Centro de Investigación y de Estudios Avanzados

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Propuesta de una Arquitectura Cognitiva para un Algoritmo de Planeación Orientado a Producir Comportamiento Similar al Humano

Tesis que presenta:
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Director de Tesis:
Dr. Félix Francisco Ramos Corchado

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Proposal of a Cognitive Architecture for a Planning Algorithm Oriented to Produce Human Like Behaviour

A thesis presented by:
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Master of Science Thesis
In Electrical Engineering

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Dies ist ein Lied für dich, weil du immer in der ersten Reihe stehst.
Ein Lied nur für dich, weil du immer mit uns schlafen gehst.
Dies ist ein Lied für dich, weil du stundenlang zuhause sitzt und brennst.
Ein Lied für dich, weil du alle unsere Texte kennst.
Kommst du aus Hamburg oder aus Berlin,
kommst du aus Zürich oder kommst du aus Wien,
kommst du aus Bielefeld, aus Dresden, aus Heilbronn.
Egal! Irgendwie haben wir dein Herz gewonnen.
Wegen dir können wir schon seit Jahren erbarmungslos punken.
Und dafür wolln wir uns bedanken.

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Sind wir zu kindisch? aber hallo! niveaulos sind wir sowieso. Na und? Dafür sehn wir besser aus
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Mit dir können unsere Fans sich nach Herzenslust zanken.
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denn der Rod hat mir gesagt, dass er euch liebt.
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ihr seid der Grund dafür, dass es uns gibt.
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Resumen

El presente trabajo describe un algoritmo de planeación y la arquitectura necesaria para la construcción de planes que sea similar a la que los humanos realizan. Para alcanzar dicho objetivo, las ciencias que estudian como los humanos utilizan sus recursos para crear planes fueron revisadas. Estas ciencias fueron las ciencias cognitivas y las neuro-ciencias.

Las ciencias cognitivas ayudaron a mostrar que es posible producir comportamiento humano simple aislando los diferentes procesos que funcionan en el cerebro. Sin embargo, para alcanzar un nivel máximo de similaridad entre comportamiento humano y el producido por el sistema, los procesos que realiza el cerebro deben de ser estudiados y vistos como parte de un todo. Ésto se pude lograr solo si todos los procesos que conforman la arquitectura son diseñados tomando en cuenta la existencia de los demás procesos. Asi, pues, este es uno de los cuidados principales que fueron tomados para el algoritmo y la arquitectura aquí presentados. Entonces, se puede decir que el presente trabajo sigue una filosofía integral.

Las neuro-ciencias definieron la manera en la que las interacciones de los procesos que corren en el cerebro deben de trabajar. El objetivo de cada uno de los procesos y como la información es transformada para producir los comportamientos observables e internos de los humanos. Asi, pues, explica las formas específicas en las que la información debe de ser compartida entre conjuntos de neuronas y procesos. Entonces, otro de los objetivos fue crear un algoritmo que cumpla con dichas descripciones.

Con base en estas ideas, el algoritmo de planeación presentado junto con la arquitectura necesaria fueron definidos como los requerimientos que deben de seguirse para construir un sistema que produzca no solo planes, si no también comportamiento similar al de los humanos. Nótese que el objetivo de ésta tesis es solamente funcionar como una guía para una futura implementación, lo que significa que no es un objetivo de la presente tesis el producir una implementación. Ésto se debe a que una implementación que provea el nivel mas alto de similaridad entre el comportamiento producido y el de los humanos requiere de muchos mas módulos y procesos. Dichos módulos y procesos son aquí presentados solo desde el punto de vista de la planeación.

Abstract

The present work describes a planning algorithm and the architecture needed in order to builds plans in the same way humans does. In order to achieve this, a revision was made of the sciences that study how human brain use the resources at hand to create plans. This sciences where the Cognitive Sciences and the Neuroscience.

The cognitive sciences help to realize that a naive simulation of human behaviour could be built isolating the different process that work in the brain. But, in order to achieve maximal similarity between human behaviour and the emerging behaviour of the system, brain process must be seen as part of a whole. This is a goal that can only be reached if all the process within the architecture are designed from its conception are built taking notice of the existence of the other processes. So, this is one of the main concerns of the planning algorithm and the architecture presented here. Thus, the presented work has an integrative philosophy.

The neuroscience defined the way in which the interactions of the processes that runs in the brain must work. The objective of each of the process and how the information is transformed in order to produce the observable and internal behaviour. Thus, explained the specific way in which information should be shared between sets of neurons and process. Therefore, other of the objectives were to create a planning algorithm that follows this descriptions.

Based in those ideas, the presented planning algorithm and the needed architecture were defined as the requirements that must be followed in order to build a system that produces not only plans, but behaviour that resembles that of humans. Note that the objective of this thesis is to only guide a future implementation, this means that it is not an objective of this thesis to produce an implementation. The reason for this is that an implementation that provides the highest level of similarity between the produced behaviour and the human behaviour several modules and processes must be described and implemented. Modules and processes that are here lightly described from the point of view of planning.

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Chapter 1

The Goal behind it All: Reproduction of Human Behaviour

This dissertation describes the proposed cognitive architecture that would support an also proposed and described planning algorithm focused in the generation of plans in a similar way to human does; and thus, produce human like behaviour. It must be clear that the proposed ideas here are part of a bigger research effort to allow a computer software to control a virtual 3D representation of a human immersed in an virtual environment. All this in order to produce human like behaviour [RGR+]. In turn, that effort is part of a bigger research. Which is to build a system that will allow a not experienced user to describe a situation using natural language and from which a three dimensional simulation of the dictated scene would be generated [PZR].

1.1 Problem Description

In order to create an algorithm that build plans like human does, it was necessary to find how human accomplish planning. This is how cognitive neuroscience was selected to be the main theory that would guide this research. Unfortunately, even for the science that study how cognitive process are carried on by humans, it is not clear how planning is done by humans [Fus08]. Furthermore, the hypothesis that describe how planning is done by humans, does not fit perfectly with other of the goals of this research; the creation of a computer software that controls a virtual 3D representation of a human so that it present human like behaviour. This is due the fact that most of those hypothesis (at least most of the reviewed) try to isolate the planning process in a effort to highlight the characteristics of the process. As a result, most of them explain in little or no detail how the planning process work with other cognitive process to generate human behaviour. And the idea here is not that this research goes against modularisation or specialisation of tasks. But that is as important to clarify how those modules work individual as how the modules work together to achieve the main goal of the system.

Based in what is said, we can resume the objectives of this thesis as follow:

- Propose a cognitive architecture that would host the planning algorithm with the help of neuroscience.
- Build a neuroscience based description of how the process of planning in humans is completed.
- Using the given description, *generate the user and architectural software requirements to build a software system that create plans like humans does.*

It must be clear that, although the algorithm can work with a simplified version of the architecture. The final objective of this dissertation is to provide the highest level of realism possible (measured in the level of resemblance of simulated human behaviour with actual human behaviour). Thus, implementation of the proposed algorithm and architecture presented here must wait till other cognitive processes be described with the same level of detail that planning. As such, implementation will not be presented in this work.

1.2 Motivation

As it was clarified, the direct objective of this thesis is the proposal of a software system that would create plans like human does. If only this objective is taken into consideration, there exist many applications for the result of this thesis. Here is a short list of the possible uses:

- As the system would generate human like plans, it could be used (together with other modules, information and with the proper calibration) as an assistant in the creation of daily activities plans. The software could be put in a PDA (Personal Digital Assistant) an use the user task information in order to provide a recommended schedule.
- The system could be used to create plans for the use of resources in different scenarios. As an example, a similar research was sponsored by the Office of Naval Research of the United State of America. This three year research has the objective of improve planning algorithms in order to aid in the creation of naval tactics, where the resources are multiple force units which can carry different task each [HRCG$^+$80].
- Video Games; the creation of "smart" enemies is a challenge in the current industry of video gaming and several tries had been made to achieve it. Just to mention one [Ork04]. The creation of plans in a similar way human does could solve the problem of creating a long enough interesting enemy, or a useful ally.

Basically, almost anywhere a plan is needed, this proposal has a possible use.

Now, as it was stated, the proposal made here is just a tinny part of a bigger research effort to create a system that recreates described circumstances. With the addition of this proposal, the system would be able to recreate occurrences in which human intervention are a main concern. Here is a scarce list of possible scenarios:

- Risk related scenes. Some dangerous situations could be prevented if human reactions could be anticipated. Emergency exits and scape route location planning could be helped by the simulation of high risk circumstances such as earthquake, fire, flood, terrorism, etc.
- Scene reconstruction. Witnesses could describe an event in order to help to build a re-creation of events such as robbery, traffic crash, murder, etc. The system could use the descriptions given to simulate the narrated circumstance to clarify some mysteries in the scenes.
- Due memory and processing constrains, basically, wherever a set of knowledge could be isolated in order to complete a task in a human way fashion this system could assist in the completion, or complete at full the task.

1.3 Thesis Organization

This dissertation is organized as follows:

- Chapter 2 explore other research with similar objectives. Focusing in how other cognitive architectures achieve the planning process.
- Chapter 3 describes the general proposal. Propose a neuroscience based theory about how planning is made by humans and states the requirements that a software must follow in order to produce plans like human does. Having special care to allow compatibility between the proposed algorithm and the base architecture [RGR$^+$].
- Chapter 4 describe the conclusion of this work and clues for the direction future work should take.

Chapter 2

The Cognitive Sciences Approach to Simulate Human Behaviour

In this chapter, is summarised how some of the most used cognitive architectures achieve planning. The reason behind selecting only cognitive architectures is the fact that the objective of the research this thesis is part of, is the reproduction of human behaviour. Although exist other approaches to face this challenge, following the description given by the neuroscience, linguistic, education, artificial intelligence, anthropology, psychology and philosophy (those sciences conform the cognitive science) of how human complete actions, could give the true explanation that fully describe the reason behind why those actions are selected and carried on the way human does. Besides, the architectures reviewed here are the ones that with most frequency are used to simulate human behaviour and help to test theories relating how parts of such behaviour is produced. Thus, in the following sections, the planning algorithms used by some cognitive architectures are presented.

2.1 SOAR

SOAR is a cognitive architecture born in 1982 and supported by the DARPA. Its main principle is that all decisions are made through the combination of relevant knowledge at runtime. In Soar, all decisions are based on the interpretation of sensory data and the contents of memory created by past experience. This architecture has been probed as general and flexible for research in cognitive modelling across different domains.

In SOAR, planning is based in symbolic rules for the application of operations (actions). Such rules are:

- **Operator Proposal**: A rule that propose the application of an operator.

- **Operator Comparison**: A rule that allows ordering between operators.
- **Operator Application**: A rule that activates operators.
- **Operator Termination**: A rule that defines when an operator has finished execution.

The planning algorithm can be described as the selection of an operator, or set of operators, based in the consideration of current input and the rules that can apply. When no rules can apply, a sub-goal is set in the hope that such sub-goal triggers the application of a rule. If a point where no rule can be applied is reached, SOAR propose the use of a operator in base to its ordering. Then, learning is applied to measure the success and modify the rule that govern the operator, which can be used in the next planning cycle [LPJW96].

2.2 ACT-R

Adaptive Control of Thought-Rational is a cognitive architecture based in a production system [ABB+04]. Such system is based in a set of rules that define some data patterns that, when they are spotted in working memory, produce the activation of an action [And83]. ACT-R, in his many years of existence, has been used as a platform where multiple physiological and neurological theories had been tested in order to get a better understanding of them.

Planning in ACT-R is through the definition of production rules that generate sub-goals. Those production rules compete with others, having no special characteristics; they are equally important as other production rules. The way in which production rules are selected, are by means of how well they are evaluated by different ways:

- **Degree of Match**: This rates how well the production rule fits into current situation.
- **Production Strength**: This is a property of the production rule that is related to the frequency of application success. A production rule is preferred if it has been applied more times and had lead to success.
- **Data Refractoriness**: This limits the amount of productions rules knowledge sets can match to one. This means, knowledge data can only be used be one production rule.
- **Specificity**: This evaluates how specific a production rule is against other. When there is a conflict, if a production rule is more specific than other, the former is selected.
- **Goal-Dominance**: As it was stated, sub-goals can exist. A preference is given to production rules that concern the goal at hand.

2.3 CLARION

CLARION is a cognitive architecture based in two assumptions: the representational differences and learning differences of two different types of knowledge: implicit versus explicit. This makes CLARION focus heavily in the learning process of the brain. In this architecture, planning is accomplished by the use of Q-Learning to guide the search of a successful action. Q-Learning is an algorithm based in neuroscience and psychological ideas, which states that repetitive use and success of an action grows the likeliness of the action being selected the next time [HWS00].

The algorithm it uses is the following [SPS00]:

1. Observe the current state x.
2. Compute in the bottom level the Q-values of the x associated with each of all the possible actions a^i's: $Q(x, a^1), Q(x, a^2), ..., Q(x, a^n)$.
3. Find out all the possible actions $b^1, b^2, ..., b^m$) at the top level, based on the input x and the rules in place.
4. Compare the values of a^i's with those of b^j's, and choose and appropriate action b.
5. Perform the action b, and observe the next state y and (possibly) the reinforcement r.
6. Update the bottom level in accordance with *Q-Learning.*
7. Go back to Step 1.

2.4 Discussion

As can be inferred by the long time the revised cognitive architectures had exists, the planning algorithms should have its limitations but are good enough for the applications they had been used on. Still, ACT-R has had a particular difficult time making the match between the modules inside the architecture and the human brain structures and processes. This is a problem that emerges from the fact that ACT-R has not been planned as a cognitive architecture from the beginning. Thus, although they have the psychological background to state that the production rules are a good approximation to how humans process information, ACT-R does not make a transparent relationship between human processes. This can be noted by the fact that emotions are not considered in the planning process.

In the other hand, although SOAR planning algorithm is similar to the one used by humans, the fact that SOAR can only consider as applicable actions those which are built in the architecture, limits the extend at which the architecture could reflect human behaviour. This is due the fact that humans can learn new actions, not only by the combination of already known skills, but by modification of the actions at hand or observed ones.

CLARION has the same weakness that SOAR, it can not do plans using actions that are not explicitly stabilised at the beginning of the simulation.

In base to the this, the motivation of creating a planning algorithm that resembles human behaviour considering all of the process that are carried on in the human brain takes more importance.

Chapter 3

The Neuroscience Description of the Planning Process

On the following pages, would be presented the neuroscience ideas that describe how humans build plans. These are the basis for the here proposed architecture and algorithm.

3.1 Planning on Humans

Fuster [Fus08], through experiments with mammals and humans, states that humans are somewhat ready for the next configuration of the environment and themselves. This comes from the fact that, in advance, humans have a set of actions that are believed to help to reach a goal. Also, he states that is a task of the prefrontal cortex to help to formulate and implement such sequence of actions. And that this is possible thanks to the pre-existence in frontal cortex of bits of plans that are associated with the current state to formulate a new plan. This stored plans are part of the executive memory, which could mean that they had been built thanks to previous experience and by the use of imprinted information. Unfortunately, he also states that it is not clear how those memories are arranged in a particular way to fit a situation. Still, he states that memories are applied in a basis of: "if this situation now, then later this action" or "if this situation earlier, then now this action". Tanji [TH01] describes that this process is also accompanied by the mixture of current sensory and emotional information and memories that are related to current action. As a result of the combination of this information, a new "idea" emerges.

Fuster stress the existence of a constant feed back between sensory and emotional neurons that regulate both planning and attention. This triggers a set of reactions in the organism, which help to coordinate all the tasks in the brain. Furthermore, as described by [Bas] and [DFAJ], planning has to do with the imagination and valuation of a hypothetical situation. Which could be also fomented by this feed back.

The works of Batson and Dunn, gives us insight of a special characteristic of planning: the act of imagining the self in a situation that has not been directly experienced. This is a really important feature in human behaviour, since it give the human the ability to produce new actions that otherwise would not be at his hand, or that would take a larger amount of effort and time to master. In order to achieve such a task, memory must be organized in a special way; which is the description that follows.

3.2 The Use of Memory

As described by [Fus08] and [Haw04], memory is organized in a hierarchical way. At the bottom of the hierarchy, although currently unknown, good chances are that exists memories inherited by the specie. This memories are arranged and combined to relate them to current event information, forming a new layer. Each time a new event is presented, memories are recombined to help to relate the new information to previous one [Haw04].

In the top layer exist what are defined by [Haw04] as invariant representations. This are memories that are generalizations of other previous information that help to classify objects. That is, a ball, whether a soccer, basket, American fut-ball, tennis, etc. is still a ball and many of the memories applied to an American fut-ball ball can be applied to other kinds of balls.

Invariant representations help humans to visualise them in situations that, in other way, could be hard to visualize. Take as an example learning to play an instrument as a guitar, although we may not have detailed information of how to produce a particular note, from the memory of viewing how others place its hands and move the fingers through the cords provides great information of how to interact with the instrument. An invariant representation shared between the person that is playing the guitar and the one that is observing such action exists (at least, they are both humans). This gives enough information to allow humans to create a plan of how to set each arm and leg in position to avoid the guitar to fall while playing it, at least. Fuster describes this ability to imitate what is memorised as part of the work of mirror neurones [Fus08].

With the found information, conclusions can be made related to how planning must be executed. This are:

- Plans are built using previous memories.
- By the use of invariant representations, plans that are not directly applicable could be adjusted to new situations.
- Constant feedback between the planning modules and other cognitive processes must exists in order to allow an ordered pursue of a goal.

Chapter 4

An Integrative Cognitive Architecture

This chapter presents the most resent ideas that describes how planning is done in human brain and the user and software requirements a software must fulfil to work in a similar way. As it was mentioned, the particular objective of this thesis is to guide the implementation of a software that would plan similarly to human beings. Also, the present thesis is the result of just a part of a bigger research effort to allow a computer to simulate human behaviour. In this research, one of the main philosophies is that described by Newell in [New94]:

> "... is that a single system (mind) produces all aspects of behavior. Is one mind that minds them all. Even if the mind has parts, modules, components, or whatever, they all mesh together to produce behavior. Any bit of behavior has causal tendrils that extend back through large parts of the total cognitive system before grounding in the environmental situation of some earlier times. If a theory covers only one part or component, it flirts with trouble from the start. It goes without saying that there are dissociations, independencies, impenetrabilities, and modularities. These all help to break the web of each bit of behavior being shaped by an unlimited set of antecedents. So they are important to understand and help to make that theory simple enough to use. But they don't remove the necessity of a theory that provides the total picture and explains the role of the parts and why they exists."

Thus, although the software requirements presented can be used to produce an algorithm that can work as a stand alone system, if left alone, the resulting planning will not behave as similarly as is desired to human beings. So, in order to achieve the maximal similarity level between the algorithm behaviour and those of humans, some considerations must be made regarding all the processes related to how humans creates plans. That is why in the following pages is presented the theory that describes how the planning process works on humans, together with the theories that describe the process that interact with planning.

A remark must be made here to make the reader notice that, at the time this thesis is being written, an explanation that fully describes how the human brain works and that is accepted by all the neuroscience community was not found. As a consequence, multiple theories that tries to explain how some of the process works were revised and a selection was made in order to use them as the building blocks of our own hypothesis of how all these processes labour and interact to produce the human behaviour. Individually, those ideas are widely known in the area of neurosciences, medicine, psychology, among others, and describe how some of the cognitive processes produce the human behaviour [Car00], [Gee09] and [GH00].

The presentation of the formulated hypothesis and the software requirements would be as follows: first, a general introduction to the concerning modules that have been identified in the brain and that will serve as the main building blocks of the planning process; next, a description of how those modules work in the processes that interacts with planning; followed by the depiction of the planning process; we will then use all that theory to describe the proposed system architecture and specify the requirements of the system.

4.1 The Main Building Block: A Human Brain Software Architecture

As was explained, if a developer focuses only in the planning process trying to resemble human planning, without having notion of the other processes that interact with it, she would produce an algorithm that is hard to integrate with other modules. This is mainly due the fact that the relationships between process in the human brain is very tight. In an effort to avoid such problem, the proposed planning system presented here would be contextualized in its own brain architecture that tries to produce human like behaviour. The 'contextual' architecture is the one presented in [RGR$^+$]. Such architecture has a set of abilities that will produce human behaviour. Here is the list of the selected cognitive processes that the refereed brain would provide and that would give the desired abilities to the simulated human creature [RGR$^+$]:

- **Perception**: is the process from which the virtual 3D creature will recollect environment and self information.
- **Learning**: the process that will modify knowledge and skills in order to adapt to new changes in the environment.
- **Memory**: this is the set of action that would allow information to be stored, retained and recalled as needed.
- **Emotions**: is the process that encodes emotional stimulus and to influence a set of cognitive process with the emotional nuance extracted from the perceived stimulus. Those new stimulus would affect other cognitive process.

- **Planning**: the creation of a sequence of actions that would lead to an expected result. This process will be guided by the attention and decision processes and would use the information stored in memory.
- **Deliberation Process**: the process of selecting a particular option taking in consideration desired goal and other constrains.
- **Attention Process**: the sequence of actions that would take the virtual entity into selecting limited processing resources to achieve optimal development [Fus08].
- **Motor Action**: the processing of how the "body" of the virtual creature would carry the activities that would lead to the desired objective.

All of those process had been related to neural activation of a certain portion of the human brain. That is how neuroscientist had modularized and isolated some areas of the brain, each of those modules completing a specialized task. In the brain architecture refereed here, each of the modules corresponds to a group of neurones that neuroscientist have related to a specific task or related tasks. Next is the description of each of the modules, its tasks and the relationship between other modules in the architecture, which is depicted in 4.1 [RGR$^+$]:

1. ***Set of Sensory System***: this module catches the environment status by means of: vision, audition, touch, taste, and olfaction. Then, sends the information to the *Thalamus*, except the olfactory sensor. Due the primitive nature of the olfactory system, this sense sends the information directly to the *Olfactory Cortex*, after a filter is applied by the *Olfactory Bulb*.
2. **(α) *Olfactory Bulb***: this module is a first filter to olfactory information. Then, it sends to the association cortex through the *Hippocampus*.
3. ***Thalamus***: this is the first processing phase for the data received from the sensors. It consists of four modules:
   (a) **(β) *Lateral Geniculate Nucleus***: receives information from the vision sensor and sends the selected information to *Visual Cortex*.
   (b) **(γ) *Medial Geniculate Nucleus***: sends the auditory information selected to *Auditory Cortex*.
   (c) **(δ) *Ventrobasal***: filters tactile sensory signals before sending them towards the *Somatosensory Cortex*.
   (d) **(ϵ) *Ventral Posterior Medial Nucleus***: all taste information is put together here and only a selected amount of it is sent to the *Gustatory Cortex*.

The submodules of the *Thalamus* are all interconnected and share the information they get. This promotes a richer interpretation of the data received by a sense. Also, all modules send information to the *Amygdala*.

4. ***Sensory Cortex***: this set of modules are the ones in charge of giving an interpretation to the data received by the *Set of Sensory System*.
   (a) **(ζ) *Visual Cortex***: in this module, all incoming information is visually interpreted with the knowledge provided by the *Hippocampus* and sent to the *Association Cortex*.
   (b) **(η) *Gustatory Cortex***: here, taste information is interpreted, using the information provided by *Hippocampus* and sent to *Association Cortex*.
   (c) **(θ) *Somatosensory Cortex***: in this module, all somatic information is transformed into terms understandable for *Association Cortex* to interpret using information provided by the *Hippocampus*.
   (d) **(ι) *Auditory Cortex***: in this module the interpretation of the auditory information is done using *Hippocampus* information. When ready, the information is sent to the *Association Cortex*.
   (e) **(κ) *Olfactory Cortex***: the olfactory information received here is interpreted using the information provided by the *Olfactory Bulb* and sent to the *Association Cortex*.
   (f) **(λ) *Association Cortex***: this module puts together current and past sensory interpretations and associations of the objects on the environment. It has connection with the *Hippocampus* to get past information and to return the deducted information, also, it has connections with the *Olfactory*, *Gustatory*, *Visual*, *Somatosensory* and *Auditory Cortex*.
5. ***Limbic system***: since two of its important functions are related to emotions and long term memories, it includes the *Hippocampus* and *Amygdala* as the constituent parts of the limbic system.
   (a) **(μ) *Hippocampus***: this module creates a context from all the information gathered. Additionally, manages the storage and recall of memories from cortex. At the signal of the *Amygdala*, store all information received in the recent past, present and recent future and creates a temporal relationship between those information.
   (b) **(ν) *Amygdala***: here the information related to context and current state is received thanks to *Sensory Cortex* through the *Hippocampus* and *Thalamus*. This information is used to organize a set of emotional reactions. Those reactions take effect on the *Thalamus* to affect perception, the *Hippocampus* to instruct when to

keep knowledge in the long term memory and affect context creation, and in the *Orbitofrontal Cortex* to modify the appraisal level of the information gathered.

6. ***Prefrontal cortex***: coordinates actions and cognition based on internal goals. Thus, it comprises the next three areas.
   (a) **(ξ) *Orbitofrontal Cortex***: this module evaluates the affective information of perceived stimulus. It mainly receives information from the *Amygdala* and projects to the *Ventromedial Prefrontal Cortex.*
   (b) **(o) *Dorsolateral Prefrontal Cortex***: it is related to the motor planning behavior, stores the current goal and integrates the information of long term memory and sensory input (comming from *Hippocampus*); the main objective is to create plans to achieve the current goal. Submits tentative plans to *Sensory Cortex* and *Ventromedial Prefrontal Cortex* for attentive evaluation. It communicates with the *Ventromedial Prefrontal Cortex* when a plan is created and decisions must be made. When the next action is decided, the order is sent to the *Basal Ganglia.*
   (c) **(π) *Ventromedial Prefrontal Cortex***: receives emotional appraisal information from *Orbitofrontal Cortex* and objective and perceived information from the *Dorsolateral Prefrontal Cortex.* With this information, chooses between possible actions to achieve the goal. When one action does not lead to the goal, the information is redirected to *Dorsolateral Prefrontal Cortex* to form a plan.
7. ***Motor System***: here, the instructions given by the Prefrontal Cortex are translated into body movement attempts.
   (a) **(ρ) *Basal Ganglia***: this module selects the possible muscles of the body to achieve the action sent by the *Dorsolateral Prefrontal Cortex.*
   (b) **(σ) *Motor Cortex***: once an action is received from *Basal Ganglia*, this module makes the needed calculations to control body and, therefore, complete the action.

Now that the base architecture has been presented, in the following sections would be explained how each of the processes that participates in it are related to planning.

4.1.1 Perception

As described previously, perception is the process of identifying the current status of the environment. Is an important part of the system since tanks to this ability, the architecture can have enough information in order to formulate judgements related to its surroundings [Bla09]. And, that is precisely the relationship between the perception process and the planning; by no other means, can the planning create a current state. But, the state that

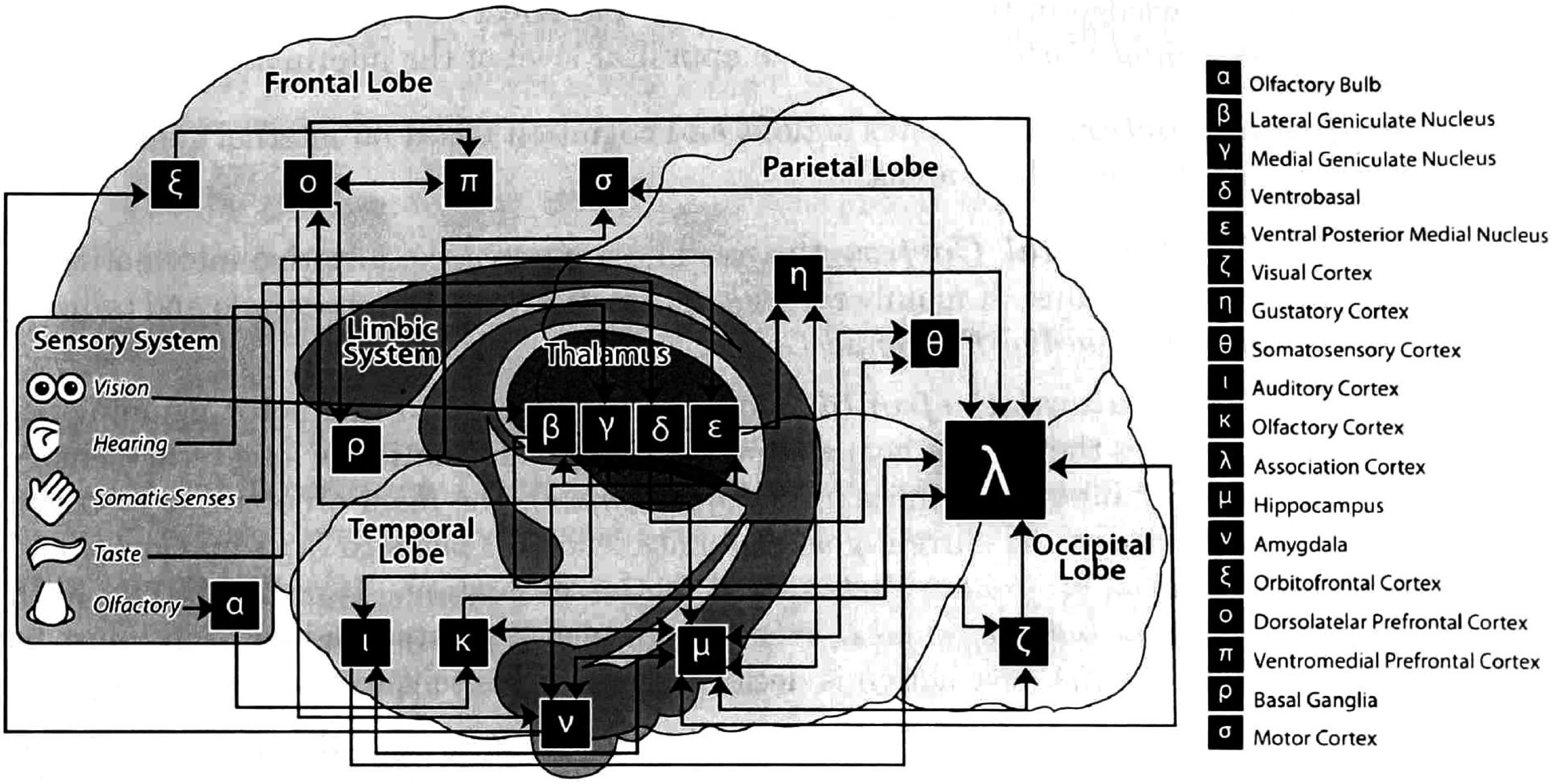

Figure 4.1: The **Cognitive architecture** design that supports the abilities for virtual 3D human creatures

receive the planning algorithm is not exactly the one that the sensors captures. The attention and emotion processes are involved in filtering and evaluating the information. In order to understand this, it is now presented the relationship between the perception process and the planning.

4.1.2 Emotion

Emotions, from the point of view o the planning process, modify the information recollected by the perception in order to add a personal and unique touch to this information [SGS]. This is, they produce a new point of view to the same information. Besides, as the emotions are the ones that rules which data gets stored in the memory, they play a decisive role in planning. This is due the fact that the information stored in memory will conform the search space of the planning, as explained in the memory section. But, before we go deep in how the memory is related to planning, first must be clear the other way in which the information perceived can be modified before entering in the planning process.

4.1.3 Attention

As explained in past sections, the attention works as the information filter that selects the information that is relevant for the system. But, actually, what goes on with the information is that it is sorted in base to its importance to the system and its objectives. By this means, the information that relates directly with the current objectives of the system is given top priority. The sorting of information occurs at various points in the architecture. At very early steps in the architecture, the *Thalamus* filter information that does not excite enough the receptors. Again, in the *Dorsolateral Prefrontal Cortex* the contextualized data sent by the *Association Area* is ordered based in the relevance to current objective. Also, in the *Orbitofrontal Cortex*, information that produces a low emotional arousal level, and coming from the *Amygdala*, is regarded in importance. This two way sorting come together into the *Ventromedial Prefrontal Cortex*, who is in charge to create the final sort for the current state information. The planning algorithm, using this sorting will ask the *Hippocampus* to search for information related to the current state and goal (as will be explained later). Also, the *Hippocampus* will generate a list of results that will be sorted based to the emotional level indicated by the *Amygdala* when they were stored. As will be explained later, at some point in planning, a state generated using memories would be evaluated at the *Ventromedial Prefrontal Cortex* and, if it meets the attentional requirements, it would be submitted for the process of imagination. Is easy to see how attention is not managed by a solely module, neither a step by step process, it is rather an emerging ability of the system. If further information on attention is desired, it is recommended to check the description of the process given at [Fus08].

Now, that has been present how the perception, emotional and attentive process manages the information of the current environment state in order to provide a search starting point to the planning system, will be presented how past information is related to the planning process.

4.1.4 Memory

Memory is defined as the ability to store, retain and recall information that some system has witnessed [Kan00]. It has been classified by many in base to the time between the information is acquired and can be recalled, the use it is made from the retained information and in other ways [And07], [Haw04], [Fus08]. Here, since the objective is clarify the relationship between the memory and the planning process, it would be enough to use a theory that fits the architecture and the proposed planning process. The objective of the memory, from the point of view of planning, is to feed planning with already know information in order to use it as the solution to current situations. Thus, for the planning proposal to perform as desired, is needed that information in memory is stored in three different ways. This property would become clearer later when the planning process be explained. But, in easy words, the reason for such organization is that information we perceive at any time is interpreted by means of other information stored [Fus08] and [Haw04]. How new information is related to stored information in memory is what create those distinctions.

So, with no further delay, next are the description of the different ways in which the information in memory should be organized.

Semantic Memory

Semantic memory is the information that humans have stored and that help them to identify everything they know. This is, it has the characteristics that define all that is perceived; from specific objects such as a pacifier, to complex situations like accidents, passing by actions such as running. It is a memory of definitions, a dictionary that relates perceived sets of information to form mental concepts and, at the same time, such mental concepts could be part of the definition of new concepts [Haw04], [Fus08].

Episodic Memory

Episodic memory is the memory of scenes. A set of mental concepts generated by the semantic memory related by its occurrence on a particular time. This is a set of sets of perceived characteristics, all related by the fact that they happen to be perceived together at the same time [Haw04], [Fus08].

Procedural Memory

This is the memory of the action. Information here are scenes that are timely related. It means that a scene is related with other if it happened in a time before or after the other [Haw04], [Fus08]. This is a set of sets of scenes, in that sense, the information stored in the procedural memory could be viewed as a motion picture of past events. A property that is prevalent in all of these memories and that is vital for the planning process to exists, is that, the temporal relationship between them emerges from the fact that the learning process concludes that the perceived information from one scene produces the action that generates the next scene [Fus08].

Exist two properties that are shared by all levels of the memory organization; they are the ability to store invariant representations of the information and the attention value related to every memory. An "invariant representations" means that although humans can identify and remember individually all the keys of its house, all of them can be identified as keys; for the process of running, in spite of the fact that every time that is realized changes in response to variations of the environment and the situation, in memory exists an invariant representation of the act of running [Haw04]. At its time, running could be part of a higher invariant that describes actions the human can complete; it could be possible that also is part of an invariant that defines sports. This creates new relationships between information at all levels of memory organization. A remark must be made here, since the invariant representations that are formed with those memories stored in the procedural memory, define with great detail that if a given scene occurs, then the next action must be one in particular [Fus08]. This 'logic rule' is other of the main tools for the proposed planning process to work.

On the other hand, the attention value that each stored memory has, is an important source of information since it describes the degree of preference that is given to a particular memory. Once is clear how memory is organized, now is presented the expected results of a search made by the planning process.

The way in which planning would use the memory is through searches, where the input of the search would be a scene as they are stored in episodic memory. The output of the search would be all the stored procedural memories that contains a scene that could be satisfactorily transformed in the input scene, together with the instructions to made the transformations. When more than one search results come, they must be ordered by the attention level they were stored with [Haw04]. Its important to clarify that for a transformation to take place between memories, at least one of its containing set of perceived characteristics must be replaceable by other that shares an invariant.

Such is the memory in the refereed architecture, and the requirements that must be fulfilled by it in order to allow the planning to work as proposed. Now, its present the process of decision making.

4.1.5 Deliberation Process

Decision making, or the process of deliberation, is the act of making elections over options. The ultimate objective of the planning process is to offer the options from which the system would take a course of actions. As such, every time a set of actions is produced by planning, the deliberation process makes an evaluation and takes a decision between the possibilities of keep planning in the same direction, change part of the plan, or executing the plan as it is. Thus, the deliberation process has an important role in the process of planning, together with attention, as it directs the search in the selected orientation.

As it was stated, the sequence of actions would be executed after a decision is made over multiple set of actions. How action execution is related with the proposed planning algorithm is the subject of the next section.

4.1.6 Motor Action

The process that carries on the selected plans is the motor action process. The objective of this part of the architecture is to allow the activation of set of muscles in order to generate the action described by the plan. Although can be argued that the activation information must be part of the plan, and sometimes it is. This happens when the action has formed an invariant that describes the action with the sufficient level of detail, or the particular memory used to construct the plan, can be applied with no modifications. But, when this does not occur, there is enough evidence to support that exist a specialized module that copes with motor action [Kan00], [GH00]. So, beside following the actions that the planning process orders, the motor action process refines the planning to adjust to current environment state from the point of view of body movement.

Now there is only one process left that interacts with planning: learning.

4.1.7 Learning

The process of learning in the refereed architecture is grounded in the idea that the whole system must search the maximization of attention level in the memories used [RGR+]. This would guide all the process to prefer information with a high level of attention and to intent to produce higher levels of attention. In the planning process that is exactly what happens, as it was explained. When memories are recalled, they are sorted by the attention level they where stored with [Haw04].

Additionally there is another important feature that learning adds to the whole system and, therefore, to planning. This is the creation of invariant representations, how those invariants are created is not the subject of this thesis, but one of the theories revised states that they may be the result of processes that could be simulated with Markov chains [Geo08].

Now, hopefully, sufficient background has been set in order to explain with enough clarity how planning is done in the brain and how is proposed that it should be related to the refereed architecture. Thus, next is the proposed explanation of how this process is done in the human brain and the requirements for the refereed architecture to implement it.

4.2 The Planning Process on Detail

As it has been repetitively described in pass sections, a theory that satisfactorily explains how planning is done by humans has not yet been found. Furthermore, there are some persons that states that such task can not be completed with the current methodologies [Fus08]. Still, here is presented the result of analysing and putting together some hypothesis about how

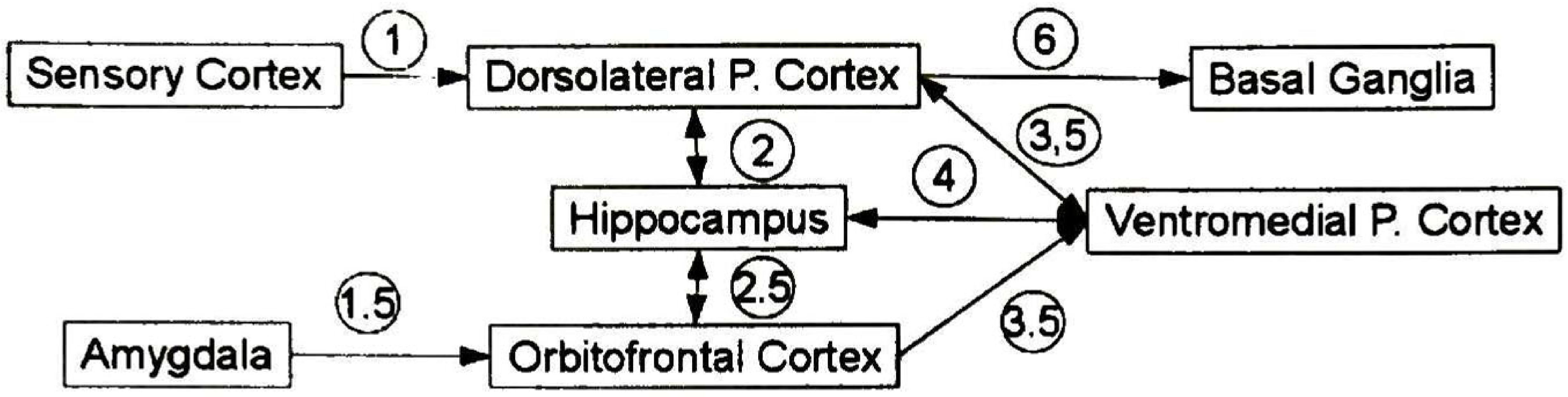

Figure 4.2: The **Planning and decision** ability granting processes as described in [RGR$^+$]

planning is completed in the human brain in order to produce a hypothesis that could work in the refereed architecture. This with the sole objective of having a cognitive architecture that could control a virtual 3D human entity and produce behaviour similar to humans. Thus, in order to explain the here proposed ideas, a global view of the process would be given, where the inputs and outputs of the process would be revealed.

As an introduction to the detailed planning proposal, first would be presented how planning was first suggested in [RGR$^+$]:

Planning and Decision Making: see figure 4.2. In this ability, two processes run in parallel. One of the processes carries emotional information with the world state, the other builds a plan based on the information provided by the *Sensory Cortex.* Following is a detailed description of both processes.

1. At the *Dorsolateral Prefrontal Cortex* (Dorsolateral P. Cortext at figure) a plan is built using the current state sent by the *Sensory Cortex* (1), the main goal established at the beginning of the simulation and the information provided by the *Hippocampus* (2).

2. At the *Orbitofrontal Cortex* the emotional information sent by the *Amygdala* (1.5) is received and a emotional appraisal level is set to the knowledge stored at the *Hippocampus* (2).

3. At the *Ventromedial Prefrontal Cortex* (Ventromedial P. Cortex) the plan built by the *Dorsolateral Prefrontal Cortex* and the appraisal level of the knowledge is received at different times (3, 3.5). Using the raw knowledge and its appraisal level (4), the plan is trimmed and sent back to the *Dorsolateral Prefrontal Cortex* (5).

4. When the trimmed plan is received at the *Dorsolateral Prefrontal Cortex* and the plan is refined, extended or returned to the *Ventromedial Prefrontal Cortex* as required. When the immediate next action is decided, the action is sent to the *Basal Ganglia* to be executed (6)

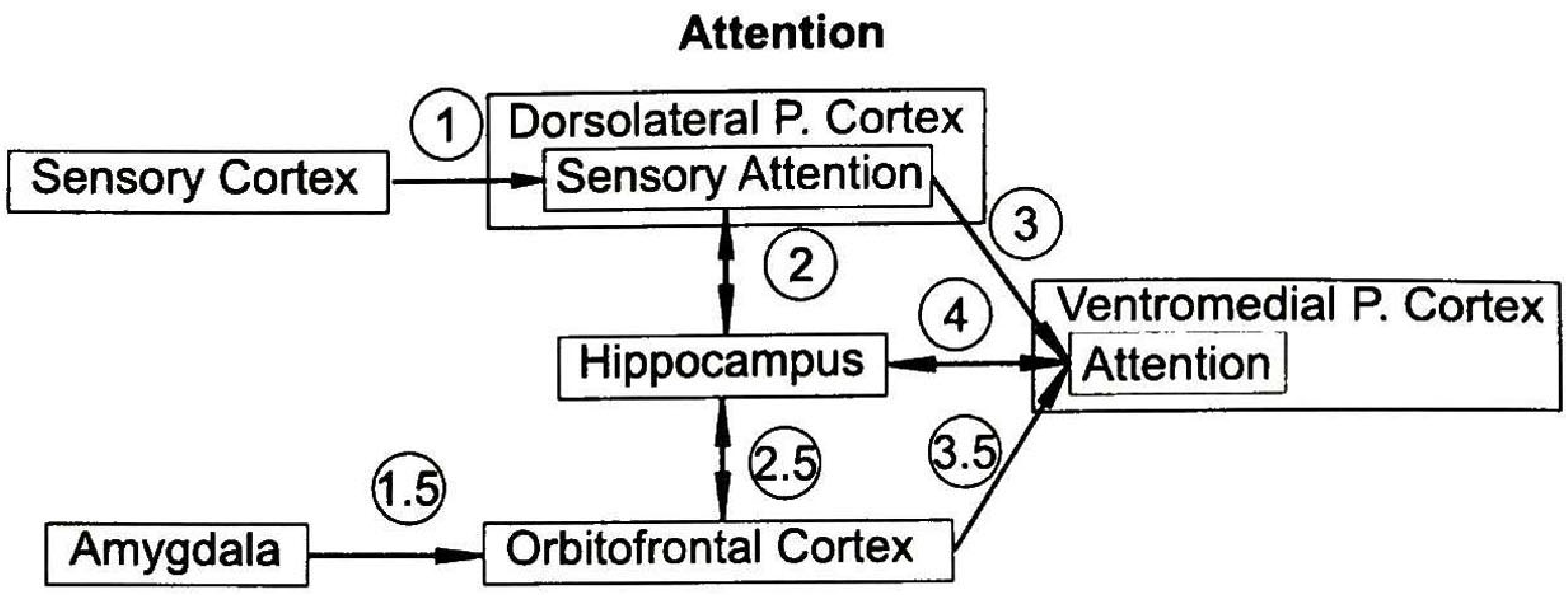

Figure 4.3: The isolated planning related **Attention Process**.

As it can be noticed, in the past description of the planning and deliberation processes there is no difference between this two processes and the attention process, as it was described in the previous section. This is due the fact that, in that proposal, the attention process was thought to be part of the planning. When more literature was reviewed ([Fus08]), it was discovered that, indeed, those steps described are of vital importance to planning, but are part of the attentional process. This is due the fact that the set of actions carried on by such steps, are related to selection of information that is relevant to current objective. That special information is the starting point of the planning process. Furthermore, when a plan is generated, the attention process assumes the role of an evaluator; from the planned states, it would select the information that must be there in order to satisfy the system goal.

So, in order to adhere to the here proposed planning algorithm, the above process must be divided, isolating the attention process from the decision making and planning. This is not a big change, it consist in create, inside the *Dorsolateral Prefronatal Cortex* and *Ventromedial Prefrontal Cortex*, modules that manages attention. Thus, the attention process would be as follows (figure 4.3):

1. At the *Dorsolateral Prefrontal Cortex* (Dorsolateral P. Cortext at figure), specifically at the *Sensory Attention* module, information sent by the *Sensory Cortex* (1) is ordered by the attention process using information provided by the *Hippocampus* (2).

2. At the *Orbitofrontal Cortex* the emotional information sent by the *Amygdala* (1.5) is received and a emotional appraisal level is set to the knowledge stored at the *Hippocampus* (2.5).

3. At the *Attention* module, inside the *Ventromedial Prefrontal Cortex* (Ventromedial P. Cortex), both pathways of information converge (3, 3.5) and a general attention level is set using memory information (4).

The information sorting made by the attention process at the *Ventromedial Prefrontal Cortex* is the initial state from which the planning must start a plan; thus, one of its inputs.

Although very little has been said about how objectives are generated in the architecture, in [RGR+] is considered that the objective is distributed to each module at the start of the simulation. Since this is a little restrictive approach (even though good enough for the current objectives of the architecture), here is mentioned a module located in the *Dorsoalteral Prefrontal Cortex* specialized in the formulation of a goal [GH00], [Kan00]. Such module could provide a more flexible behaviour to the virtual 3D human creatures. Another remark must be made here since the idea of such module has been discussed by the authors of [RGR+]; is just a matter of time for the publication of a document that includes this module. Thus, trying to anticipate to the addition of this module, the presented planning process supposes its existence and its role as the provider of other of the important inputs: the goal. Due the lack of a better name for this module, it would be called the *Goal* module.

Now that the enough context information has been given, next is presented an outside view of the planning process.

4.2.1 The Planning Process from the Outside

As is described by many sources ([GH00], [Kan00], [Fus08], [TH01], just to mention some), planning construction is build by a set of neurones located in the *Dorsolateral Prefrontal Cortex*. Is here where all the modules would send its inputs to be considered during the planning process. In order to ease the explanation of the relationship between the planning process and other modules, it would be first detailed the relationships during the segment of the planning cycle here defined as plan creation.

Plan Creation

Thus, plan creation as viewed from other modules, consists in sending and/or receiving information from this module at two particular moments depending if the modules work for the attention or the decision making process (see figure 4.4). This is due the fact that, in the first phase, with the goal sent by the *Goal* module (1) and the relevant current state information sent by the *Attention* module (2), the *Planning* module generates the first set of actions and states that will be part of a plan using the information retrieved by the *Hippocampus* (3), and those generated states would be submitted to the attention process evaluation. For that matter, the new states are sent to the *Attention* module (4). Then, the *Attention* module makes a fast evaluation of the states and, if they are relevant enough, an instruction would be send to the *Planning* module to send them to the *Sensory Cortex* and the *Amygdala* for a full evaluation (5). As it was said, the attention process ends with the

Attention module in possession of an evaluated state. When the state sent to the attention process arrives at the *Attention* module with a fresh evaluation, it is returned to the *Planning* module (6).

Here is when the next phase begins, the part of the planning process on which decision making have its mayor participation. Once the new state has been evaluated by the attention process, it is submitted, together with the plan it belong to, to the deliberation process at the *Decision Making* module (7). Here, as was previously described, the decision process chooses between executing the plan or continue planning. In both cases, the *Planning* module is informed of the decision and in case the instruction is to execute the plan, a message is sent to the *Basal Ganglia* (8) containing the plan for it to execute it. Due some conditions, later explained, mid therm goals could be established, when this occurs, communication between the *Planning* module and the *Goal* module is given in order to set this.

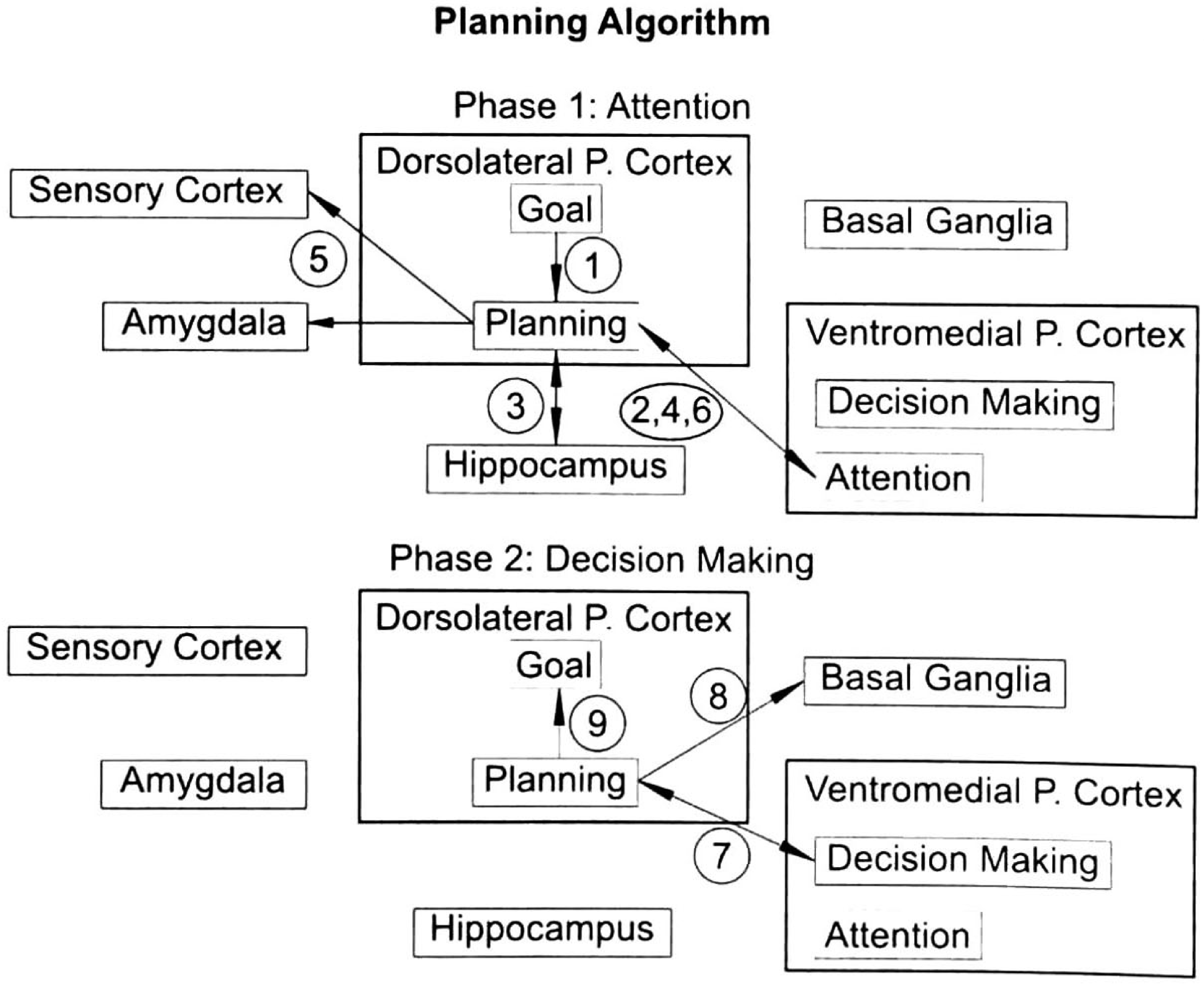

Figure 4.4: The **Planning Process** as viewed from the outside. In this view, two phases can be identified.

It could seem that the second evaluation given by the full attentional process is redundant and unneeded. But, as described by [Bas], [DFAJ] and [Fus08], this is part of the evaluation done not only by the attention, but the sensory and emotion systems. Furthermore, the pass of the state built by the plan through the sensory and emotional systems, could produce the act of imagination.

Now that is described the plan creation, another property of the human brain, thus of this system and the planning algorithm, can be introduced: the possibility of believe modifications at any moment.

Believe Update

As it was described, the learning process will seek the maximization of the attentional levels. This could possible imply that changes to memory attention levels could occur. As other parts of the system, the planning process must be affected by those changes. Thus, communication from the *Hippocampus* and *Ventromedial Prefrontal Cortex* (from both the *Decision Making* or *Attention* modules) to *Planning* module must be allowed at any moment in order for updates to occur as described in [Fus08].

This information paths can also be seen at the figure 4.4. The effect they have is different, depending of the module that makes the update. The *Hippocampus* updates the attention level of the memories that were asked for; this modifies the memory list on the planner (the function of this list would be clear in the next section). The *Attention* module updates the attention level of the already evaluated plans; this affects the lists of already created plans (other feature that would be described later). Finally, the *Decision Making* module could, at any moment, decide that a previous plan must be executed, this must be informed to the *Planning* module.

So, those are the inputs and outputs the planning process has with other process in the brain. At this point, its only left the description of how plans are built at the *Planning* module.

4.2.2 Plan Construction

As is stated by [Haw04] and [Fus08], plans are not built completely as news, they are built using previous plans. Thus, following those ideas, the planning process proposed here begins with the recollection, at the *Planning* module, of the goal and current state. Next, those states are used as the search query passed to the *Hippocampus*, which would bring those procedural memories that could be transformed into the the current state and the goal, and the way invariant representations must be used in order to transform them. As it was told, many procedural memories could return from the search, the order at which they would be processed is determined by the attention level they reached when they where stored. This conforms the memory list that was referred in the previous section. Therefore, the following procedural memory with the most activation level is selected, the needed transformations are applied, and the state used for the query of that result is related to the transformed procedural memory as part of the plan. Notice how, depending if the query was made with the current state or the goal state, the new information is added as a step after or before respectively to the state used. The plan, containing new states, is sent to the *Attention* module and evaluated; if indicated by this module, the plan is subject to the full attention process evaluation.

Once the first phase of the planning process had been completed, if the just created plan has been build from the current state, the plan is sent towards the *Decision Making* module to evaluate if its application would lead to a desired state; the *Planning* module is informed of the selected option. If the execution is selected, every plan built at the moment is send to the *Hippocampus* in order to be stored, the plan is sent to the *Basal Ganglia* and the planning algorithm is set for the arrival of the new current state. On a negative answer or if the plan was built from the goal state, the just created sub-plan is subject of an evaluation process. In this process, the activation of each of the scenes of the plan is revised. When a scene of a plan is found which activation level is less than the previous scene, the plan is duplicated to this point. Then, the original plan together with the duplicated trimmed plans are set in one of the two list of plans. These list contains the plans that had been build with the same global goal ordered by the attention level set by the *Attention* module. One of the list corresponds to those plans that are generated from the current state, the other corresponds to the plans that had been created from the goal state.

At this point of the planning process, a selection is made between continuing formulating plans from the procedural memories brought back from the memory using the current and goal states, or using the last and first states of a couple of already built plans. To work with a couple of plans, one of them would be selected from the list of plans generated using the current state; from this plan, the new current state would be used. The other plan would be took from the list of plans generated using the goal, from this plan, the first state would be used as sub-goal. All plans in each of the list must be combined with all the plans of the other list. So, for this decision to take place, all the information is send to the *Decision Making* module, and the result is informed. If the choose is to continue with the current state and goal, the process removes the already used memories from the list of brought back memories and the next memory is used to build a new plan. If the choose is to set new objectives or current states, the process stores the state of the algorithm and the process starts with the new current and goal state. In this new run, the only difference is that, when a plan is submitted to decision over continuing planning or acting, the plan from which it was first generated is appended to the submitted plan.

Due the dynamism of the environment, it is possible that a new current state arrives from the *Hippocampus*, before a plan is selected to execution. In this case, memories retrieved and plans created, are sent to the *Hippocampus* for storage and if a plan is being built, it is left finish its building cycle in order to save all work done and start from the new current state as new. Thanks to the storage of plans created in a previous state, it is possible that, if the plan is still applicable at the new current state, that they are used or, at least, part of them.

In the extremely uncommon case that all the memory and possible plans are exhausted with no decision over the action to take or change in the objective, the planning algorithm will send a special signal to the *Decision Making* module and it will have to let the *Basal Ganglia* decide the proper action. Which, most likely, it would be a reflex movement [GH00]. This case is rated as really uncommon, since the planning in humans tends to go no further than 7 ± 2 searches before an action is choose or the objective begins to be seen as less appealing [Kan00], [PWMG01].

From the point of view of the neuroscience, all the memories returned when a query and plans on the plan list are made go through the planning process at the same time. At the current time, the implementation of such system could imply the creation of a new thread for each of those objects. Since the amount of memories a human being have stored and the state explosion of planning will easily overwhelm any system if implemented in such way (at the time of the writing of this thesis); it is recommended that more studies be made on how the human brain allocate resources in order to adequate to the needs of the situation, and this guides dynamically the amount of processes that must be created in the planning process. Some insights related to the occurrence of this regulation are given by [dMG+05], and that here are described as part of the attention process.

It is possible that, during the mixture of plans in order to decide whether continue with a sub-goal or continuing with current goals, lots of combinations could be produced. In the human brain, this is regulated by the learning process, which grants the brain with more capacity to hold information, and by the same process that regulates resource allocation, which puts a limit in the amount of resources that can be used.

4.3 Planning in Action

To get a better understanding of the presented planning algorithm, two executions of the algorithm would be given next. The first is a well known neuroscience test: the towers of London task [NCVJ]. The second is a daily life situation: playing during a basket ball game.

4.3.1 Towers of London

This test consists in the presentation of a current and a goal state, and the instruction to go from the current state to the goal state. The states are formed by the use of three different capacity bins and three different color balls; the position of the balls in the bins corresponds to a state. One of the bins can contain three balls, other two and the last just one ball.

For this test, minimum previous information must be provided to the system. This information must be:

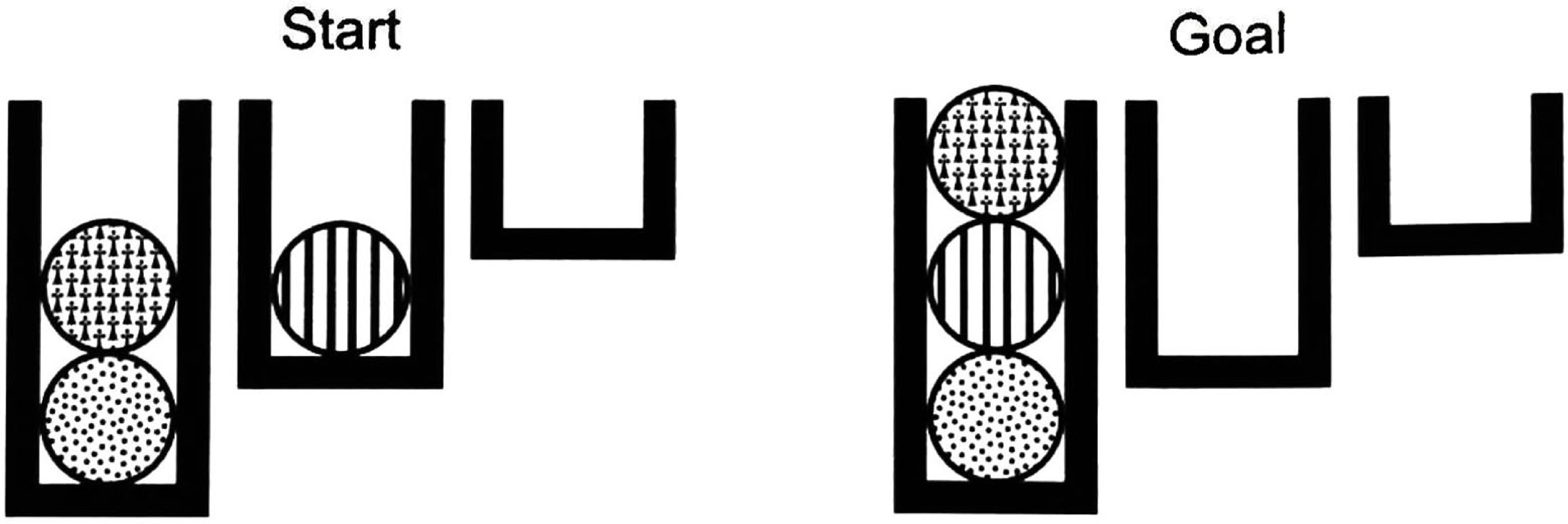

Figure 4.5: Start and goal states of the **Towers of London** test case.

- Memories of the system moving the balls from one bin to other. Whether completed by the system or other entity.
- Memories involving invalid states must be associated with a negative feedback.
- Memories involving achieving the goal state must be associated with a positive feedback.

The reason behind the need of these memories is because, if left alone with the situation, the system would face a learning phase. In this phase, the system would act in random ways till it learns the rules of the task (due the fact that it does not have any memories related to the task, as was explained in previous section). Such process is not part of the scope of this dissertation (although the case is cover in the previous section).

The example that will be used is one of the proposed by [NCVJ] (see figure 4.5). Although it may seem like a really simple test case, it tends to fall easily in state explosion. Also, this example is enough to show that the proposed algorithm works as expected and that can carry on the task of building plans using the help of other modules of the architecture. Last but not least, the complexity of such case will help clarify on a higher detail the planning algorithm. Thus, lets start with the description of the planning algorithm applied to this neuroscientist planning test.

First, the start and goal state would be used to make searches in the memory, lets suppose that only memories related with the start state are returned; furthermore, that those memories are invariant representations. Remember that an invariant representation is a memory that represents a set of memories that are in a particular sense equals. In this case, invariant representations are as pictured in figure 4.6. Note how only the important information is keep; in order to go from one state to the next, the only thing needed is to move a particular ball from one bin to other, it does not matter which ball it is, but its position and that of the others.

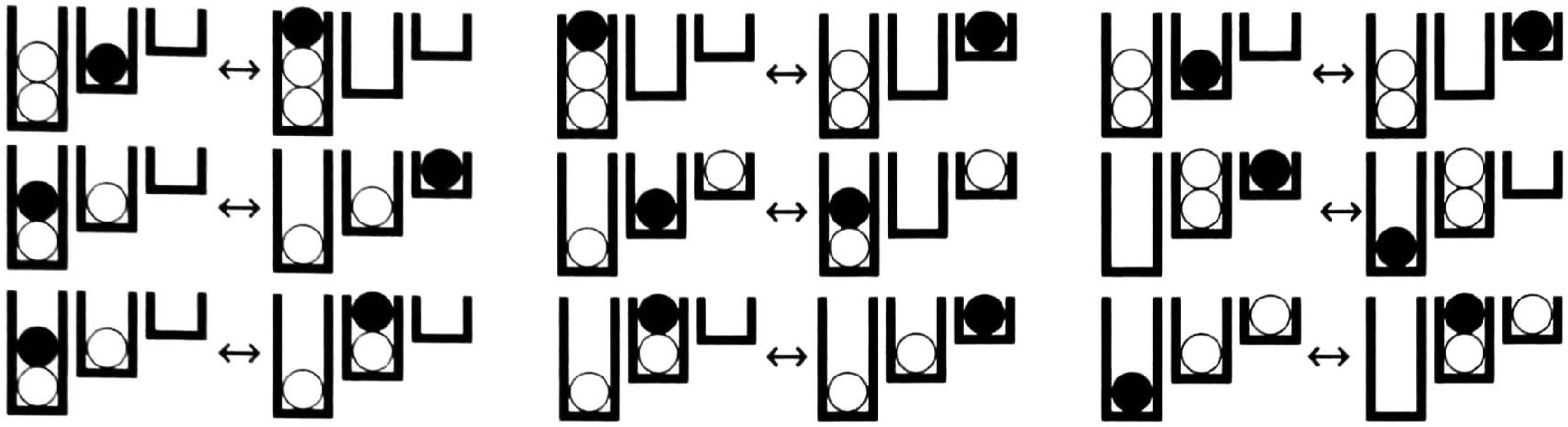

Figure 4.6: Invariant representations used **Towers of London** test case.

So, when the invariant representations applicable to the current state arrive in to the *Planning* module, the memories are selected based in the activation level (a at figure 4.8). Lets suppose that the order of selection is as seen in the column **I** of the figure 4.7. Thus, the start state will be took and, by the use of the invariant representation, transformed in the next state, at column **II**. Then, it would be put together with the first state and the plan would be formed. As it was described, many threads that manages state creation should exists; thus, at probably the same time that state was generated the other were also created, each with its respective plan. The just created plans would be send to evaluation to the *Attention* module at the *Ventromedial Prefrontal Cortex* and, if directed by this module, submitted completely into the attention process (b at figure 4.8). For sake of simplicity, lets suppose that the plan with the state **4** was selected by the attention process as the most relevant state. Thus, the plan consisting of state **1** and **4** would be sent to the *Decision Making* Module (c at figure 4.8).

Lets now suppose that the *Decision Making* module decides not to execute the plan. So, this plan together with the other created plans would be stored into the list of plans created in base of the start state. At this moment, a choice between continue with the creation of plans from the start state would be the next step or if a sub-goal would be set; as it was explained, al the options would be send to the *Decision Making* module. Lets say that continuing with sub-goals is the selected choice. Thus, *Planning* module is informed of the new choice and, since the most relevant plan is the one formed by states **1** and **4** it would be the one used to create the new plan creation. For that to occur, the state **4** would be set as the new state and the goal would remain the same.

Then, a process similar to the one already described would occur to generate the next state. The invariant representations that could be applied from the state **4** would return from the query, and the new states would be created and submitted to the attention process, with the help of the threads (the new states can be seen at the column **II** in the figure 4.7). Now, lets suppose that the plan formed by the states **1**, **4** and **8** has the highest attention level. This will motivate the selection of this plan as the next step in the sub-goal creation phase, after the *Decision Making* module chooses to continue planning. So, once again a new current state would be took, state **8** this time, and the search as described above would continue. But, when the *Decision Making* module get the plan formed by **1**, **4**, **8** and **14**, it would order execution, since it has the starting and final state. This would trigger a special message to the *Planning* module, which would take the plan and send it to the *Basal Ganglia*, send all the plans created to the *Hippocampus* for storage in memory and get ready for the new objectives (d at figure 4.8). Notice how, tanks to the storage of all of the plans created, the next time a search is made this information will be available.

Lets use this example to review how the algorithm modules resembles neural activation in the brain using the information published by [GH00], [Kan00], [Fus08] and [NCVJ]. In those publications is describes the collection of current state and goal in the *Dorsolateral Prefrontal Cortex*, and a constant communication between this module and the *Sensory Cortex*, limbic system, *Ventromedial Prefrontal Cortex* and *Basal Ganglia*. If it is remembered that plans are built from memories and that the neurons in charge of the memory are at the *Hippocampus*, then it can be concluded that the communication between the *Dorsolateral Prfrontal Cortex* allows the storage and retrieval of memories. Although none of them assures the exact time at which each communication occurs, they left clear that good proves exists to say that communication with *Sensory Cortex*, *Amygdala* and *Ventromedial Prefrontal Cortex* are part of the evaluation of task at many stages. From this, it can be deduced that plan formulation is made at the *Dorsolateral Prefrontal Cortex* and that constant communication is maintained between the *Sensory Cortex*, *Amygdala* and *Ventromedial Prefrontal Cortex* in order to regulate the value of the plans. Now, at the *Ventromedial Prefrontal Cortex* decisions are made and at the *Basal Ganglia* execution of motor action is completed. Then is easy to deduce that first exist communication between the *Dorsolateral Prefrontal Cortex* and the *Hippocampus* (1). Communication between the *Dorsolateral Prefrontal Cortex* and the *Ventromedial Prefrontal Cortex*, *Sensory Cortex* and limbic system occurs next (2). After, communication between *Basal Ganglia* and *Dorsolateral Prefrontal Cortex* exists (3). Last, if it is intended to store information related to what is done during the planning, communication must exists again with the *Hippocampus* and the *Dorsolateral Prefrontal Cortex* (4).

Now, as can be seen at the figure 4.8, activation between the algorithm and the neural evidence is similar. This gives good clues that the algorithm works as the human brain during planning, one of the main propose of this thesis.

4.3.2 Day life Planning: Basketball Game

On this test case, a basketball player faces a opponent face to face during a game in front of the enemy hoop. At any time, a basketball player has the option of keep advancing, pass the ball or shoot at the hoop. Thus, in this situation, the player remembers previous games and trainings in which he faces a similar situation. But this are not the only memories he has lived. He also can relate the current situation to games he has seen, even on video games or cartoons. This allows the player (and the planner) to innovate in a situation.

So, the *Planner* module receives the current and goal states. And, as described, this states will be used to search in the memory for procedural memories that could be transformed in the current state with the use of invariant representations. Thus, lets suppose that a plan is created and selected for execution (just as they were built in the Towers of London task) to pass the ball to a player at its right. Then, motor action starts moving the body according to plan. Every time a new state arrives informing the changes on the body and the environment, the plan to pass the ball is revised and, if it is still applicable, the same plan is selected from the next execution point. Lets suppose that a state arrives indicating that the ball, still on hands of the player, is about to be throw to the right and the opponent has opened its legs and stretched its arm in an attempt to catch the ball in mid air and revealing that a team-mate was just behind him. At this point, the selected plan of passing the ball is still valid, but not so appealing as it was since now the goal of keep advancing would be hard to complete if the ball is intercepted. So, the previous plan is put in the list of plans and a new one is built. Then, as a fanatic of the soccer, the next available memory is one coming from a soccer game where the ball is passed through the legs of an opponent in order to pass a ball to a team-mate. Thanks to the invariant representations, the soccer ball can be changed into a basketball ball and the foot pass into a hand pass. This makes possible the generation of a new plan using this memory. Since the position of the team-mate behind the opponent is more appealing to a direct shoot to the hoop, this plan is selected for execution. The change in the plan produces a weird movement of hands in order to pass the ball between the enemy legs, but the plan is executed satisfactorily, asserting a pass.

This example show how the use of invariant representations allows the creation of the complex behaviour the human resembles. Which is one of the main objectives of this dissertation.

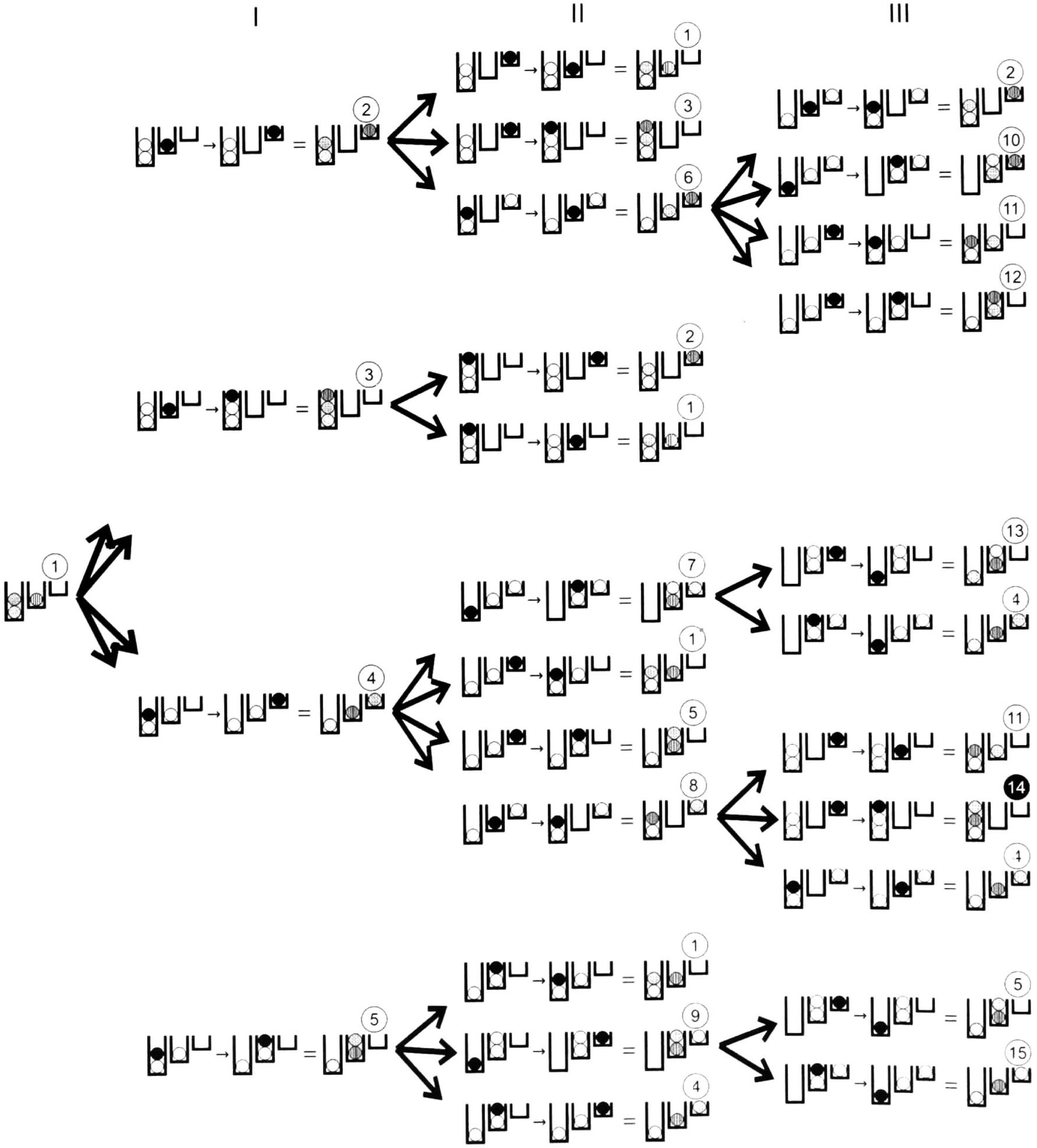

Figure 4.7: Trace execution of the planning algorithm.

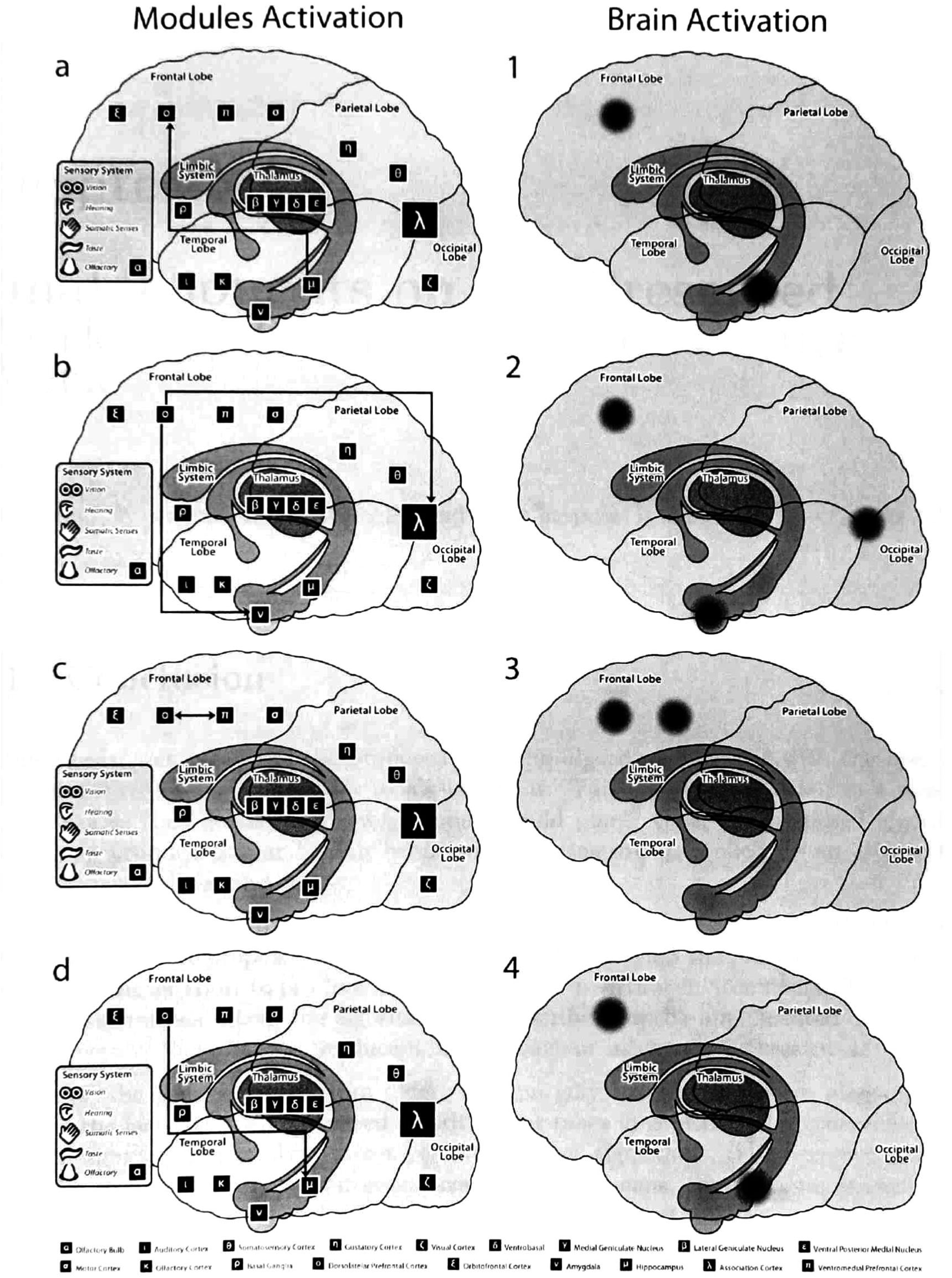

Figure 4.8: Activations occurring at the human brain and at the modules of the planning algorithm during the Towers of London task.

Chapter 5

Final Thoughts on the Presented Work and the Direction of Future Work

In this chapter, conclusions are presented and a last proposal is made: the direction for future work.

5.1 Conclusion

In this thesis, was presented the proposed planning algorithm together with the user and architectural requirements in order to implement it. This algorithm is based in a selected set of theories that describes the way humans build plans; thus, the proposed algorithm should help produce similar human behaviour in a creature controlled by an architecture that implements the algorithm.

For the proposed algorithm, special care was took in order to allow an smooth integration with the architecture proposed at [RGR$^+$]. This due the fact that the present research results are part of a bigger effort to produce human behaviour in virtual environments. Thus, thanks to the considerations taken, the algorithm here described can be implemented directly into the architecture; then, help to produce human behaviour in virtual 3D creatures.

Besides, the proposed algorithm differs substantially to other cognitive planning algorithms in the fact that, as the revised algorithms, it takes in consideration generalization of rules of action application; but, in comparison to other algorithms, the presented proposal, allows the consideration of action generalization. This means, that actions carried on by entities different to the one controlled by the cognitive architecture, can be applied or tried by the entity controlled by the system.

5.2 Future Work

To continue in the same line of this research, the next logical step would be to implement and integrate the proposed algorithm into the architecture defined by [RGR$^+$]. This is an essential step in order to clarify whether the integration of this module would help to produce human like behaviour in such architecture.. As a recommendation, is proposed the use of a test environment where task similar to the Towers of London, the Wisconsin cards sorting test and the Towers of Hanoi are used, to test the architecture.

Although the proposed algorithm is based in a set of theories that describes the functioning of the planning process in the human brain, others theories exists and new ones are created every day. Thus, is recommended that, before considering the establishment of the here presented algorithm as an standard; new theories that explains the human planning process be considered.

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El Jurado designado por la Unidad Guadalajara del Centro de Investigación y de Estudios Avanzados del Instituto Politécnico Nacional aprobó la tesis

Propuesta de una arquitectura cognitiva que soporta un algoritmo de planeación orientado a producir comportamiento similar al humano Proposal of a cognitive architeure that support a planning algorithm oriented to produ

del (la) C.

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