A BRDL-based Framework for Motivators and Emotions*

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Abstract. Motivation and emotion are essential for finalising human reasoning and behaviour toward the accomplishment of life objectives. In this paper we extend our modelling and analysis framework, based on the Behaviour and Reasoning Description Language (BRDL), to include motivation and emotion. We use labelled transition systems to model both external environment and internal human physiology. Their composition with the BRDL model of human cognition supports the description of the way motivation drives need satisfaction and generates emotional responses. When the external environment is a computer/physical system, our approach provides a realistic model of human-computer interaction.

Keywords: Behaviour and Reasoning Description Language (BRDL) · Labelled Transition Systems (LTSs) Theory of Motivation · Theory of Emotion · Human-computer Interaction

1 Introduction

The old view that emotions are in opposition to reasoning and prevent humans from behaving in an effective way has been recently challenged by a number of studies in psychology and neuroscience. After all, if emotions have developed throughout human evolution, they must be important and useful. And this should apply to both positive and negative emotions. In fact, emotions play two important roles: they motivate human behaviour and drive it toward directions that are beneficial to the individual as well as the human species as a whole, and they support the decision-making process by finalising human reasoning and other rational processes toward a single practical outcome.

Positive emotions, such as joy, are essential to motivate individuals to meet physiological needs. For example, our joy in eating food contributes to motivate us to regularly feed ourselves, thus guaranteeing the survival of both individuals and the human species. Fear is an essential negative emotion that allows individuals to avoid dangers, thus also contributing to survival. Positive emotions

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related to sentimental relationships, such as joy and acceptance, make up the feeling of love, which is essential for reproduction and, hence, for the survival of the human species.

In his book "Descartes' error — Emotion, reason and the human brain" neuroscientist Antonio Damasio [12] describes the change of behaviour that occurred in one of his patients, whom he called Elliot, after a surgery for removing a brain tumor. The damage to Elliot's prefrontal cortex, expecially the right one, did not affect his reasoning ability but made him unable to feel emotion and, as a consequence, unable to make decisions.

In our previous work [6], we defined a high-level notation, the Behaviour and Reasoning Description Language (BRDL) that allows psychologists and cognitive scientists to model and analyse human tasks in terms of their required attentional, reasoning and action components. BRDL has also been implemented using the Maude rewrite language and toolset [18], thus providing a framework for the in silico simulation of human reasoning [10], some aspects of human learning [8, 11] and the human behaviour in interacting with an external environment consisting of heterogenous physical components [3, 5].

In this work, we incorporate motivation and emotion in our framework. In our previous work [3], we used labelled transition systems to describe human interaction with the external environment. Now we also use them to describe the interaction between human cognition and human physiology.

The rest of the paper is organised as follows. Sect. 2 provides the necessary psychological background on theories of motivation and emotion. Sect. 3 starts with an overview of BRDL and then presents our approach for using labelled transition systems to model external environment and internal human physiology and for combining them with the BRDL model in order to describe how motivation drives need satisfaction and generates emotional responses. Finally, Sect. 4 draws conclusions and discusses possible future work.

2 Motivation and Emotion

Motivation is an impulse or desire, often determined by a need, that causes human beings to act. Emotion is a psychological feeling, usually accompanied by a physiological reaction. Motivation and emotion are very closely related, which makes sometimes difficult to distinguish them. In fact, they both are perceived as feelings that drive human behaviour, they both seem to originate within us and they both involve some physiological sensations. However,

- the prompting stimulus is generally observable for emotions, but not for motivations;
- motivations (e.g., hunger) seem to be cyclical and tend to directly sustain human activities, whereas emotions (e.g. fear), tend to interfere with or change human activities;
- motivational responses are normally directed toward the external environment whereas emotional responses are normally directed toward internal physiological and cognitive activities.

The first explanation of human motivation was given by William James [13] in terms of two kinds of instincts: *physical instincts*, such as sucking and locomotion, and *mental instincts*, such as curiosity and fearfulness. Other theories of motivation tried to look for the influence of human physiology: *homeostatic-regulation theory* [2] explains motivation as the tendency of the body to maintain a state of equilibrium (e.g., hunger is balanced by eating), *opponent-process theory* [20] links motivation to emotion by explaining the acquisition of motivation as the result of a pattern of emotional experience (e.g., the motivation to use psychoactive drugs) and *arousal theory* [1, 21], according to which the activity of the central nervous system determines the appropriate level of arousal for a given task in relation to the individual's personality (e.g., in general a low level of arousal would help in a complex task to prevent anxiety, but this is not the case for anxious personalities).

In Sect. 2.1, we briefly recall two approaches that emphasise on the fact that physiological and psychological needs influence motivation. In Sect. 2.2, we introduce basic emotions and we briefly discuss their relations to motivation.

2.1 Needs and Motivation

Henry Murray [17] defined a set of 20 needs that are based in human physiology and determine the core of human personality. For example, the need for food has 'hunger' as its *motivator*. Murray believed that the environment creates forces to which humans have to respond in order to adapt. In this sense, motivation can be understood in terms of the interaction between the individual's internal need and the stimuli from the environment.

Abraham Maslow [14, 15] organised needs in a hierarchy, from physiological needs at the lowest level, to safety and security needs, belongness and love needs, esteem needs, up to self-actualisation needs at the highest level. Only when we have satisfied a specific level of needs, we move to the higher level. Thus, according to Maslow, we consider our safety and security only after having satisfied our physiological needs, such as food, water, sleep. Maslow's need hierarchy is illustrated in Fig. 1.

2.2 Basic Kinds of Human Emotions

A number of basic emotions have been commonly recognised as being fundamental to all humans: joy, fear, anger, sadness and disgust. Some other emotions have been added, such as surprise, which appear fundamental across cultures. Plutchik [19] suggested that emotion can be organised in a circle, as shown in Fig. 2. Emotions that are close to each other in the circle are closely related. Relatedndess between emotions decreases with the distance along the circonference. Emotion that are opposite to each other in the circle are semantically opposite and represent a pair consisting of a positive emotion and a negative emotion.

Motivation is strongly related to emotion. Positive emotions, such as joy, may occur as the result of need satisfaction. For example, we feel joy after eating

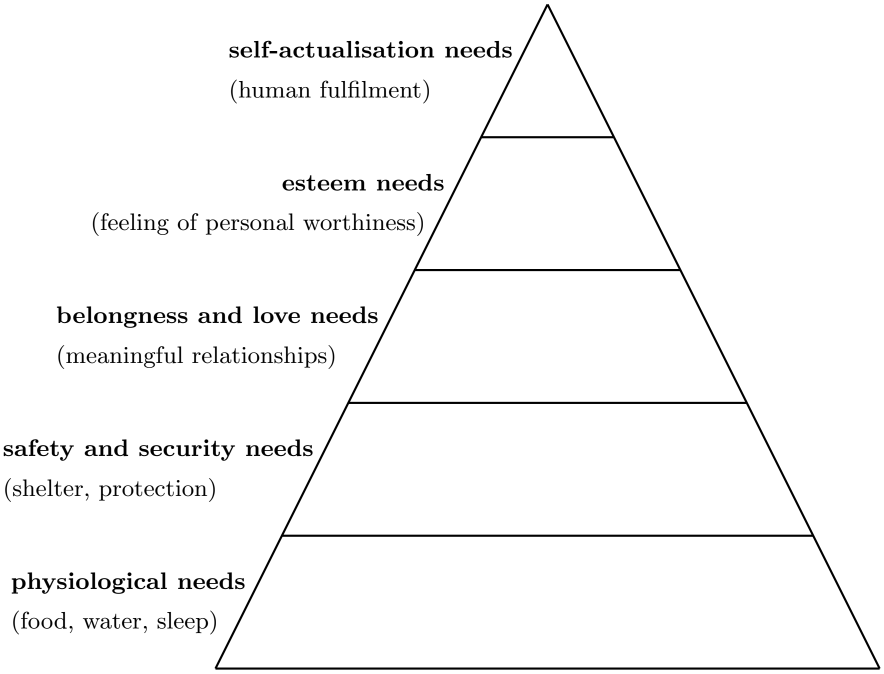

Fig. 1. Maslow's need hierarchy

food to satisfy our hunger. Furthermore the expectation of feeling joy acts as a psychological motivation in combination with physiological motivators such as hunger. Negative emotions, instead, may occur as the result of failing to satisfy our needs. For example, if we are hungry and do not have food availability, we are likely to become sad and possibly angry.

3 BRDL-based Model

3.1 An Overview of BRDL

BRDL models the content of *long-term memory (LTM)* in terms of *cognitive rules* (also called *LTM rules*) that either drive selective attention or represent *factual knowledge* or *procedural knowledge*. In this paper we focus on the rules for attention and procedural knowledge, which determine human behaviour. Cognitive rules drive the processing of information that has been transferred to *short-term memory (STM)* and may consists of

- facts retrieved from LTM;
- perceptions from the environment;
- action to be carried out on the environment;
- goals defining the will of carrying out tasks.

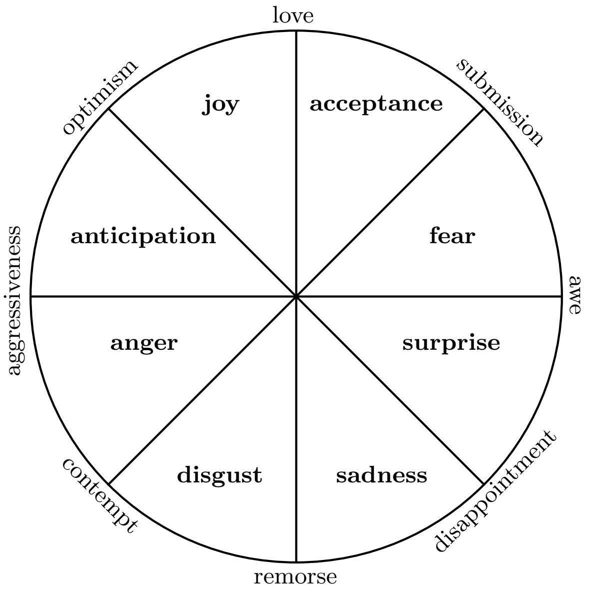

Fig. 2. Plutchik's emotion wheel

Thus STM acts as temporary store and is often called *working memory* (WM) when it is considered together with all its information processing functionalities.

Each cognitive rule has a general structure

$$g : info_1 \uparrow perc \Longrightarrow \; act \downarrow info_2$$

where

- g is a goal;
- *perc* is a perception from the environment;
- *act* is an action performed on the environment;
- $info_1$ is the information to be removed from STM;
- $info_2$ is the information or goal to be stored in STM.

Symbol $\uparrow$ suggests removal from STM whereas symbol $\downarrow$ suggests storage in STM. We call *enabling* the part of the rule on the left of $\Longrightarrow$ and *performing* the part of the rule on the right of $\Longrightarrow$. Thus the execution of a cognitive rule is enabled by information $info_1$ from STM and/or perception *perc* from the environment and results in the human performance of action *act* on the environment and/or the storage of new information $info_2$ in STM.

The information consists of a set of basic items, syntactically represented as a sequence whose elements are separated by commas (the order is irrelevant). Each basic item may be a perception, an action or a cognitive state. Depending on which components are present, a cognitive rule models distinct cognitive activities.

When the goal g is present in the rule, the control of attentional selection and behaviour is *deliberate* and is finalised to accomplish the information that is the arguments of the goal. For example goal $goal(eat)$ is finalised to the accomplishment of eating, which is represented by the *eat* action. The goal is achieved when its argument is accomplished, because its elements are either performed as action or stored in STM. When a goal in STM is achieved, it is removed from STM. Moreover, since STM has limited capacity, 7 ± 2 items according to Miller's experimental results [16], it needs to be freed once the goal is achieved. This memory process, called *STM closure*, aims at removing information that is no longer needed from STM. How exactly this is carried out is not fully understood and a number of alternative hypotheses have been proposed. When the goal g is not present in the rule, the control of attentional selection and behaviour is *automatic*.

In this paper, we consider two cognitive rules for cognitive activities under deliberate control: the deliberate behaviour rule and the the explicit attention rule.

Deliberate Behaviour rule: $g : \mathit{info}_1 \uparrow \implies act \downarrow \mathit{info}_2$

This rule models a basic activity of human deliberate behaviour, that is, the performance of an action *act* that is driven by a goal g stored in STM as a response to the presence of some information info_1 (which is not a goal) in STM and may result in further information info_2, which may be a goal, stored in STM. Only g and *act* are necessary, the other rule elements are optional.

For example, a person who wants to eat (the $goal(eat)$ is stored in STM) and is aware that there is $food\ available$ (i.e., information $food\ available$ is stored in STM) will perform action *eat*:

$$goal(eat) :\ food\ available \uparrow \implies eat \downarrow \tag{1}$$

Once the action *eat* is performed, the goal $goal(eat)$ is removed from STM. In rule 1 $\mathit{info}_1 = food\ available$ whereas info_2 is not present. If we suppose that there is only one burger available, a person who eats it also becomes aware of the fact that there is no more burger available. This can be expressed as:

$$goal(eat) : one\ burger\ available \uparrow \implies eat\ burger \downarrow no\ burger\ available$$

where both $\mathit{info}_1 = one\ burger\ available$ and $\mathit{info}_2 = no\ burger\ available$ are present.

Moreover, we may suppose that the food is in a cupboard in the kitchen and we do not know if there is food available at the moment. Then, if we want to eat, we open the cupboard and discover that there is no food available:

$$goal(eat) : \uparrow \implies open\ cupboard \downarrow no\ food\ available$$

where info_1 is not present whereas $\mathit{info}_2 = \mathit{no\ food\ available}$ is present. Finally, if in the morning we open the window to allow some fresh air in the room, then neither info_1 nor info_2 is present:

$$\mathit{goal}(\mathit{open\ window}) : \uparrow \implies \mathit{open\ window} \downarrow$$

Explicit Attention rule: $g : \mathit{info}_1 \uparrow \mathit{perc} \implies \downarrow \mathit{info}_2$
This rule models a basic activity of human explicit attention, that is, the explicit selection, driven by goal g and possibly by the presence of some information info_1 (which is not a goal) in STM, of focusing on a specific perception *perc* from the environment and transfer such a perception to STM by representing it as information info_2. Such information may be a direct representation of the perception (e.g., $\mathit{perc} = \mathit{info}_2$) or include some form of processing. Only *perc* and info_2 are necessary, whereas info_1 is optional.
For example, a person who wants to eat will focus on the perception of food available and will internalise such a perception as information in STM:

$$\mathit{goal}(\mathit{eat}) : \uparrow \mathit{food\ available} \implies \downarrow \mathit{food\ available} \tag{2}$$

In rule 2 $\mathit{info}_2 = \mathit{food\ available}$ whereas info_1 is not present. We may suppose that the person's explicit attention is triggered not only by the will of eating (expressed by $\mathit{goal}(\mathit{eat})$) but also by the information, previously stored in STM, that the food, if available, must be on the table. This can be expressed as:

$$\mathit{goal}(\mathit{eat}) : \mathit{on\ the\ table} \uparrow \mathit{food\ available} \implies \downarrow \mathit{food\ available}$$

where both $\mathit{info}_1 = \mathit{on\ the\ table}$ and $\mathit{info}_2 = \mathit{food\ available}$ are present.

Therefore, if we start from an STM containing $\mathit{goal}(\mathit{eat})$ and an environment containing $\mathit{food\ available}$, only cognitive rule 2 is enabled. The execution of rule 2 results in the storage of $\mathit{food\ available}$ in STM. Now STM contains both $\mathit{goal}(\mathit{eat})$ and $\mathit{food\ available}$, thus enabling rule 1, whose execution results in the removal of $\mathit{food\ available}$ from STM and in the performance of action *eat*. Moreover, the accomplishment of performing action *eat* determines the goal achievement. Thus also $\mathit{goal}(\mathit{eat})$ is removed from STM, which is finally empty, thus completing the eating task.

BRDL is a flexible notation, which can be used at different levels, with various degree of formality. It may be used informally, at an intuitive level, to provide a conceptual model of human behaviour. For example, cognitive rules 1 and 2 provide a conceptual model of the eating human behaviour.

Formality may be added to this conceptual model by defining how information and goals are stored in and retrieved from STM, according to alternative cognitive psychology theories. For example, there are several questions on how STM closure is carried out: how much information is removed? under which circumstances? which information is removed first? Different answers to these questions lead to different hypotheses, whose implementations can provide distinct formal semantics for BRDL. Also quantitative aspects may be introduced at the semantic level, such has STM capacity as well as persistence, storage and retrieval times. These semantics variants have been used to compare alternative cognitive psychology theories [9, 11].

Finally, each component of a cognitive rule may also have different levels of formality: from an informal phrase in natural language to a complex data structure. For example, the information to be retrieved from STM is described in rule 1 by phrase $food\ available$, whereas the goal is structured as the operator *goal* and its accomplishment action *eat* as an argument. In our previous work we used a linguistic approach to formally define such components as linguistic structures [7].

3.2 Modelling External Environment and Internal Physiology

BRDL describes human reasoning through the manipulation of information in STM and human behaviour through the generation of a sequence of performed actions. How these actions model the interaction with the environment is not described by BRDL. It requires instead another notation.

This is another aspect of BRDL flexibility. When describing human interaction with a computer system, the system component may be modelled using any formal approach. In our previous work we have used labelled transition systems [3], process algebras [4] and rewrite systems [3, 5]. In this work, we consider labelled transition systems, not only to describe human interaction with a computer system (*external interaction*), but also the interaction between human cognition and human physiology (*internal interaction*).

Labelled Transition Systems (LTSs) We define an LTS by

- a set of perceptions;
- a set of invisible atomic states;
- a initial state consisting of a set of perception and a set of invisible atomic states;
- a set of transition rules having the form $visible_1\ [invisible_1] \xrightarrow{act} visible_2\ [invisible_2]$ where sets of perceptions $visible_1$ and $visible_2$ and set of invisible atomic states $invisible_1$ and $invisible_2$ are represented by element separated by commas.

The system evolves starting from the initial state. Each transition rule models the transition from a source state consisting of a visible components $visible_1$ and an invisible component $invisible_1$ to a target state consisting of a visible components $visible_2$ and and invisible component $invisible_2$. The transition is triggered by action *act*.

External Interaction It is the action performed by the user on the environment (interface, device, human/animal, etc.). The interaction between the human and the system is given through the synchronisation between a cognitive rule

$$g : \mathit{info}_1 \uparrow \mathit{perc} \Longrightarrow \ \mathit{act} \downarrow \mathit{info}_2$$

and a transition rule

$$\mathit{perc}, \mathit{visible}_1 \ [\mathit{invisible}_1] \xrightarrow{\mathit{act}} \mathit{visible}_2 \ [\mathit{invisible}_2]$$

which share the same action *act*. The transition is enabled if the current state of the LTS includes $\mathit{perc}, \mathit{visible}_1$ as a subset of its visible component and $\mathit{invisible}_1$ as a subset of its invisible component. The transition changes the state of the LTS by replacing $\mathit{perc}, \mathit{visible}_1$ by $\mathit{visible}_2$ in its visible component and $\mathit{invisible}_1$ by $\mathit{invisible}_2$ in its invisible component.

For example, a vending machine selling both food and drink has a display showing burger and drinks and contains m burgers and n drinks. The machine action of selling a lunch consisting of one burger and one drink is formalised by transition rule

$$\mathit{burgers}, \ \mathit{drinks} \ [b(m), d(n)] \xrightarrow{\mathit{buy\ lunch}} \mathit{burgers}, \ \mathit{drinks} \ [b(m)-1, d(n)-1] \tag{3}$$

where $m > 0$, $n > 0$ and the machine action of selling is actually formalised by the human action of buying (*buy lunch*). The application of the transition rule makes invisible atomic states $b(m)$ and $d(n)$, describing that the machine contains m burgers and n drinks, change to $b(m-1)$ and $d(n-1)$, since a lunch (one burger and one drink) has $b(m)$ and $d(n)$ been purchased.

After the user has perceived through explicit attention the availability of burgers and drinks and internalised this information in STM, transition rule 3 may interact with cognitive rule

$$\mathit{goal}(\mathit{buy\ lunch}) : \uparrow \mathit{burgers}, \mathit{drinks} \Longrightarrow \mathit{buy\ lunch} \downarrow \tag{4}$$

Note that the user only see the writing $\mathit{burgers}$ and drinks on the display (visible state of the vending machine), which show the availability of at least one burger and one drink, respectively, but does not know how many items are available (invisible state of the vending machine).

Finally, we point out that the environment may evolve independently of human actions. This is expressed by a transition rule of the form

$$\mathit{perc}, \mathit{visible}_1 \ [\mathit{invisible}_1] \longrightarrow \mathit{visible}_2 \ [\mathit{invisible}_2]$$

Internal Interaction It is the interaction occurring between cognition and physiology of the the same human. Such an interaction is modelled through the direct effect of a transition rule on STM or through the transition being triggered by the content of STM. There are three kinds of transition rules that directly effect STM. Given a piece of information or goal *info*,

- $\mathit{visible}_1 \ [\mathit{invisible}_1] \xrightarrow{\downarrow \mathit{info}} \mathit{visible}_2 \ [\mathit{invisible}_2]$
  stores *info* in STM;
- $\mathit{visible}_1 \ [\mathit{invisible}_1] \xrightarrow{\mathit{info} \uparrow} \mathit{visible}_2 \ [\mathit{invisible}_2]$
  removes *info* from STM;

- $visible_1\ [invisible_1] \xrightarrow{\downarrow info \uparrow} visible_2\ [invisible_2]$
  is triggered by the presence of *info* in STM but does not change the content of STM.

The use of these transition rules is illustrate in Sects. 3.3 and 3.5.

3.3 Motivator Activation and Need Saturation

In this section we show how to model motivators and emotion at a physical level. We consider basic needs, the ones that occur at the physiological level, the lowest in Maslow's need hierarchy.

As an example, Fig. 3 refers to the feeling of hunger, which is the motivator determined by the need of food. We can identify the need with the feeling/motivator (the need of food is identified with its motivator 'hunger') and associate a numerical value with the need. We consider two threshold for the need, an activation threshold α and a saturation threshold σ such that $0 < \sigma < \alpha$.

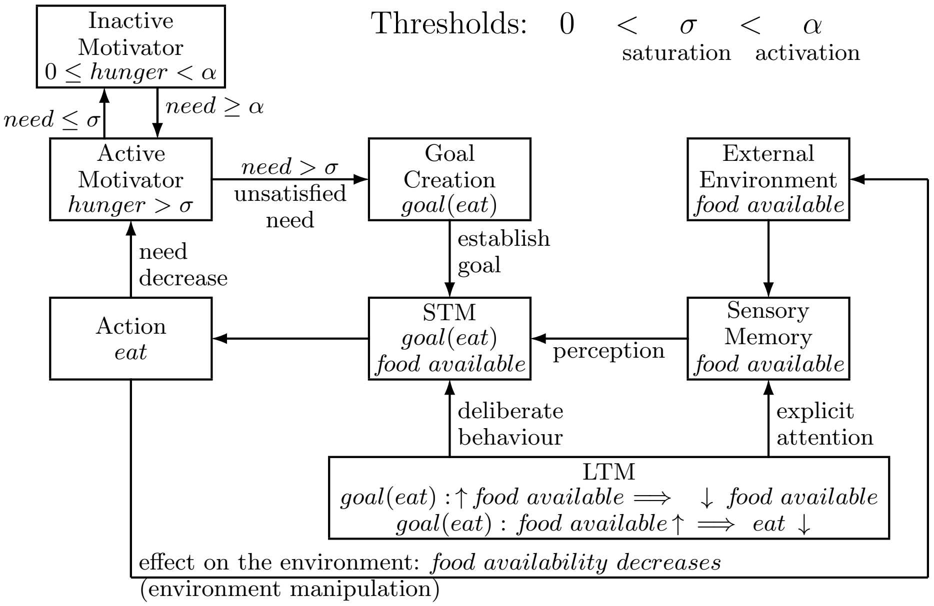

Fig. 3. Model of motivator activation and need saturation

We can suppose that initially the value of the need, which in our example is *hunger*, is below the α threshold. In this situation the motivator is inactive. The passing of time makes the need increase as a function of the human activity. When the need reaches the α threshold, the motivator becomes active. This means that we must carry out the appropriate activity, driven by a goal, to satisfy the need and, as a result, decrease its numerical value. Therefore, an iterative activity is carried out until the need has dropped down to the saturation threshold σ. Each step of the iterative cycle is driven by the goal, which is the eat action ($goal(eat)$) in our example, and continues while the need is greater than the saturation threshold σ. Such a goal is established in STM and drives the deliberate behaviour of eating, first by directing the explicit attention toward food availability

$$goal(eat) : \uparrow food\ available \Longrightarrow \downarrow food\ available \tag{5}$$

and then by eating the food

$$goal(eat) :\ food\ available \uparrow\ \Longrightarrow eat \downarrow . \tag{6}$$

Once the need is as low as the saturation threshold σ, the motivator goes back to the inactive state.

LTM rules 5 and 6 model the cognitive aspects of hunger, that is our deliberate eating activity. However, there are several physiological aspects that control the feeling of hunger and motivate us to eat and to stop eating. We use LTSs to model such physiological aspects.

With reference to our example, the *physiological motivation process* can be modelled using three transition rules:

activation $[hunger > \alpha,\ inactive] \longrightarrow [active]$
: This transition rule is enabled when condition $hunger > \alpha$ holds and the motivator state is *inactive*. The transition changes the state from *inactive* to *active*.

iteration $[hunger > \sigma,\ active] \overset{goal(eat)\downarrow}{\longrightarrow} [active]$
: While condition $hunger > \sigma$, the motivator state is *active* and there is no goal $goal(eat)$ in STM, goal $goal(eat)$ keeps being stored in STM.

saturation $[0 \le hunger \le \sigma,\ active] \longrightarrow [inactive]$
: This transition rule is enabled when condition $0 \le hunger \le \sigma$ holds and the motivator state is *active*. The transition changes the state from *active* to *inactive*.

At the end of each iteration step of the physiological motivating process, the STM closure process driven by cognitive rule 6 causes the removal of the $goal(eat)$ goal from STM. In this way a physiological process modelled by an LTS and a cognitive process modelled by STM work in synergy.

The *physiological satisfaction process* is determined by the feedback of the eating activity, which decreases the feeling of hunger. By denoting such a decrease by δ, we can model the satisfaction process as follows:

$$[hunger > \sigma] \xrightarrow{eat} [hunger\ -=\ \delta] \tag{7}$$

This transition rule is enabled when condition $hunger > \sigma$ holds and the transition occurrence decreases $hunger$ by a quantity δ.

We note that physiological states, such as needs, are modelled as invisible states since they are not directly visible from outside the LTS that models them. What is visible is the resultant behaviour, for example the fact that we eat.

3.4 Environment Manipulation

In Sect. 3.3, we have used LTSs to model physiological processes. Now we use LTSs to model the environment.

The actions included in cognitive rules should be considered as directives to the motor system and synchronise with physical actions carried out by the motor system. Thus the environment manipulation should occur through the synchronisation on the action label shared by the LTS that models the motor system and the LTS that models the environment. However, since our focus is on modelling cognition and its interaction with some neurophysiological aspects, for sake of simplicity we do not model the motor system and we assume that actions established at cognitive level directly act on the environment.

In our example, we can quantify the *food available* as discrete quantity $food(q)$, with $q > 0$. We can thus also model *food unavailable* as $food(0)$. We can assume that the food is eaten as a discrete unit at a time, which corresponds to each iteration step of the feedback provided to the physiological satisfaction process described in Sect. 3.3.

Therefore, the environment manipulation in the form of eating food can be modelled by the following transition:

$$\begin{aligned} food(q) &\xrightarrow{eat} food(q-1) \\ &\quad\text{if } q > 0 \end{aligned} \tag{8}$$

Differently from transition rule 3 in Sect. 3.2, in which the precise quantity of burgers and drinks available is not visible, because it is stored in the vending machine, here the human can see the actual quantity of food, for example because it is visible on a plate.

3.5 Modelling Emotions

In Sect. 3.3, we have modelled the effect of the eating activity on the feeling of hunger by transition rule 7. However, on the one hand, eating also determines a positive emotion, which can be classified as joy. On the other hand, unsatisfied hunger determines a negative emotion, which can start in terms of sadness, but may also escalate to anger. In order to capture the development of such emotions, we need to modify transition rule 7 depending on the current emotional state. If joy is already a current emotion, the rule is:

$$[hunger > \sigma, joy] \xrightarrow{eat} [hunger -= \delta, joy] \tag{9}$$

If joy is not already a current emotion and neither $sadness$ nor $anger$ is also a current emotion, joy is added to the emotions:

$$\begin{aligned} [hunger > \sigma, emotions] &\xrightarrow{eat} [hunger -= \delta, emotions, joy] \\ &\quad\text{if } joy, sadness, anger \notin emotions \end{aligned} \tag{10}$$

However, if either *sadness* or *anger* is a current emotion, such a negative emotion is replaced by the positive emotions:

$$[hunger > \sigma, negative] \xrightarrow{eat} [hunger -= \delta, joy] \\ \text{if } negative = sadness \text{ or } negative = anger \tag{11}$$

Note that emotions are modelled as invisible states. In fact, we do not see emotions directly, but as the interpretation of the visible behaviour they yield.

Negative emotions are caused by the failure in satisfying a need. In our example, the need of food is not satisfied when food is not available. The acquisition of awareness of food unavailability occurs at the level of explicit attention and can be modelled by the following cognitive rule:

$$goal(eat) : \uparrow food(0) \Longrightarrow \downarrow food\ unavailable. \tag{12}$$

Such awareness causes *sadness*, which is modelled by transition

$$[hunger > \sigma, emotions] \overset{\uparrow food\ unavailable \downarrow}{\longrightarrow} [hunger, emotions, sadness] \\ \text{if } joy, sadness, anger \notin emotions \tag{13}$$

when neither *joy* nor *sadness* nor *anger* is a current emotion, and by transition

$$[hunger > \sigma, joy] \overset{\uparrow food\ unavailable \downarrow}{\longrightarrow} [hunger, sadness] \tag{14}$$

when *joy* is a current emotion.

Finally *sadness* may escalate to *anger*

$$[hunger > \sigma, sadness] \overset{\uparrow food\ unavailable \downarrow}{\longrightarrow} [hunger, anger] \tag{15}$$

and *anger* is preserved by food unavailability

$$[hunger > \sigma, anger] \overset{\uparrow food\ unavailable \downarrow}{\longrightarrow} [hunger, anger] \tag{16}$$

In our model emotions are not quantified, they are either present or absent. Although a quantitative model could be defined, we believe it would be just arbitrary. In fact, we cannot really measure emotions but we can identify them based on observable physiological responses. For this reason we have chosen the approach to quantify physiological aspects and just consider emotions as present or absent.

4 Conclusion and Future Work

We have extended our framework for modelling and analysing human reasoning and behaviour [6] by including motivators and emotions. The extended framework is based on BRDL and LTSs, which cooperate by identifying human perceptions expressed in BRDL with the visible states of the LTS and through two kinds of syncronisation:

external syncronisation between the actions carried out by the cognitive human component (BRDL model) and the transition labels of the external system component (LTS model);

internal synchronisation between goals stored or to be stored in the STM of the cognitive human component (BRDL model) and the transition labels of the internal physiological human component (LTS model).

The mechanism for defining internal synchronisation and the distinction between visible and invisible LTS states are novel in this work.

Psychologists and cognitive scientists may use the framework for formalising theories of motivation and emotion and compare alternative theories. Computer scientists and usability analysts may use it as a general tool to explore human-computer interaction and verify physical/computer systems taking into account not only cognitive aspects but also motivational and emotional aspects of the human component.

Our extended framework is based on the same notations, BRDL and LTSs, and the same cooperation mechanisms, identification of perception and visible states, and synchronisation on the transition labels, as in our previous work [6]. Therefore, as part of our future work, we plan to extend the Maude-based implementation of BRDL [3, 5, 8–11] by modifying the rewrite rules for external interaction to distinguish between visible and invisible states and to add the new operators for defining the LTS information-based labels ($\downarrow \mathit{info}$, $\mathit{info} \uparrow$ and $\downarrow \mathit{info} \uparrow$) and new rewrite rules for external interaction. This extended implementation will then be incorporated in our web-based tool [7].

Finally, we plan to test our extended framework and its Maude-based implementation by revisiting our previous case studies and applying it to new case studies. Our previous work analysed the possible emergence of post-completion error in the interaction with an automatic teller machine (ATM) [3, 5]. However, this possibility may become reality only under certain motivational and emotional conditions. For example, if we have a specific motivation to withdraw cash, the emotional state determined by this motivation is likely to make us more vulnerable to post-condition error. Moreover, if we unexpectedly see our card returned to us before the cash is delivered, a strong motivation to withdraw cash may make us more persistent in reattempting the transaction, whereas the fear to have the card confiscated will inhibit us from trying again.

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