Stage de master 2

Rapport

Avoiding the pain or pursuing the pleasure? The affective roots of decision making, from humans to robots and back

par

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I. Introduction

Artificial intelligence has many purposes. One of them can be the better understanding of our brain, our behaviors, our learnings, and our nervous system functioning[1]. AI is also used to create machines that make better decisions, more intelligent ones. This decision-making improvement and the continuous back-and-forth movement between living observation and robot experiment can define what *neurocybernetics* is. In this work, we will study the relationship between pain, pleasure, and behavioral selection.

Through many aspects, we can be defined by our relationship with our emotions. In our emotional spectrum, pain and pleasure hold a special place; we can define our relation to life with them. Aristote even said:

"The aim of the wise is not to secure pleasure, but to avoid pain."

Thus, we can say that to build better artificial intelligence and, even one day, a robust artificial intelligence, we need to understand and learn how to model pain and pleasure [2].

So we will elaborate a bio-inspired robot model from affective mechanisms related to decision making and more specifically based on painful and pleasure/well-being mechanisms on human and mammalians

In the short term, we will provide critical analysis of neuroscience literature on the impact of pain and pleasure on decision making. We will then create the first bio-inspired robotic model on pain and its impact on autonomous decision-making. With this model, we will elaborate a protocol of experiments in an ecologically valid scenario that can be later used in pain and well-being further studies.

This work will be discussed with Amanda Williams, an academic and clinical psychologist at University College of London who specializes in pain and affective technology.

In further work, we will elaborate a subtle decision-making algorithm for complex and autonomous robots and have a more extended reflection and development of a model which could be used as a theoretical and experimental tool for neuroscience and psychology.

II. State Of the Art

To get a perspective on our subject, we shall first do a literature review regarding pain and pleasure, from human first then to robot.

First, we can take a look at the neuroscience literature to understand pain mechanisms better.

i. Keys idea of the biology of pain - some history

Pain is an old mechanism that Walter and Williams have defined along with history in a Walter and Williams paper[3]. We can get from this paper a perspective on how pain and related mechanisms have been observed over time and history.

Evolution of mechanisms important for nociception and pain

First of all, we can get a perspective on the essential mechanisms that are useful for pain.

We learn that nociception begins when energy produces or threatens to produce imminent injury. Some analysis suggests the TRPM (i.e. Transient Receptor Potential Melastatin, a receptor that has for function heat sensation and inflammatory pain) was present in ancestral Precambrian bilaterians, which means that valuable sensors for nociception were present in ancestral species.

We also learn two essential proprieties for pain and nociception :

1. Nociception and pain has complex modulation that can occur at all stages of sensory transmission
2. Nociception and pain become chronically enhanced after injury, which can lead to long-term sensitization

It is interesting to note that chronic pain in humans is often caused by peripheral nerve injury, having no actual injury to the body.

Unlike other sensory systems, nociceptive systems can sometimes undergo very long-lasting, even permanent, enhancement of function following sufficiently intense activation.

Adaptive and maladaptive features of pain behavior and its mechanisms

It is also essential to understand how pain behaviors can be either adaptative either maladaptive depending on the context.

For example: while pain is often associated with pathology in the body, this certainly does not mean pain itself is pathological.; which means pain is often expressed inappropriately. It is the «smoke detector principle» ([4]) that shows that the over responsiveness of many defenses is an illusion (you can activate your smoke detector by error, but frequent minor annoyances are necessary to avoid possible catastrophes).

We further can learn that chronic pain results from a mismatch of the pain system with the modern environment as we, in our modern societies, no longer die killed by predators or by natural danger and because we have medicine.

Pain evolved to guide adaptive behavior; this assesses contingent relationships between noxious stimuli and behavioral actions.

Long-lasting, pain-related hyper-vigilance is also likely to influence the estimate of risk and thus behavioral decisions in mammals.

We can also learn that the adaptiveness of persistent pain is consistent with evidence from fossils, meaning it is an ancient mechanism.

Evolutionary aspects of pain-related social behavior

Finally, the pain has a relationship with social behaviors, and we can learn some interesting facts from the paper.

Predators, seen or unseen, can behave in a threatening or non-threatening depending on if they are perceived as a potential mate or competitor, to impress or deter by appearing healthy and strong [5]. This related social behavior means that perceived pain can affect impression.

Parental and family care evidence has been found in dinosaurs, meaning that pain-related social behaviors have been in species since Jurassic.

We also have found a rudimentary form of empathy in mice [6] and an emotional contagion caused by intense pain, meaning that pain impacts others in a social context. [7]

Evolution has enhanced the pain experienced by women during the initial stages of labor in order to obtain help and protection from others during childbirth more effectively

ii. Keys idea of the biology of pain - nowadays

In a book *Principles of neural science - fifth edition* [8] we have the following definition of pain given by Allan I. Bascbaum and Thomas M. Jessel:

"Pain describes the unpleasant sensory and emotional experiences associated with actual or potential tissue damage."

Further we can get from the book that :

1. Pain is a complex sensory state that reflects the integration of many sensory
2. Pain perception is influenced by emotional state and environmental contingency
3. Some mutation in the genes can lead to insensitivity to pain

We can complete these definitions by adding that pain is helpful because it grabs and dominates attention. Pain is adaptive because it prioritizes escaping and promotes recovery and healing by amplifying pain to prevent further damage. Pain promotes learning of avoidance or vigilance of cues and context [9].

It is essential to remark that pain is not necessarily proportional to damage. It needs to be sufficient to motivate the animal to take evasive and protective action. This needs a sensory system, orientation/attention, aversiveness, learning [10].

pain related behaviors

Behaviors and functions are associated with pain; we can found the following table by Walters [11] modified by Amanda Williams.

	Function	behaviour
Immediate	Injury detection	identify location identify severity by change in rate
	Withdrawal	startle type responses
	Memory	store context and cue info
Rapid	Passive defence (mild or potential injury)	freeze / retreat protect site, assess risk prepare for active defence
	Active defence (severe or likely injury)	escape or retaliaty suppress competing responses tonic immobility when this fails
	Wound protection	**shelter, hide, stay vigilant & immobile** **sensitise wound site** **prime defensive actions** **remember cues & context**
	Recuperation	**clean & disinfect wound** **immobilise injury** **monitor healing** **conserve energy**

Noxious Insults activate Nociceptors

Nociceptors are a major part of the pain process. They are the ones who induce pain sensation. There are several types like pain or silent, and their unnatural activation is considered pathologic.

As we can observe on the following schema, when pain is induced, there is a first pain peak, followed by a second and longer peak, which has a lower but still high intensity and is called "second pain." This phenomenon can be observed in [Fig. 1]

When it comes to persistent pain, it can be characterized by many clinical conditions, and it is usually the reason patients seek medical attention.

We usually give two definitions for pain [12]:

1. Nociceptive: activation of nociceptors in the skin or soft tissue in response, accompanying inflammation
2. Neuropathic: direct injury to nerves in the peripheral or central nervous system and is often accompanied by a burning or electric sensation

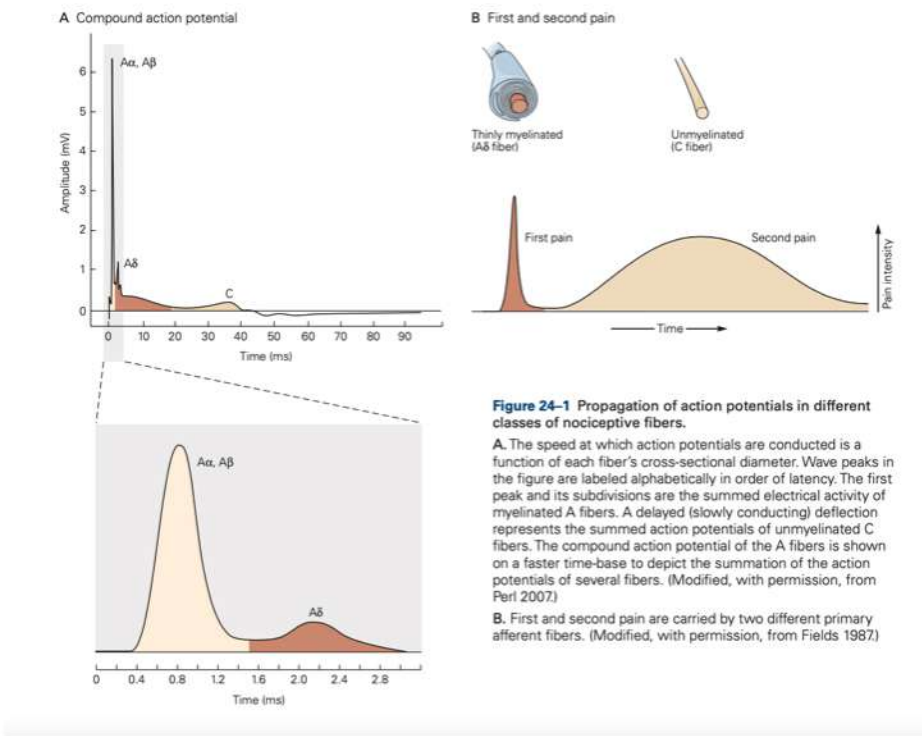


Figure 1: Propagation of action potentials in different classed of nociceptive fibers.

Central distribution of pain

We learn, further in the book, that a main characteristic of pain is its *"central distribution of pain"* which means that signals from nociceptors are conveyed to neurons in the dorsal horn of the spinal cord, as we can see in [Fig. 2].

What is interesting for our robot about this is that we can build a *centralized system of pain* which manage all the nociceptor rather than computing pain for every sensor.

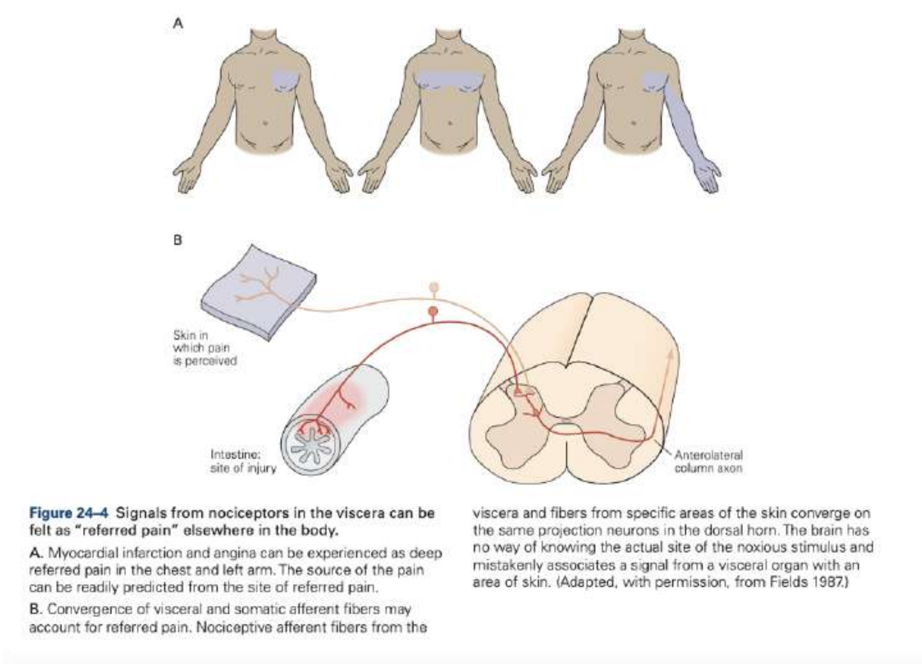


Figure 2: Signals from nociceptors in the viscera can be felt as "referred pain" elsewhere in the body.

Nociceptive Information Is Transmitted from the Spinal Cord to Thalamus

As we can observe in [Fig. 3] there is a specific part of the brain which is dedicated to pains mechanisms. It is essential to understand that there is a central distribution of pain and central processing of pain; it is not processed all along the body but in the brain.

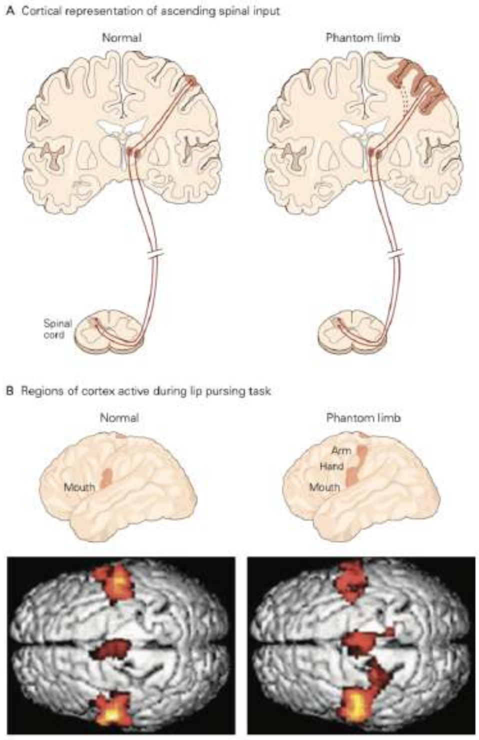


Figure 3: Thalamus and cerebral response to pain

Cortical Mechanisms control pain

As brain mechanisms control pain, we can localize and generate *Illusory Pain* in the Cerebral Cortex. For example, an experiment has been done, as we can see in [Fig. 4]. In this experiment, we use warm and cold tubes arranged one after another and put a hand on them. We should experience a lukewarm feeling resulting from the mix of warm and cold tubes, but, instead, burning heat is experienced. This means that the central system can misinterpret nociceptor outputs.

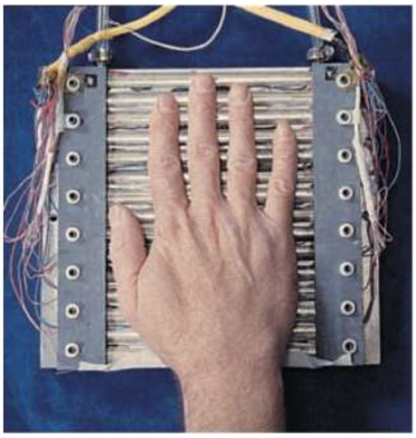


Figure 4: Burning heat experiment illusion

iii. Chronic pain - adaptative or maladaptative ?

When we talk about chronic pain, or long-lasting pain, several questions can come. The more important for our project are

- How is it characterized?
- Why does it come?
- Is it adaptive or maladaptive?

Chronic pain can consist of repeated exposure to painful stimuli, which will result in habituation to those stimuli and several brain mechanisms.

When we come to the question: why does it happen? Answers are more complex: we do not know. The sensitization (at peripheral and central levels) that characterize acute pain has a direct survival advantage by making the animal more vigilant and risk-averse, usually remits as healing occurs and the behaviors above fade. However, in some cases, they do not. [13]

It is essential to note that chronic pain is related to habituation to potentially life-threatening events, but prey animals never fully habituate to nearby predators. Chronic pain can fail to detect that a harmful stimulus may be fatal.

If we look at computer science, it can sort of be compared to indirect learning.

Here is some of the known risks in humans and the evolutionary models.

- Genetic factors influence onset more than persistence [14].
- post-surgical or trauma pain (easy to investigate): extent of nerve damage; pre-and postoperative pain intensity; pre-and postoperative distress; greater age; female.
- For low back pain: little exercise; depression (affects onset), anxiety (affects persistence).
- Depression with failure to inhibit emotional response to injury, and failure to mobilize descending inhibition [15].
- Disruption of reward, learning, and motivation [16].
- Early life stress [17], including repeated pain [18]; maternal care may protect.

In rodent studies, early life stress (temporary maternal deprivation) can lead both to hypersensitivity and hyposensitivity but does confer a higher risk of developing chronic pain after injury; this has been replicated in sheep [19].

iv. The Neuroscience of Happiness and Pleasure

In another reading by [20] we can study the neuroscience of happiness and pleasure. First of all, it is a tricky question to face because of its subjective aspect. We can read in the paper :

« The most difficult questions when it comes to face pleasure research question is the nature of its subjective experience, the relation of hedonic components (pleasure or positive affect) to eudaemonic components (cognitive appraisals of meaning and life satisfaction), and the relation of all these components to rooting brain systems.»

However, we can learn several lessons by looking at the principle of hedonic pleasure. First of all, we can see in [Fig. 5] that there is a complex but functioning system of reward measuring generating hedonic pleasure. After this complex system, we have a fully functional hedonic brain circuitry ([Fig. 6]).

For our robot, we can learn from this that pleasure is built on multiple sources but, in a homeostasis (i.e. viability) environment, one of them can be the hedonic satisfaction of consuming resources.

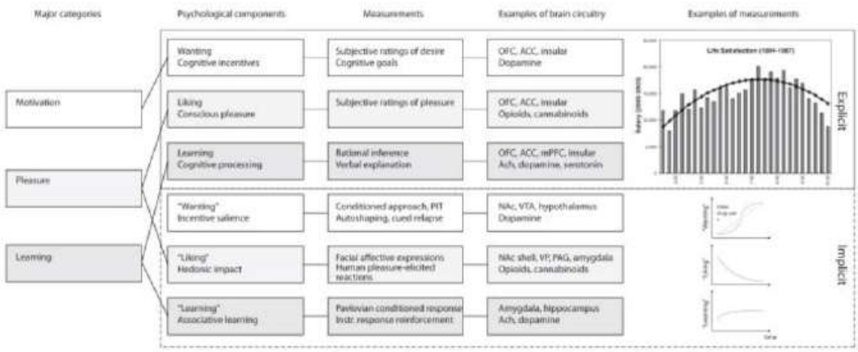


Figure 5: Measuring Reward and Hedonia

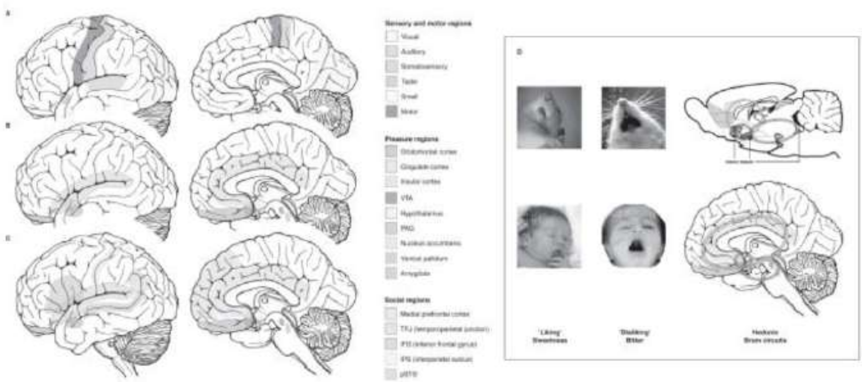


Figure 6: Hedonic Brain Circuitry

III. Bio-Inspired Robot Model

Now that we have done a preliminary literature review, we will elaborate on a bio-inspired robot model that will fit these characteristics.

i. Research question

In this work, we want to study how pain and pleasure will impact a fundamental decision-making architecture? Looking at different ecologically valid scenarios, will they be adaptive or maladaptive? Which type of solutions or problems can it provide for our robot? Looking at the relation between pain and physical damage, how can hypersensitivity or insensitivity be adaptive or maladaptive depending on the environment?
To answer these questions, we are going to use as a base an architecture that was made for modeling Obsessive-Compulsive spectrum disorders (Lewis, Feinberg, CaÃ±amero[21] [22]).

ii. The robot

To work on our robot model, we will use a Thymio-II made by Aseba ([23]). Thymio has 9 IR sensors, LEDs, a microphone, and buttons on its surface. If we take a different look at IR sensors disposition, it has two rear sensors and five front sensors which give distance to an obstacle as output, and two ground sensors that can detect ground color.

Figure 7: Aseba's Thymio-II

iii. The environment

To respond to our research question and provide our robot an appropriate environment, we will create an arena containing two different types of resources, obstacles to induce pain, and the possibility to simulate predators.

For this, we have built a 59,4 x 84,1 cm wooden arena composed of 16 tiles of 21,0 x 29,7 cm and a wall to disallow the robot from exiting it. Upward these tiles, we will print three different grounds :

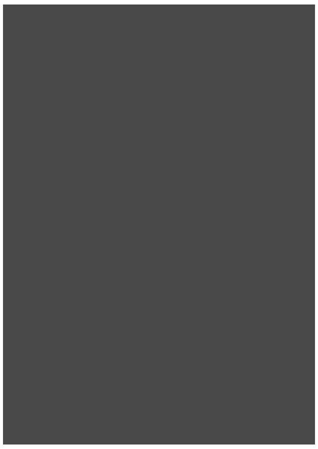


Figure 8: Neutral ground tile

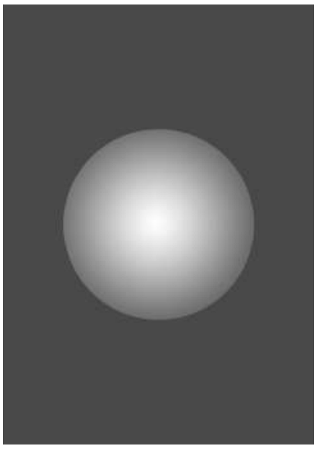


Figure 9: Food resources tile

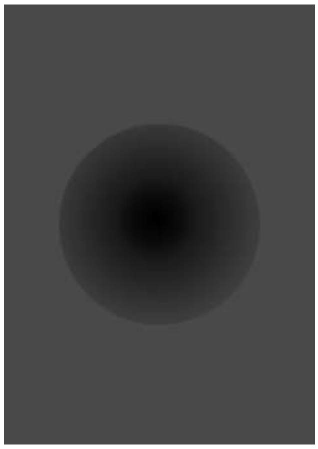


Figure 10: Grooming resource tile

Resources ground is composed of a white or black gradient circle. Neutral grey is chosen to be perfectly defined as the *"perfect middle ground color"* using Thymio's ground IR sensors.

We will add on our physical arena obstacles that can be placed among resources tiles. We can see in [Fig. 11] we have added a circular black obstacle on the grooming resources. These resources are meant to represent a *grooming spot* which will be helpful for our robot model.

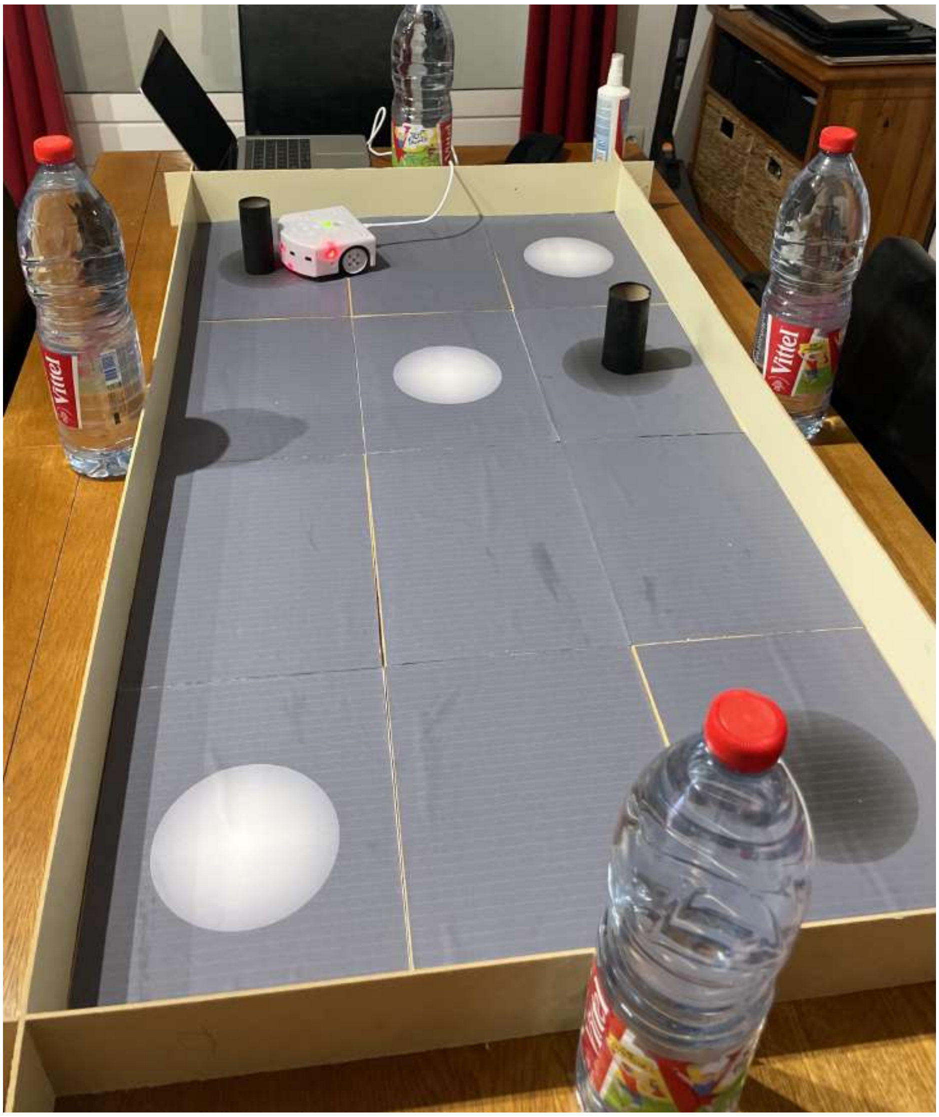


Figure 11: 59,4 x 84,1 cm wooden arena

iv. From theory to robot

We have studied before pain, pleasure and their mechanisms. We have also seen that we have little robot sensory information.

To go from the theory to a bio-inspired model, we will need to take some of the main biological characteristics and *"scope them"* to our robot capacities. As we summarize in the following schema (see Fig. 12), we take the main characteristics of pain:

- Behavioral impact
- First and second pain principle
- Pain radiation
- Nociception
- Chronic pain
- Social impact

With these principles and using an *decision making problem* and our robots IR sensors we will build and *artificial. skin* composed of *artificial nociceptors* used by a *robot architecture* which will have a pain and pleasure *hormonal modulation*.

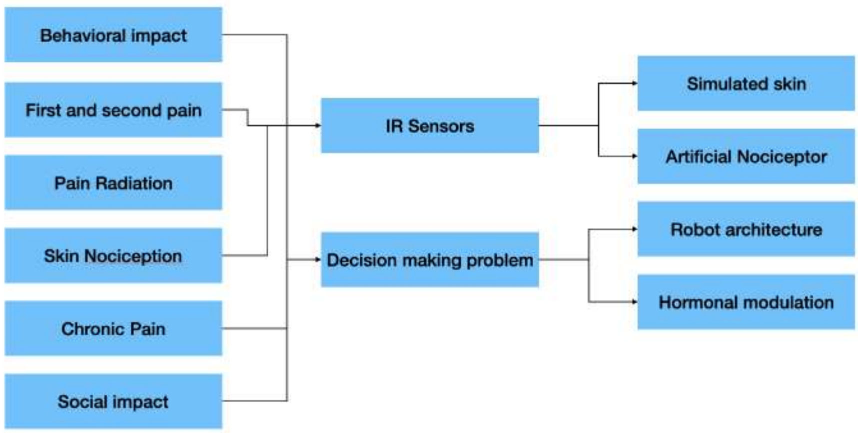


Figure 12: Bio-inspired scope

It is crucial to determine adaptative and maladaptive aspects of pain to allow behaviors that can induce homeostasis satisfaction and physical damage.

v. Physiological Variables

To better understand how pain and pleasure will work in a specific context, we need to make a context where the robot has to make decisions and see how they can be improved with neuromodulation. Thus we will be working in a Two Resources Problem (TRP) where the robot will have to maintain homeostasis (i.e. viability).

To represent this problem, we will give our robot physiological variables that he needs to satisfies aiming to stay alive.

1. **Integrity** which represents the physical integrity of the robot. It can be reduced with physical damage caused by predators or by obstacles collision and, when integrity is over, the robot is dead. This resource is added a third resource to the TRP to represent better physical damage that induces pain

2. **Integument** which is present in many animals and is the natural covering of an organism. It can explain the state of its external surface, analogous to an animal's fur or feathers. It can be satisfied by a grooming action and decay regularly when uncared.

3. **Energy** which is the basic representation of the energy system of an organism. It is consumed among time with the body needs and can be satisfied while eating or sleeping. To simplify our problem, we will consider eating food as the only way to satisfy energy. need.

Variable	Fatal limit	Ideal value	Maintenance
Integrity	0	100	decreases when robot gets damage
Integument	0	100	decreases over time; increases when robot passes close to a grooming post
Energy	0	100	decreases over time; increases when the robot's left side passes close to a food ressource

Table 1: The robot's physiological variables

vi. Sensor, cues and motivation

For our three physiological variables corresponds other internal variables.

Deficits : As we have seen before these values have and ideal target θ. And as, for different reasons, the physiological variables decay or increase over time they vary and get different of θ. This differences is named *deficit* and is computed as following :

$$deficit_i = \theta_i - value_i$$

Thus for physiological variables there is a corresponding deficit. We have ***def:integument*** that correspond to *integument*, ***def:energy*** for *energy* and ***def:integrity*** for *integrity*

Sensors : As we have seen before, our robot is equipped with *IR Sensors*, we will use its *front sensors* values to get distance from objects and its *ground sensors* to determine ground color. For the front sensor, we get a value in the [0-4500] range corresponding to the distances shown in the following graph [Fig. 13]. For our ground sensors, we have a [0-1024] value going from black (0) to white (value depends on brightness condition).

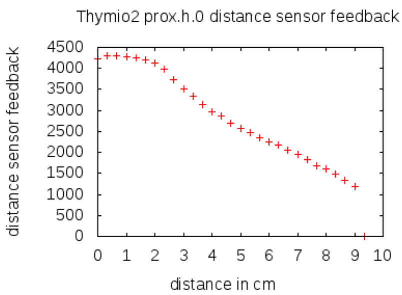


Figure 13: Thymio-II proximity sensors

Cues : A *cue* is a value that is meant to represent incentive stimuli. Perceived cues can be compared as input stimuli to determine if there is an obstacle or grooming post or food resources accessible. Its value is in the [0-100] range and is computed by the object's sensed distance or by the color detected by the ground sensors for the energy resources and grooming posts.

Motivations : Motivations represent the will to adopt a behavioral group; each physiological variable has a corresponding motivation. They are all linked to variable deficits and incentive cues. Motivational intensity is calculated according to the formula proposed in Avila- GarcÃa and [24] (modified from a classical formula in ethology; [25] :

$$m_i = d_i + (d_i * c_i) \tag{1}$$

vii. Basic decision-making model

We have computed three motivations, each one corresponding to a physiological variable and leading to a behavioral :

1. Avoiding behavior for integrity
2. Eating behavior for energy
3. Grooming for integument

For **action selection**, we use a *WTA* (i.e. Winner Takes All) to compare the three motivations variables and determine which behavioral group to take. This basic decision-making model can be summarized in the. following architecture [Fig. 14].

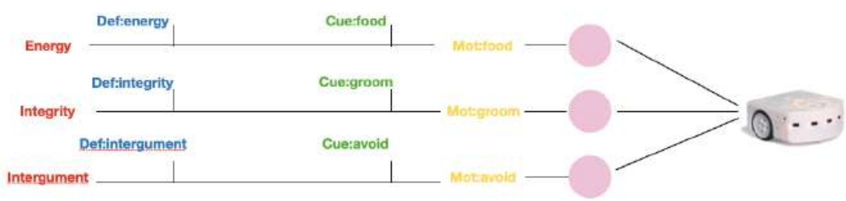


Figure 14: Basic robot architecture

viii. behavioral groups

As we have seen, we have three behavioral groups that can be selected. They can be separated into two subgroups:

1. Avoiding group : there is only one sub-behavior in it which is obstacle (here obstacle represent either real obstacle or predator) avoidance.

2. Resource behavioral group (Food and Grooming). In these resources there is multiple sub-behaviors :

   - Resource seeking
   - Checking resource availability
   - Resource consuption

To define our robot commands depending on behaviors, we will use a Braitenberg [26] motor control to define multiple simple behaviors based on sensory inputs.

Avoiding

As we have seen before, there is only one behavior when avoidance is selected. Based on Braitenberg architecture, it will avoid obstacles as we can. see in [Fig. 15].

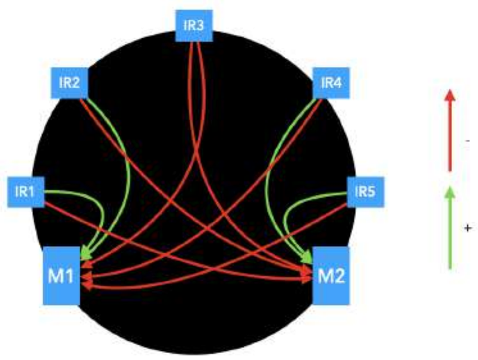


Figure 15: Braitenberg avoidance

Equation used is then given by :

$$\begin{pmatrix} motor_1 \\ motor_2 \end{pmatrix} = \begin{pmatrix} -3 & -2 & -1 & 2 & 3 \\ 3 & 2 & -1 & 2 & 3 \end{pmatrix} * \begin{pmatrix} IR_{left} \\ IR_{frontleft} \\ IR_{front} \\ IR_{frontright} \\ IR_{right} \end{pmatrix} \tag{2}$$

Grooming and Food behavior

For our second behavioral group, we will have three subgroups. The first one is seeking resources based on a Braitenberg approach, as shown in [Fig. 16]. Let us specify that IR sensor values are not the same for Grooming and Food; a white circle represents food, so that we will take higher than grey to white values; black circles represent grooming, so we will use grey to black values. To simplify reading, we will give the same model and equations for both behaviors.

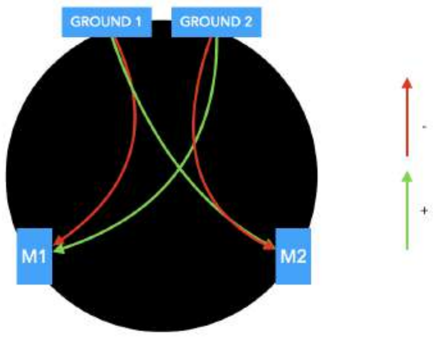


Figure 16: Braitenberg seeking for resources

Equation used is the following one :

$$\begin{pmatrix} motor_1 \\ motor_2 \end{pmatrix} = \begin{pmatrix} -2 & 2 \\ 2 & -2 \end{pmatrix} * \begin{pmatrix} IR_{ground_{left}} \\ IR_{ground_{right}} \end{pmatrix} \quad (3)$$

Then we will check if resources can be consumed by using ground IR sensors to see if the robot is in a black or white circle, and finally, we will go the resource consumption behavior :

1. **grooming :** grooming is represented by a circular movement in front of the grooming spot.
2. **eating :** eating is represented by a go back forward movement in the white circle.

General behavior

As brainteberg's behaviors can make the robot go slow, a constant **cst** will be constantly added to the robot's wheels' speed.

$$wheel[g/d] = wheel[g/d] + sign(wheel[g/d]) * cst \tag{4}$$

IV. Neuromodulation and Nociception

Now that we have a simple decision-making model, we will add nociception to induce damage and then generate pain and pleasure using neuromodulation [27] technics.

i. Artificial Nociceptor

First, to model damage in an ecologically valid way, we need to consider our robot surface as an **artificial skin** composed of **artificial nociceptors** [28]. We will use our IR sensors as a basis for creating them. Our nociceptors will be sensible to two different types of damage to fit best a natural nociceptor.

Impact damage

Our first type of damage is based on the *speed of the impact*; thus, we will use our *IR sensors* to compute the speed of approach of the object and, following a linear line, the quicker the obstacle goes on, the stronger the object is engaged, the more the pain is induced.

$$speed = \frac{\Delta d}{T_{iteration}} \tag{5}$$

For each sensor, we compute this speed and then store it for each iteration. If speed is increasing from iteration to iteration, damage induced will proportionally increase.

Scratching damage

We can induce damage by reproducing a scratching mechanism represented by an object moving quickly from one sensor to another.

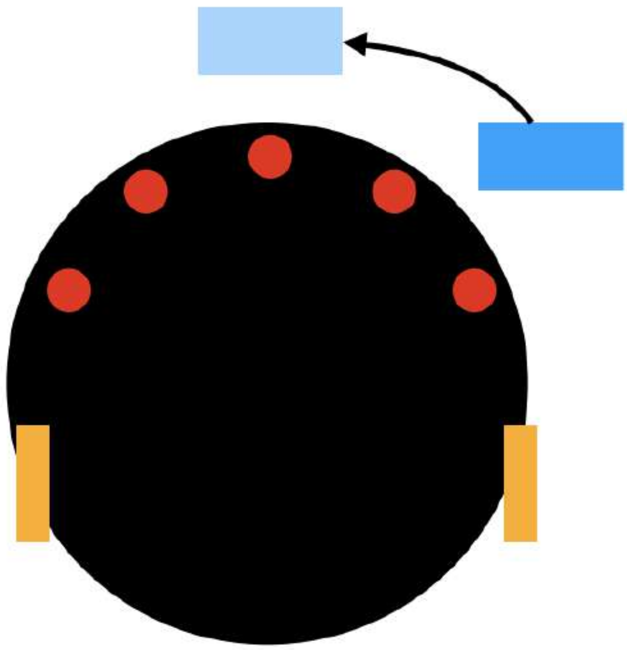


Figure 17: Scratching movement

To determine damage level with this kind of movement, we must first compute the angular speed of the object moving following the next equation where θ is equal to a fraction of 2π corresponding to the degree separating our robot sensors ($\theta = \frac{\pi}{6}$ and $r = 5,5cm$ for Thymio-II).

$$speed = \frac{\theta r}{T_{iteration}} \tag{6}$$

Speed can be computed by generating an array of *IR* sensor values and a second array stacking previous iterations sensors values. Then we can compare previous values with close neighbor sensors, and we can use a previous formula to get the speed of the moving object.

We will repeat this and doubly increase damage for each iteration if an object keeps scratching more and more sensors.

Nociceptors and irradiation of damage

We then have our five angular scratching damage sensors and our five speed impact damage sensors which make five artificial nociceptors using the following formula.

$$nociceptor[i] = 0.5 * impact[i] + 0.5 * scratching[i] \tag{7}$$

As we have the nociceptors, we need, aiming to have an ecologically bio-inspired model, to induce damage irradiation. So we will use the following algorithm

1. Generate 5 arrays of 5 values $array_i[5]$
2. for i in range (5) :
   (a) $array_i[i]$ = $nociceptor[i]$
   (b) Following a gaussian, intensity of a $array_i[i]$ will radiate to its neighbors
3. for i in range(5) : $nociceptor[i] = \frac{\sum_{j=1}^{5} array_j[i]}{5}$

To finish, we can get compute an *damage hormone* by getting nociceptors means.

ii. Pain

Now that we have our damage level, we will generate a **pain hormone**.

Hormonal computation

Based on CaÃ±amero and Avila-Garcia work we will, based on our damage hormone compute a *pain hormone* inspired by Canamero and Avila-GarcÃa's work([29]) released by a *gland*.

First, we compute the release gate r_{pain} which is build on the damage.

$$r_{pain} = \alpha * damage \tag{8}$$

α is an important value that allows us to determine if pain is normally **correlated** to damage, or if it's **hypo-correlated** or **hyper-correlated** to damage. α value varies from 0.1 for hypo to 0.4 for hyper and goes by 0.2 for normal value.

Now that we have our release gate, we can compute hormonal concentration c_pain which is a value that goes from 0 to 1.

We can propose three way to get this concentration level :

- $c_{pain}(t+1) = min(1, c_{pain}(t) * \psi_{pain} + r_{pain})$ where there is a memory of hormone with ψ_pain is the decrease rate.
- $c_{pain}(t+1) = (r_{pain} + c_{pain}(t)) * 0.5$ where there is a short time memory with a mean approach of the concentration
- $c_{pain}(t+1) = r_{pain}$ where there is no memory

To better fit ecologically variable, we will use hormonal memory in our robot model.

Second pain

To correctly fit the "second pain principle" [8], once pain concentration is computed we are going to make it vary following the first and second peak. For this we are going to use a bimodal distribution [Fig. 18] to get the two peaks. Then, we'll take the max value between c_{pain} and $secondpain$ distribution over time depending on c_{pain}.

$$secondpain(x) = max(1 * e^{-(0.5*(-3+18*x))^2}, 0.5 * e^{-(0.5*(-3{,}4+3*x))^2}) \quad (9)$$

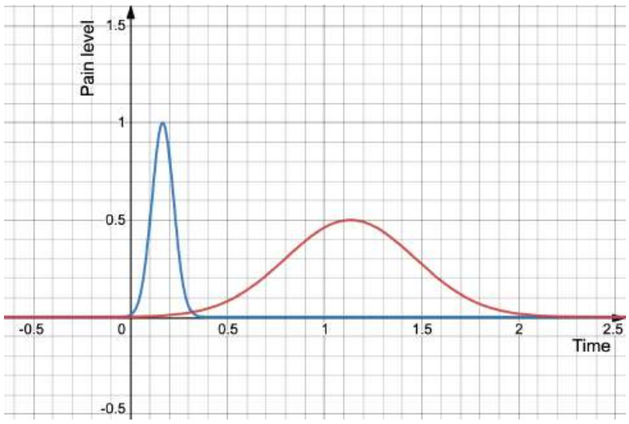


Figure 18: Bimodal distribution used for second pain computation

Impact on robot model

Pain will have a double impact on our robot model :

1. First, to fit *"pain make engage strongly its actions"* principle, it will by modify the constant added to motors speed :
   $wheel[g/d] = wheel[g/d] + (1 + c_{pain}) * sign(wheel[g/d]) * cst$
2. Then we will increase obstacle avoidance motivation to fit ecologically valable *"escape feature"* :
   $m_{avoid} = m_{avoid} + m_{avoid} * \beta * c_{pain}$

iii. Pleasure

For our robot model we will also elaborate a **pleasure hormone** based on **well-being**, inspired by Cos Canamero [30], to fit the hedonic pleasure of resources consumption. *well-being* is a value that goes from 0 to 100

$$wellbeing = 100 - (def_{energy} + def_{integument} + def_{integrity}) \tag{10}$$

Then we compute release gate and hormonal concentration in the same way we did for pain :
$r_{pleasure} = 0.01 * well - being$
$c_{pleasure}(t+1) = min(1, c_{pleasure}(t) * \psi_{pleasure} + r_{pleasure}$

Impact on robot model

Pleasure will have an impact on food and grooming motivation by adding them a bonus over time : $m_i = m_i + \beta * c_{pleasure} * m_i$

iv. Model updated

Finally, we can resume our model looking at its variables [Fig. 19] and its looping cycle [Fig. 20].

	Min	Max	Ideal	Comment
Physiological Variables	0	100	100	
Deficits	0	100		
Cues	0	1		Normalized
motivation	0	1		
Well-being	0	1		
Damage	0	1		
Releases gates	0	1		
Hormonal concentration	0	1		

Figure 19: Values table

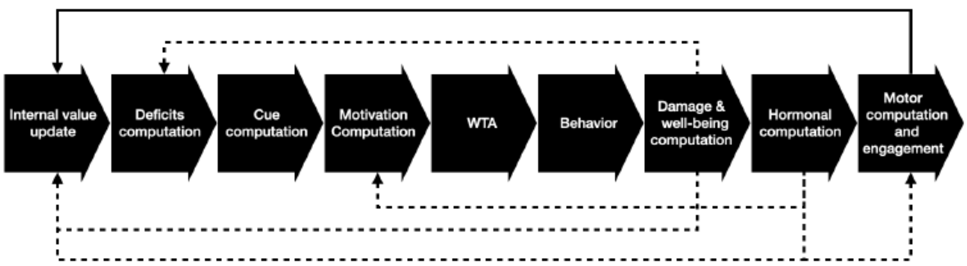


Figure 20: robot model recap. Full line represent loop, dotted line represent *"has impact on"*

V. Experiments and results

It is now time to evaluate our robot model in the homeostasis TRP and see if the pain is adaptative or maladaptive in a different context. We will search to compare hypo-correlation, normal-correlation, and hyper-correlation between damage and pain and lack of pain. We will study pleasure to determine if our robot seeks to pursue pleasure rather than escape pain.

Please note that for simplification of reading, we will note :

- hypo-pain: hypo correlation between pain and damage
- normal-pain: normal correlation between pain and damage
- hyper-pain: hyper correlation between pain and damage

i. Condition tested and scenarios

To do these experiments, we will elaborate the following protocol :

1. The arena is built with random placement of tiles
2. Obstacles are, or not depending on the scenario, placed on resources spot (grooming and possibly food)
3. Robot is placed at the bottom middle of the arena looking upfront
4. Robot is launch
5. If a predator is in the scenario, at predetermined frequency and time, a hand is placed over the robot's front sensors to represent predators
6. When the robot dies, the experiment is over

The following metrics are stored for result analysis :

- Survival Time
- Internal variable levels over time
- Deficits levels over time
- Cues over time
- Motivations Overtime
- Behavior selected over time

- Damage level over time
- Pain level over time
- Well-being over time
- Pleasure over time

We then will elaborate on three scenarios to determine the pain impact on our robot model. We are, for each scenario, going to evaluate hypo, hyper and normal correlation between pain and damage and compare them to no pain. In these scenarios, we are going to make various predators and obstacles present in the arena.

<table>
<tr><th></th><th>Hypo-Pain</th><th>Normal</th><th>Hyper-Pain</th><th>No pain</th></tr>
<tr><th>No Obstacles</th><td rowspan="2">1Hypo</td><td rowspan="2">1Norm</td><td rowspan="2">1Hyper</td><td rowspan="2">1None</td></tr>
<tr><th>No Predators</th></tr>
</table>

Figure 21: Scenario 1 - no obstacle and no predator

<table>
<tr><th></th><th>Hypo-Pain</th><th>Normal</th><th>Hyper-Pain</th><th>No pain</th></tr>
<tr><th>Obstacles</th><td rowspan="2">2Hypo</td><td rowspan="2">2Norm</td><td rowspan="2">2Hyper</td><td rowspan="2">2None</td></tr>
<tr><th>No Predators</th></tr>
</table>

Figure 22: Scenario 2 - obstacles but no predator

<table>
<tr><th></th><th>Hypo-Pain</th><th>Normal</th><th>Hyper-Pain</th><th>No pain</th></tr>
<tr><th>Obstacles</th><td rowspan="2">3Hypo</td><td rowspan="2">3Norm</td><td rowspan="2">3Hyper</td><td rowspan="2">3None</td></tr>
<tr><th>Predators</th></tr>
</table>

Figure 23: Scenario 3 - obstacles and predators

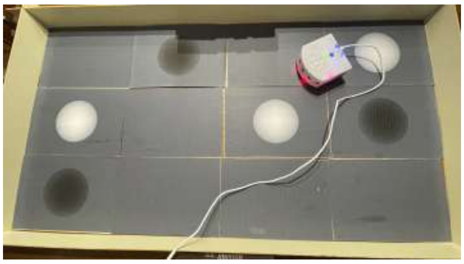


Figure 24: Robot in arena during scenario 1

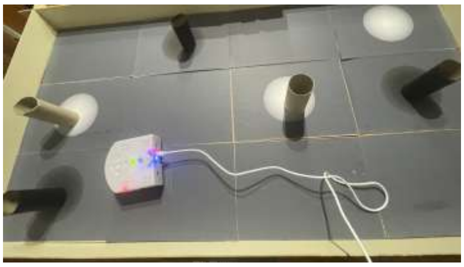


Figure 25: Robot in arena during scenario 2

Figure 26: Robot in arena during scenario 3

ii. Predictions

Based on our scenarios, preliminary literature review, and own hypothesis, we will make the following predictions :

1. When there is no predator or obstacles, pain is maladaptive
2. When there is no predator or obstacles, insensitivity to pain is adaptative
3. When there are obstacles and no predator, pain is adaptative but can induce compulsive behaviors
4. When there is both obstacle and predator, pain is adaptative
5. When there is both obstacle and predator, hypersensitivity to pain is adaptative

iii. Results

As we launch five runs of each scenario, we can observe remarkable results.

Lifespan

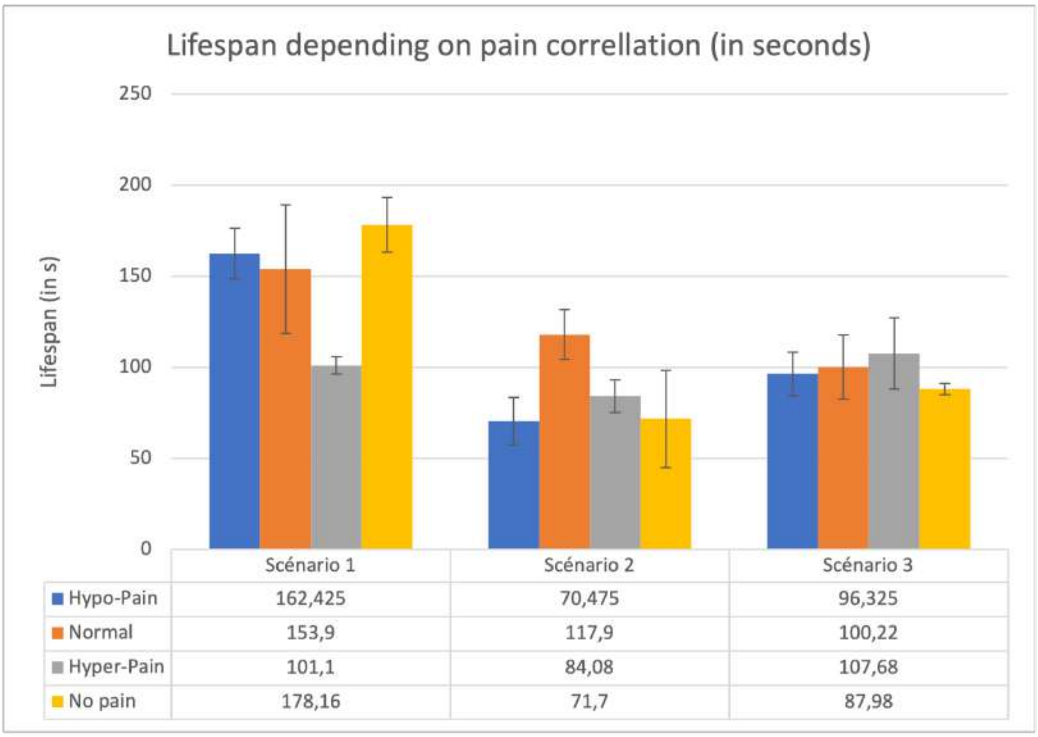
Firstly, we will evaluate the lifespan of our robot depending on pain-damage correlation and scenarios.

As we can observe in [Fig. 27] there are notable differences in lifespans.

For scenario 1 (no obstacle, no predator), we can see that pain is maladaptive compared to lack of pain and, the more the pain is correlated to damage, the less long the robot survives. It is important to remark that both hypo-pain and normal pain slightly differ from no pain, but hyper-pain results in hyper-compulsive behavior and the lack of consuming resources, leading to a faster death. This is confirmed by the minor standard derivation that confirms that most runs lead to death in the same closer moment. This can be interpreted as evidence that in a modern environment with a lack of danger or predators, pain is maladaptive.

For Scenario 2 (obstacles, no predator), it is shown that pain is adaptative regarding lifespan. Nevertheless, this must be considered that both hypo-pain and hyper-pain are not as adaptative as normal pain. First, hypo-pain does not show particular differences rather than any pain, but if we look at standard derivation, we can see that model is more precise and show a smaller range of lifespan with hypo-pain. This improves robot reliability but reduces, in some cases, its lifespan. Hyper-pain improves way less lifespan than normal pain, which can be explained by too strongly engagement in actions, leading to death while not consuming resources. It confirms that, regarding lifespan, pain is adaptative in a context where there is static danger, but hypersensitivity to pain is less adaptive than standard pain.

For Scenario 3 (obstacles, predators) results are also interesting and show that the more the damage causes pain, the longer the robot survives, with close to be a linear factor. Indeed hyper-pain will be particularly adaptative in this scenario, which can confirm that in natural scenarios reproducing prey-predators and inhospitable environment, otherwise in nonmodern environment pain is adaptative.



	Scénario 1	Scénario 2	Scénario 3
Hypo-Pain	162,425	70,475	96,325
Normal	153,9	117,9	100,22
Hyper-Pain	101,1	84,08	107,68
No pain	178,16	71,7	87,98

Figure 27: Robot's lifespan (in s) depending on pain-damage correlation and scenarios

Cause of Death

Another metrics to look at when we want to understand our model and evaluate pain efficiency is the cause of death.

For scenario 1 (see [Fig. iii]) We can observe that our robot mainly dies of lack of energy and sometimes of the other homeostasis resources, grooming. Whatever pain correlation is proportion stays almost the same;

For scenario 2 (see [Fig. 29]) When there are obstacles, the first cause of death is due to integrity. This does not happen when there is pain, whatever correlation with damage which means that the robot is more efficient in obstacle avoidance when pain is on.

For scenario 3 (see [Fig. 30]) We can see that robot only dies from lack of energy or integrity. It is remarkable to see that with hyper-pain, the leading cause of death is integrity. It can be explained that because the robot engages more decisive in its actions, causing damage in grooming and more violent obstacle avoidance, the robot will consume resources within reach, even if it is hurting him.

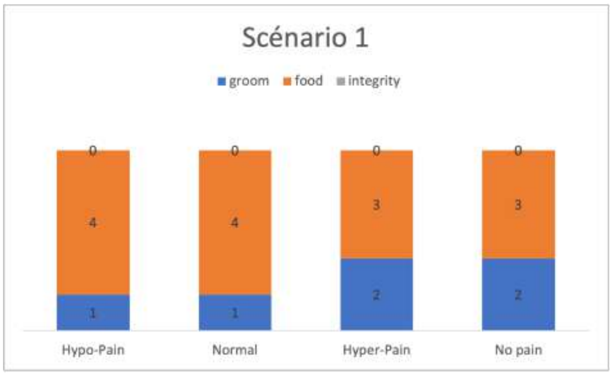


Figure 28: Cause of death for scenario 1

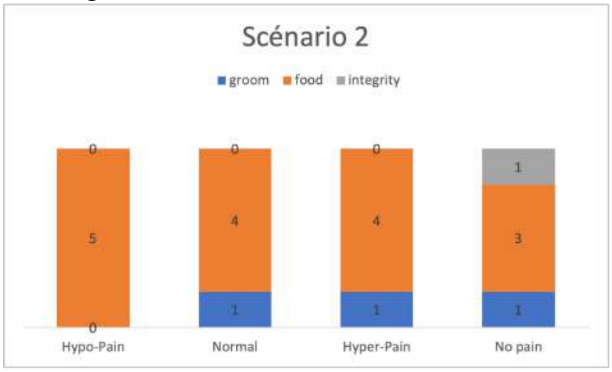


Figure 29: Cause of death for scenario 2

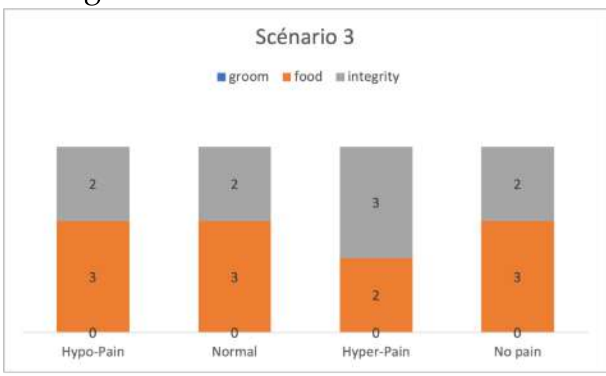


Figure 30: Cause of death for scenario 3

Particular runs

Now that we have studied lifespan and cause of death, we will have a distinct look at some prototypical runs that are remarkable to get a better understanding of our model and the impact of pain on it.

Hyper-Pain in scenario 3 In this case, we have a particularly adaptive feature of pain. We can observe in [Fig. 32] that pain goes to a high ridge and maintains a high and long peak of pain, which results in having a mostly avoiding behavior ([Fig. 33]) and consuming resources only when the robot is placed on a spot. Damage is way less important than pain, as observed in [Fig. 34].

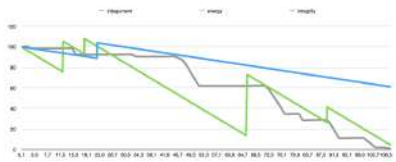


Figure 31: Physiological variables over time (green- energy, blue- integument, grey-integrity

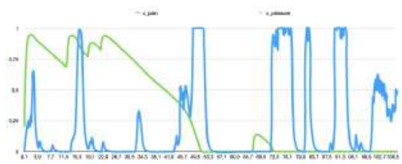


Figure 32: Hormonal level over time (blue pain, green pleasure)

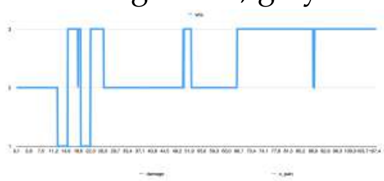


Figure 33: Selected scenario over time (1- groom, 2-food, 3-avoid)

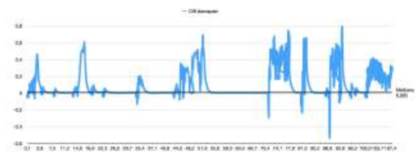


Figure 34: Difference between damage and pain

If we take a detailed look at internal variable curves [Fig. iii] we can see that there is a lot of resources consumption, even in pain peak, which confirms that the robot will consume resources, even if it damages the robot's integrity. In this run, the robot dies of a lack of integrity.

No Pain in scenario 3 If we compare the previous run to the following one with no pain, we can see how differently our model reacts without pain hormonal modulation. We can see in [Fig. iii] there is fewer resources consumption in this scenario which both [Fig. 36] and [Fig. 37] can explain: if we get a closer look at the end of the run, we can see that damage cause and behavioral avoidance selection which is not canceled by a stronger action engagement or pleasure neuromodulation, resulting in no resource consumption and, then, death. It confirms the adaptative feature of both pain modulation and pleasure-seeking.

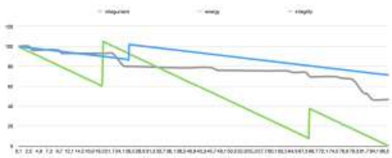


Figure 35: Physiological variables over time (green- energy, blue- integument, grey-integrity

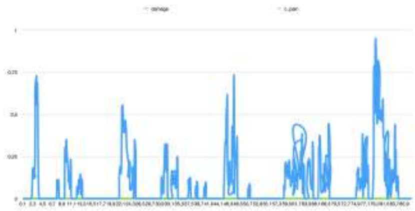


Figure 36: Damage level over time

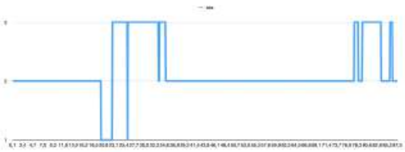


Figure 37: Selected scenario over time (1- groom, 2-food, 3-avoid)

Normal pain in scenario 2 This run shows interesting results to explain how pain is adaptative and acts on the robot's model. We can observe in [Fig. iii] that there is a lot of resources consumption and away more stable homeostasis as we have sawn in other runs. Nevertheless, we can see compulsive food consumption, even when not needed as in middle life. We can see that pleasure is going down quickly, and we have a pretty normal level of pain [Fig. 39]. As shown in [Fig. 40], death has resulted from a pain modulation that leads to choosing avoidance over resource consumption at the end of life.

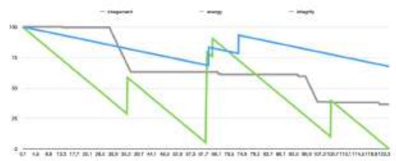


Figure 38: Physiological variables over time (green- energy, blue- integument, grey-integrity

Figure 39: Hormonal level over time (blue pain, green pleasure)

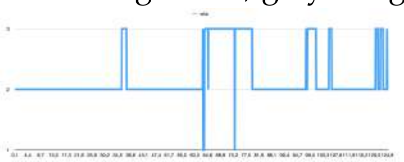


Figure 40: Selected scenario over time (1- groom, 2-food, 3-avoid)

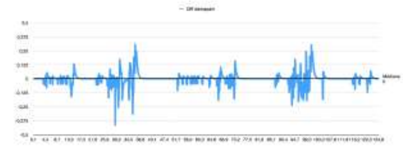


Figure 41: Difference between damage and pain

Hypo-pain in scenario 1 For our last particular run we are going to observe the last *"extreme case"* (hyper-pain scenario 3 vs hypo-pain scenario 1). We can see in [Fig. iii] and [Fig. 44] that, even with regular grooming and integrity, a lot of food consumption is allowed even if, in the end, obstacle avoidance will finish by causing death. Compared to previous prototypical remarkable runs, this happens way later, explaining the longer survival time but reproducing the same mechanisms that lead to death. We finally see in [Fig. 43] that pleasure is maintained at a high level for most of the run. It can show that in a modern environment, hedonic pleasure is more important than pain (and more adaptative).

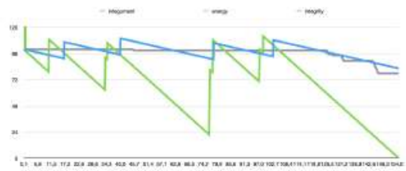


Figure 42: Physiological variables over time (green- energy, blue- integument, grey-integrity

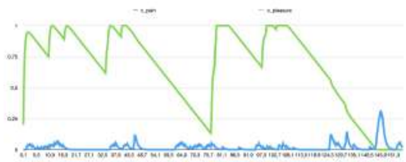


Figure 43: Hormonal level over time (blue pain, green pleasure)

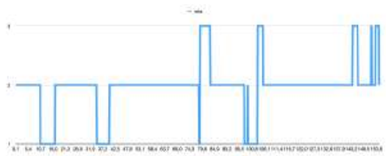


Figure 44: Selected scenario over time (1- groom, 2-food, 3-avoid)

Figure 45: Difference between damage and pain

iv. Prediction confirmation

As we have studied our results, we can see our predictions see that we made pretty accurate ones :

1. When there is no predator or obstacles, pain is maladaptative : **true**
2. When there is no predator or obstacles, unsensitivity to pain is adaptative : **true**
3. When there is obstacles and no predator, pain is adaptative but can induce compulsive behaviors : **true**
4. When there is both obstacle and predator, pain is adaptative : **true**
5. When there is both obstacle and predator, hypersensitivity to pain is adaptative : **true**

VI. Conclusion and perspectives

, In conclusion, we can say that we did a literature review around the subject of pain and pleasure, elaborated a robot model in a homeostasis

TRP context, and added pain and pleasure neuromodulation to it. We settled up an experiment process to determine adaptative and maladaptive aspects of pain and pleasure and confirmed some hypotheses in preliminary bibliographic research.

Pain is maladaptive in a modern environment with no life-threatening obstacles or predators, resulting in an adaptative insensitivity to pain. Pain is adaptative to more natural, ecologically correct environments with dangers and prey-predators. Furthermore, in dangerous places, hypersensitivity to pain is adaptative.

In further work, we will evaluate long-lasting and chronic pain impact on our robot model to understand the topic better. To make this, we will add chronic pain to our robot model and compare early-life predation with later-life one to determine the adaptative aspect of pain, depending on the scenario.

	Hypo-Pain	Normal	Hyper-Pain	No pain
Obstacles Predators in early life	4Hypo	4Norm	4Hyper	4None

Figure 46: Scenario 4

	Hypo-Pain	Normal	Hyper-Pain	No pain
Obstacles Predators in later life	5Hypo	5Norm	5Hyper	5None

Figure 47: Scenario 5

We will try to confirm or infirm the following predictions :

- Early relation to predators will result in adaptive hypersensitivity and maladaptive insensitivity
- Later relation to predators will result in maladaptive hypersensitivity and adaptive insensitivity

We could also use our model to study *OCD spectrum disease* [31] (i.e. Obsessive Compulsive Disorder spectrum disease) to determine pain and pleasure impact in these specific cases.

Concluding this work, we have sawn how avoiding the pain or pursuing pleasure can be adaptive or maladaptive in decision making, studying neuroscience, psychology, and history to model an ecologically valid environment and robot model.

VII. Acknowledgments

As I am ending a five-year academic course at CY Cergy Paris University, I would like to mainly thank Pierre Andry for his support and the opportunity he gave me by accepting me to CMI SIC.

I would like to thanks my parents who have supported me and made possible my wish to study something I like and am passionate about, even in difficult times. I want to give a special thank you to my dad for his DIY advice on this project.

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