adapting to this belief that it is the opposite way around, and I'm in a transitional state at the moment.

Experimenter: Could be.

Subject: That's actually what it felt like. Previously it hasn't felt like that.

Experimenter: When you say 'that' it means that you are "feeling", literally, the position of the object or that you are thinking either intuitively or by reasoning "it has to be this way or another..."

Subject: It felt that by moving around and doing this angle-thing trying to find the point that comes into view on either side I was again doing this triangulation, so to detect the object.. but it felt like it was there [pointing at the object far away], and again for this one [the closest one] it was very big and I was trying to compensate by reasoning, thinking that it must have been smaller...

Experimenter: Ok. Another one, please

Subject: [puts blindfold on] Ok. I think it's the same situation again. Actually I suspect that it's exactly the same position, that one feels closer and that one feels further away. [this time the objects are located at the same distance, but have different textures and shapes; one is cylindrical, the other has a rectangular shape. In the previous trial the two objects were located at different distances]

Experimenter: Ok. Check please.

Subject: [removes blindfold] Ah, ok. Right.

Experimenter: I had a similar situation happening before - two object at the same distance, both of them had the same size, but nearly everybody felt that this one [points to the curved one] was closer.

Subject: I wonder if it is due to the curvature.

Experimenter: Perhaps. How did you feel that this one was closer?

Subject: I really suspected that they were the same pieces in the same positions, because this is kind of what it felt like. Again, trying to find the angles was not a very clear distinction between the two, and it was quite hard to tell.

Experimenter: Ok. One more trial please.

Subject: [puts blindfold on] I think I got stuck, there's something here [removes the cable that goes from the Torch handle to the Torch body, then continues the trial] Ok. I think this one is closer. [points to the closer object]

Experimenter: Ok.

Subject: [removes blindfold] That's not a surprise, this configuration. I think it does take me some time and I have to do it again and again to work out what it is I'm experiencing.

Experimenter: Ok. Now, for the last set of experiments we are going to move to the proper experimental part, so you will not be allowed to check your responses. Now I'm going to place just one object on the table; it might be close or far away and you'll have to tell me which one is the case.

Subject: Sure.

Experimenter: As before, you'll tell me your answer, I'm going to say "Ok", replace the object and you can do another trial

Subject: No problem. [puts the blindfold on]

Experimenter: Ok, you can start.

Subject: Right. Straight away, by the fact that there's such a narrow angle I'd say that's very close. [answer was correct]

Experimenter: Ok. [removes object]

Subject: That feels ... let me think about it... Yes, that feels farther away than the previous one, but it doesn't feel like it's like farther away. Perhaps depends on the size of the object, I'm not sure. [answer was correct]

Experimenter: Ok. One more.

Subject: Yes. That feels like it's quite far away. And actually when I'm feeling comfortable about my estimate I'm doing something in my head, I'm projecting my consciousness forward from the angle here. Again this triangulation thing, by trying to do it it's like I'm mentally reaching out. By concentrating on this angle I think that's what I'm doing

Experimenter: Good. One more please. [the correctness of the following trial was not recorded as a result]

Subject: Sure.

Experimenter: That feels close.

Subject: Ok. Do you want to check this last one.

Experimenter: [removes blindfold] Right. It felt somewhat smaller, but definitively, the way I was experiencing to do this was by imagining the cone coming out of here [points to the ultrasonic sensor on the Torch handle] and "touching" the edge – I mean, the sides.

Subject: Right. You said something before about "projecting your consciousness"...

Experimenter: Yes.

Subject: Was it a feeling or some sort of thinking or mental imagery you had...

Experimenter: It's a little bit of both, I suppose. It's hard to think.. I suppose what I was doing was – when I'm doing this [rotates the Torch] my attention is here [points to the sensor], then here, then here [points to the edge of the objects] and then by feeling how far I've moved my arm left or right and remembering where my place was, I was concentrating here [points to the back of the object] because this was the point where the two angles would meet behind the object.

Subject: Sure, it makes sense.

Experimenter: That's it for the experiment. If you have any questions about it...

Subject: Yes. Actually it was very interesting because it was brief, but it did feel like I was getting to understand how it works better...

Experimenter: Indeed it happens to everybody, it's part of the minimal training required to use the device

Subject: Also because what I was doing was this triangulation, I wonder if having two of them would be more effective in a way, because currently part of the problem it's almost like seeing in two dimensions... you have a point sample here, another here, and you have to try to infer what's in between. But I think that with two you can almost describe a plane rather than a line...

Experimenter: Yes, actually this would be interesting. Unfortunately at the moment we have only one prototype.

Subject: But it would certainly be interesting for next studies. Anyway, nice experiment.

Subject: Thank you very much.

[end of tape. Total length: 34' 24"]

Appendix B

Source Code

The program included below is based on the SIMD-oriented Fast Mersenne Twister (SFMT) [19] for the generation of random numbers and on FANN (Fast Artificial Neural Network) library [14]. The following section report authors' name and software license of both packages.

Section B.2 shows the source code of the program used to evolve the artificial strategies described in Chapter 5.

B.1 License

SFMT

FANN - Fast Artificial Neural Network library

The FANN library is released under the GNU LESSER GENERAL PUBLIC LICENSE version 2.1[7].

```
Project Administrator:
Steffen Nissen (lukesky@diku.dk)
 - Creator and maintainer of the fann library

Contributors:
For a list of contributors see http://leenissen.dk/fann/authors.php
```

B.2 Source Code

The following source code is released under the GNU LESSER GENERAL PUBLIC LICENSE [7].

Makefile The `Makefile` is used to build the entire program; due to difference in the handling of dynamic and shared libraries in GNU/Linux and Mac OSX, a separate `make linux` target is provided. Default target builds on a OSX environment. Targets `testevolution` and `testscenario` build unit tests (non included in the source code below).

Program Initialisation Program initialisation and running is taken care by `simulation.c`. It parses command-line options and executes `evolve()` from file `evolution.c`.

Evolutionary Algorithm The file `evolution.h` include required parameters for the artificial neural network. The default ANN has been shown to be good enough for the task at hand without having to manually intervene on the network's parameters (learning rate, etc.). The number of input neurons corresponds to the number of steps required by the strategy; the neurons in the hidden layer are set to be equal to the number of input neurones + 5. Experimental verifications showed that such number of hidden neurons proved to be sufficient for a good training of the ANN.

File `evolution.c` contains the routines for the generation of strategies, the genetic algorithm and the evaluation of a strategy through the neural network.

Scenario Files `scenario.h` and `scenario.c` contain the necessary parameters and functions to generate a scenario and to execute a strategy within the defined scenario.