Periodic activations of behaviours and emotional adaptation in behaviour-based robotics

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The possible modulatory influence of motivations and emotions is of great interest in designing robotic adaptive systems. In this paper, we will try to connect the concept of periodic behaviour activations to emotional modulation, in order to link the variability of behaviours to the circumstances in which they are activated. We will study the impact of emotion, described as timed controlled structures, on simple but conflicting reactive behaviours. We will show, through this approach, that the introduction of such asynchronies in the robot control system may lead to an adaptation in the emergent behaviour without having an explicit action selection mechanism. The emergent behaviours of a simple robot designed with both a parallel and a hierarchical architecture will be evaluated and compared.

Keywords: behavior-based robotics; emotional modulation; adaptive perception.

1 Introduction

In Robotics one of the main issues in designing a control system is to make an autonomous robot able to react and adapt in useful time to environmental changes [1]. This reaction depends on the perception of the environment and on the identification of objects and their properties by appropriate sensor devices, with a strong emphasis on the concept of the stimuli-response loop. In particular, in behaviour-based architectures, the effective integration of temporal aspects in a control system is a key issue [2]. According to [2] such integration does not mean to allow, at each instant of time, only one behaviour to control each actuator, but to efficiently combine different concurrent processes to generate relevant behaviour-based dynamics. Moreover, the robotic community started to pay attention not only to the robot-environment interactions, but also, so to speak, to interactions that may arise within the robots itself [3] and how these internal states may influence the emergent behaviour of the robot. The interest for such “internal mechanisms” comes within the robotic community taking inspiration from ethological, biological and neuroscience studies.

Furthermore, in last years some researchers [3-9] started to analyze also the role that emotional and motivational states may play in the adaptation of the emergent behaviour of a Robotic System (RS). In particular, emotions and motivations have been introduced for behaviour modulation [4, 5], coordination and selection of actions [8, 9], narrowing attention and biasing of perception [10, 11]. While cognitive
psychology considers thinking, learning and memory activities as a problem of information processing, the description of motivational issues and emotional states as a processing problem is not an obvious task [4]. However, emotional behaviour has also to affect the reactive level of a robotic architecture being in charge of monitoring the environment and reacting to salient stimuli.

In our opinion, in order to model different and new architectures for controlling the robot behaviour, both these aspects (the interaction with the surrounding world, the internal states and the role of emotions) have to be considered, since they influence each other. For example, the simple perception-action response to an external stimulus may produce different patterns of actions depending on a different internal state of the robot. This internal state and the robot behaviour may change according to his emotional reaction, or motivational state, or following its past perceptions and it will tune and adapt both the executions of robot’s different behaviours and the processing frequency of the sensors’ inputs.

Our working hypothesis is that such adaptive behaviour can be achieved starting from self-regulated periodic mechanisms that control sensors readings and behaviours activations. In previous papers [12, 13] we highlighted the opportunity of managing the frequency of processing the sensors inputs in an efficient way, in order to avoid negative effects on the robot behaviour. This kind of problems leads us to find a solution for the efficient use of the Robotic sensor apparatus for simple behaviours. Therefore, we moved to study how rhythmic computations may be introduced in a control mechanism for multi-behaviour RS and how such introduction may lead to a framework that will cope with some of the common problems in designing general control systems for robots.

In this paper, we will analyze such architecture in terms of emergent behaviour driven by emotional states. We present a robotic architecture that has the capability of adapting its behaviour to the rate of change of emotional elicitors in dynamic environment - e.g., of tuning the velocity of reaction to the external stimuli coherently to particular changes occurring in the environment. On the other hand, we want our model to take into account that such stimuli may come not only from the external environment, but they can also be generated by the robot itself [3] - e.g., the robot has to adapt its perceptual system and its emergent behaviour according to its “needs”.

Finally, since emotions have to play some roles also in decision making and action selection, we foresee that simple forms of action selection processes may emerge even in the case of a behaviour-based architecture without an explicit arbitration module. To test this hypothesis, we describe how this architecture may deal with conflicting behaviours (for example, predator avoidance and food acquisition), when the normal activity of the robot’s behaviours is influenced by an emotional modulation induced, for example, by a change in the internal states (e.g., the risk of starvation) or in the external area (e.g., the risk of predation).
2 Emotions for Action Selection

In the literature there is a number of different definitions, with different levels of agreement, for concepts such as emotions or motivations. However, in this work we are interested in the characteristics of emotional behaviour that many theorists associate with coordination of actions, narrowing attention and biasing of perception [10, 11], and that have some role in decision making and action selection. First of all, we have to highlight that most of the theorists give special attention to the role of emotion on high level cognitive activities. For example, in neuroscience, while classical theories of sensory processing view the brain as a passive, stimulus driven device, more recent approaches [14] view the perception as an active and highly selective process. In a robotic system these approaches will imply that the role of emotion is fundamental in order to modulate and drive planning activities, while in the reactive level, that is in charge to react in useful time to urgent needs, it is neglected. This is to say that in a simple reactive architecture, in which there is a stimuli-action loop, there is no potential space for emotions [15]. Even if we consider an action selection problem, in simple reactive architectures there is a sort of arbitration module that is in charge to select the action to perform.

However, we have to note that one of the functional characteristics of emotions is biasing perception and selecting of the focus of attention. In this way, the effect of emotions manifests itself and has effects on the reactive, or behavioural, level of a robotic architecture. In fact, the reactive level is in charge of monitoring the external/internal environment and also of reacting to salient stimuli. Finally, we believe that a full specification of an action selection process, overt attention or preattentive behaviour [10], and a reactive modulation of simple behaviours has to include a bottom-up approach that does not necessary have to depend on high order function and may be included in the reactive level. For example, a direct response to a threat, which can come from the environment (e.g., the presence of a predator), or from an internal state (e.g., the threat of starvation), should have an impact directly on the reactive level and imply emotional modulation of the behaviour, before having an impact on high level cognitive processes.

An emotional state, in our work, has to be interpreted, following the Damasio definition [16], as an unconscious and automatic response in reaction to a stimulus that involves an adjustment in homeostatic balance as well as the enhancement of specific behaviours. In this sense, while motivation can drive the activity in normal circumstances, helping the selection of the appropriate behaviours to accomplish a task, emotions may play a remarkable role in enhancing behaviours that, in particular conditions, need an urgent response or a focusing of attention [15].

In order to model an emotional behaviour at the reaction level we have to hypothesize the presence of particular stimuli (internal or external) that elicit a specific reaction. Such stimuli, or elicitors of an emotional reaction, according to Frijda [17], are not the stimuli per se, but, depend on the interpretation of such stimuli. At the reactive level this means that such stimuli, which in common architectures for behaviour-based robotics may act as a releasing of particular
activities (e.g., the presence of predator releases escape behaviour), have to produce a different effect in respect to a releaser.

Moreover, a model of emotional behaviour has to include some notion of time. In fact, as elicitors may induce a change in the robot’s emergent behaviour, such change has to persist in time and is not directly connected to the presence of the elicitors itself. For example, the changing of behaviour due to the perception of a threat will continue to influence the behaviour even if the threat is gone. Finally, while the elicitation of an emotion can be rapid and depends on the salience of the elicitors, the decay of such emotional reaction may follow a different decay process depending on different factors. This decay process is different from the decay due to a fulfilment of a goal. In fact, in the latter case, the behaviour induced by a motivation can be instantaneously dropped.

Finally, we foresee that simple cases of action selection processes may emerge even in the case of a simple reactive architecture, if we take into account an emotional modulation. According to [18], we also believe that an action selection mechanism, when generated at the reactive level, has to include the possibility of the compromise. Conflicting or parallel goals may require, in fact, not only the possibility of selecting the optimal action from a set of options that satisfies one of the goals, but also an action that is good for achieving several of those goals in conjunction [18]. The controller could select an action that is the combination of different possible actions. For example, Ingle [19] observed that frogs and toads, whose behaviour is characterized as a visual response to moving objects, when they are presented with two flies simultaneously, may snap at neither fly, but in the middle.

When we have different stimuli, different behaviours have to compete in order to select the appropriate action. Hinde [20] identified nine different forms of competitions. Among them, we can select one of the possible actions, the alternations of different actions or a combination of actions.

In conclusion, an “emotional” reactive architecture has to satisfy the following requirements:

- Modulation of behaviours activities: emotions have to play a role changing the action readiness or action tendencies [17];
- Adaptive sensor readings: for each behaviour, at the reactive level, emotions have to act increasing or decreasing attention towards a particular aspect of the environment the robotic system is interacting with or of the robot itself. In this way, emotions have an impact on sensing activities focusing or narrowing the perception;
- Rapid reaction to elicitors: sources of saliencies or elicitors of emotions may be behaviour and task dependent. Such elicitors can depend on either internal states (e.g., the risk of starvation) or external stimuli (e.g., the perception of a threat, unexpected variations in the environment, and so on). Elicitors of emotions induce different reaction in different contexts and robot needs to be able to quickly react;
- Decay process: we have to allow the possibility of different mechanisms to decay an emotion;
- Action selection process: the overall behaviour emerges from the interrelations of the emotional mechanisms associated with each behaviour, and emotions contribute to settle conflicts among different goals.

3 Periodic Releasers and Emergent Behaviour

In order to model an adaptive control system for a behaviour-based architecture, we started considering that a wide type of behaviours is generated by the so-called central pattern generators [21], i.e., central oscillators whose output modulates rhythmic movements. The role of such oscillator in coordination of motor patterns [22], such as breathing and walking, is well accepted in neuroscience [23]. Moreover, basic drives (e.g., thirst or hunger) also are periodical processes. So, we would like to have a control system for the perceptual inputs that performs a quasi-periodic activity (i.e., it has at least an active and inactive phase) and should be flexible (i.e., dynamically adapt its period to external and internal constraints). In particular, we would like to associate a periodic control system to the activation of each single behaviour.

Lorenz [24] and Tinbergen [25] identified in many animals an innate releasing or inhibiting mechanism (IRM) able to control and coordinate behaviours. An IRM presupposes a specific stimulus that releases a pattern of actions. For example, a prey animal may have, as an IRM, the stimulus coming from the perception of the predator, which activates the escape behaviour. IRMs were included in the schema representation of behaviours [26] in the form of releasers, controlling their activation or inhibition. A releaser may be an activation mechanism that depends both on exogenous factors (a particular environmental condition - for example a prey that detects the presence of the predator), and on endogenous factors (a motivation or a drive - for example hunger).

The releaser's function, somehow, recalls the notion of “internal clock”, already introduced in some approaches [8, 27] in order to activate motivational states for a robot. In fact, an internal clock, as a releaser, is a mechanism which regulates the behaviour of living organisms. Starting from this analogy, we try to abstract the concept of internal clocks and to connect it to periodic activations of behaviours in a robotic architecture, similarly to a mechanism for releasing in Schema Theory [26]. In [12, 13] we associated the concept of IRM to the concept of a periodical activation of behaviours (AIRM - Adaptive Innate Releasing Mechanism).

Our working hypothesis is that each behaviour of a RS may be provided with a clock that controls the motivational periodic activation of behaviours. Such clock must not to be confused with an appropriately faster machine clock, whose period is supposed to be constant, which fixes the time abscissa \( t \) for the RS behaviours, and defines the time units for the robot control cycle. We may think that each of the releasers, managing the various micro\(\text{-}\)macro behaviours, is activated by an individual clock with period \( p_b \), as will be explained in the following, depending on the purpose of the behaviour and on the sensors data involved in the behaviour. In order to describe such a time controlled structure in a robotic architecture, we use a Schema...
Theory representation for the robot behaviours [26] (see Figure 1.b). For each behaviour we consider a schema composed by a coordinated control program, in which there is a clock combined with a releasing function ($\rho(t)$); a perceptual schema and a motor schema, obtained through the application of a transfer function on sensory inputs and on the releasing function. Timed releasing function takes data from a perceptual schema and returns an enabling/disabling signal to the Perceptual Schema itself. In this way, the perceptual schema of a behaviour is regulated by an internal clock that controls how frequently the inputs has to be processed. For example, if the period of a clock is four, it means that the input from the sensors for this particular behaviour will be processed only every four time units. If the clock is on and the input condition for releasing the behaviour holds, then the motor schema of the behaviour can be executed. In addition, during the inactivity state of the perceptual schema no new commands will be sent to the motor schema and so no new actions will be executed.

![Diagram of releasers and AIRM schemas](image)

Figure 1. A schema representation of releasers (a) and AIRM (b). The function $\sigma_r(t)$ represents the input coming from sensors at each time interval; $\pi(t)$ is the command sent to actuators; $\sigma(t)$ represents the inputs elaborated by the perceptual schema and sampled by the function $\rho(t)$.

There are, however, substantial differences between the two concepts. An internal clock is responsible for the activation of a particular behaviour, but has something more than a releaser. The releaser acts as a control signal for the whole behaviour and it, somehow, may involve an elaboration of the input (for example a releaser may be the presence of a predator) (see Figure 1.a). An AIRM, instead, works only on the perceptual schema (the perceptual schema elaborates, by a transfer function, the input only when the AIRM is active) and has an active (or inactive) state that also depends on endogenous factors. In this way, no computational resources are spent to elaborate not needed stimuli, because the corresponding control systems are kept “inactive” until a new periodical activation takes place. Furthermore, an internal clock may imply a regular and periodic activation of the perceptual schema of a behaviour, whose activations in time may be predicted - and so, also the amount of resources spent for the processing of inputs. Instead, the activity of a releaser depends only on contingent factors. Finally, the introduction of internal clocks, within a robotic architecture, has also the effect of controlling behaviours that may require a fixed pattern of activation in time. This behaviour activation may be interpreted as
large time scale motivational activities, for example the activation of macro-behaviour like feeding or sleeping, or as short time scale activities, in the sense of central-pattern generators in controlling rhythmic movements of a robot as walking, but also as a general mechanism for controlling activation of simple behaviours. At this point we have to clarify the role of the motor schema while the perceptual schema is inactive. First of all, let us make a distinction among two types of behaviours that we called “continuous” and “temporary”. A continuous behaviour is characterized by a motor schema that keeps its output constant until a new event will come. For example, a “continuous” behaviour may set the velocity of the wheels of a robot and keeps this value until a new elaborated percept will come from the perceptual schema. On the contrary, a “temporary” behaviour is characterized by the fact that its output will produce an action with its own proper duration. For example a temporary action is a gripper that lifts a box, a muscle contraction, the movement of a leg and so on.

3.1 Emotional Adaptation of AIRMs

Up to now we referred to the sensing activity as a discrete event, sampled by the period of the internal clock and related to a particular task the robot has to accomplish or a motivation the robot has to fulfil. The difference between the common interpretation of a sensing activity and a monitor activity, however, is well defined. As a sensing activity, we usually refer as a natural activity that has the goal to keep world model up-to-date. On the contrary, a monitoring activity requires an explicit interrogation of the sensor system in order to evaluate how the surrounding environment has changed. In robotic architectures also the sensing process requires an explicit interrogation of the sensor apparatus. Monitoring and sensing will collide if our monitoring strategy is to update our word model as frequently as possible. In our architecture, monitoring activity is fixed by a motivational state or a drive that decides how frequently the sensor inputs have to be evaluated. However, an emotion-based architecture should be able to integrate a combination of internal and external factors to modulate the appropriate behaviour. Unfortunately, motivational architectures are not always sufficiently adaptive to unpredictable environmental changes [5].

What we want to achieve is the ability, for a RS, of adapting its emergent behaviour to the surrounding environment and to its internal state. At the same time we want the robot to appropriately react according to environmental changes and to efficiently spend the resources necessary to monitor the surrounding area. In this sense, an emotional component in a robotic architecture may produce an adaptation to changes in the external environment as well as in the internal state of the robot. Emotional behaviour, which is not periodical or cyclical, depends on contingent factors and may produce a perturbation in the normal activity of the robotic system.

In order to introduce such perturbation in the control system, we recall again some concepts from neuroscience, physics and psychology. In particular we refer to the concept of “entrainment” of oscillators. This hypothesis rests on two assumptions. The first one is that internal rhythms or oscillations, that control perceptions and motivational activities, play a fundamental role in generating expectations for the occurrence of events in time (in our case they set the baseline periods $p_b$ for
monitoring the external world). The second hypothesis is that the rate of changing of the external events in some way drives the internal clock [28]. These hypotheses are in accordance with our need to have flexible and adaptive control mechanisms. In particular, McAuley introduced the idea of oscillators with preferred periods [29]. The main feature of such oscillators was of adapting their period to the dynamics of the events occurring in time. Such events, in fact, according to the authors, generate an external rhythm that is able to entrain the internal one. The entrainment process of neural rhythms was connected to the perception of time and to the ability of tracking events in time [28].

In our work, we propose an architecture with some periodic releasing mechanisms of activation of behaviours derived from motivations and drives. Emotional elicitors and saliencies have an impact on the value of the period of each behaviour, so they can regulate and modify the perceptual abilities of the robot as well as its actions in time. Such mechanisms, according to the rate of environment changing, speed up or gradually slow down the period of behaviours activation and thereby the reading frequency of the sensors. Emotional behaviours may be induced both by internal states of the robot (for example the risk of starvation), coded as linear time-dependent functions, and as an emergent process from the interaction with the environment (for example the perception of a threat). In our system, in fact, the feedback does not come only from the outside, but can also be generated by the robot itself [3], allowing the robot to adapt also according to its internal state. Moreover, such components may induce a coupling of the robotic system with the external environment, and may modulate the monitoring activity of a behaviour in order to bias perception or focusing the attention. However, even in the absence of such link, long term needs and survival activities are guaranteed through the normal periodical releasing.

In our approach, an emotional state has not to be considered as a changing value of a variable, but is modelled in a functional way. Such as, an emotional state does not correspond to some data associated to a behaviour, but is a result of the activity of the behaviour itself in an emergent way due to the changing of the releasing period. A behaviour may have several perceptual inputs ([σᵣ₁, ..., σᵣₗ], see Figure 2), either internal or coming from the environment, that must be elaborated in order to compute the motor output, but only some of them may be considered as elicitors of an emotional behaviour. In particular, an AIRM can include different functions for evaluating changes in percepts. Such changing can be estimated in a simple way as a difference of values. However, we believe that in order to evaluate the rate of changing, these functions have to include a component that depends on the incremental ratio of the change in the input percepts. According to the changing of the values of the elicitors [σᵢ, ..., σᵢ] the functions implemented by the AIRM can temporarily modify the sampling period of the behaviour, speeding up or slowing down such period in order to appropriately react.
Finally, we foresee that the introduction of such asynchronies in the robot control system may lead to a modification or adaptation in the emergent behaviour, according to its context and without having an explicit action selection mechanism. Indeed, such modulation works implicitly as an action selection mechanism. In Figure 3 we consider different examples of possible modulation of clocks associated to two different conflicting behaviours (namely a and b). Each clock is independent from the other, but the emergent behaviour of the robot will depend on the combination of the two. For example, the first case (a.1 and b.1) represents a balance between the actions of the two behaviours (see Section 2). Indeed, the autonomous modulation of each behaviour will have as a result that the selected action is a combination of the two behaviours. In the second case behaviour a.2 will be activated more often than behaviour b.2 and so the emergent behaviour will have a predominant component corresponding to the behaviour a.2. Finally, in the third case, we will have that, at each time step, the robot will execute alternatively the action provided by the behaviour a.3, and then the action provided by the behaviour b.3. In this way, we have the possibility of selecting one of the possible actions, or the alternations of different actions, or a combination of actions.

4 Implementation and Testing

An interesting case study, that includes emotional modulation of behaviour and the necessity of an action selection mechanism, is represented by the prey/predator domain. This type of interaction is widely analyzed in the field of ethological and behavioural studies. In particular, we are interested in the case of foraging in the
presence of a possible threat. This behaviour is usually analyzed in terms of the cost/benefit of feeding opportunity in opposition to the risk of predators [30]. However, few cases analyzed these costs also in the presence of the risk of starvation [31-33]. These kinds of studies try to include different and broader contextual elements to model and understand animal behaviour. However, emotional states, such as “fear”, may be used for balancing the risk of predator activities. In this paper, we are not referring to any specific animal behaviour, neither do we aim to provide a model that may reflect a real prey/predator interaction. Anyway, inspired by these studies, we propose a prey/predator case study, where we test the effect of the modulatory influence of emotional and motivational behaviour in the case of conflicting actions. In particular, we will simulate the case of the risk of foraging behaviour in the presence of a threat if the robot is dying of starvation.

Let us assume that each behaviour of the robotic system has a variable period initially equal to a preferred value $p_b$ (in our experiments, we assumed that these periods are proportional to powers of two)\(^1\). We designed a system whose behaviour is mainly guided by the visual information in a 3D environment. In particular, according to [6], the reaction of the robot may be driven by moving objects. In order to achieve the proper reaction of the robot in respect to a moving object, we implemented a control schema that changes the period of the clock following the Weber-Fechner law of perception. We already discussed, in Section 3, the perceptual schema modulation according to a periodic releasing function. In particular, we noticed that the robot can evaluate the perceptual inputs only when the releaser clock is on. While the reaction of the robot depends on the perceptual inputs (for example, the robot that sees a predator will produce an action to escape) the self-regulation mechanism, encoded in the internal clock, will compare the current percept with the last available percept, stored in a temporal or working memory of the robot. The change in its emotional state (encoded as a change in the releasing period) depends on how much this value has fluctuated. Clearly, in order to set the appropriate thresholds for evaluating this change and for mapping such function into a change of period, we cannot refer to absolute values. In this sense the Weber law allows us to compute the relative change in the perceptual input ($\sigma(t)$) as $\Delta\sigma(t)/\sigma(t)$ (where, $\Delta\sigma(t)=\sigma(t)-\sigma(t-p_b)$), and $\sigma(t-p_b)$ is the last value of the percept, sampled according to the releasing activity). In Figure 4 the $\Delta\sigma(t)/\sigma(t)$ values of an experiment and the consequent adaptation of the period are plotted. The dotted lines represent the thresholds we use to adapt the period of the releasing function. In order to make the robot able to react in time, for a quick change in the percept we let the period decrease according to the changing rate of the input percept. Let us remark that, in our approach, the period of a behaviour may change its value, varying according to the powers of two.

Furthermore, also the selected thresholds for changing the period are proportional to a power of two. For example, if $\Delta\sigma(t)/\sigma(t)$ exceeds the first threshold, the period will be halved; instead, if $\Delta\sigma(t)/\sigma(t)$ exceeds the second threshold, the current value of the period will be reduced to a quarter, and so on. On the contrary, when we have a decreasing function, we make the process for going back to the maximum value of the period, for instance, as a linear function. In this way the
disappearing of the threat does not imply a strong change in the emotional behaviour that disappears smoothly.

Figure 4. Changing of the perceptual input plotted as $\Delta \sigma/\sigma$. The dotted lines represent thresholds for the adaptation of the period.

In order to test our working hypotheses, we used a PIONEER 3DX provided with a blob camera (see Figure 5). The robot architecture is composed by four simple behaviours: WANDER, FIND_FOOD, EAT and ESCAPE. In this experiment, we were interested in observing only the FIND_FOOD and ESCAPE behaviours, whose perceptual schemas were controlled by AIRMs and whose activity, being potentially in conflict, requires an action selection mechanism. We implemented both a subsumption architecture (see Figure 6.a) with ESCAPE subsuming FIND_FOOD and a parallel architecture (see Figure 6.b) where the output of the two behaviours are summed. The output ($\pi_1(t)$) of the FIND_FOOD behaviour generated a predefined velocity and a direction towards the food, while for the ESCAPE behaviour the output velocity ($\pi_2(t)$) depends on the internal clock and the direction is the opposite direction respect to the threat. In particular, if the value of the clock is equal to the initial preferred value, the module of the ESCAPE velocity will be equal to the velocity set by FIND_FOOD. If this value is equal to the minimum value, the velocity will be set to a higher value in order to safely escape. In all the other cases, velocity will be a constant medium value in between the maximum and the minimum values.

Figure 5. Snapshots from the case study: (a) the robot wanders looking for food; (b) food and predator are in the same direction; (c) the predator moves towards the prey.
Let us suppose that a red object represents a possible threat and a green object represents food (see Figure 5.a). What happens when the system detects in the same direction both the food and the predator (see Figure 5.b)? In this case, the emergent behaviour will depend on emotional states (e.g., the risk of predation versus the risk of starvation) and will be influenced by their impact on behaviours’ activations. The FIND_FOOD behaviour has an internal clock with a period whose value depends on the risk of starvation. This state is regulated by a linear time-dependent function, and this means that, at the beginning, when the value of the hunger is low, the FIND_FOOD behaviour is released with a predefined period that depends on the life cycle of the robot. During the tests, the hunger value will grow in time and, accordingly, the period of the clock of the corresponding behaviour will be reduced. When the behaviour is enabled and the robot perceives a green object, the output of the FIND_FOOD behaviour will set the direction of movements towards the food. The ESCAPE behaviour has an internal clock that simulates the emotional state of “fear”. At the beginning of each test, the value of the period is set in order to safely check the presence of possible threats. If the robot perceives a red object and the behaviour is enabled, the output of the behaviour will be a movement in the opposite direction of the predator. The period of this clock does not depend on the variation of an internal variable (like in the case of FIND_FOOD), but on the changing of the value of the percept itself according to the Weber law. This means that the robot’s “fear” will increase if the predator is moving towards the prey (i.e., the period will be reduced). In addition, let us emphasize that this process will produce, as a consequence, an adaptation of the behaviour of the robot if the predator is not moving. Furthermore, in the case of both the food and the predator in face of the robot, while approaching the food, the movements of the robot itself may induce a change in the perception of the dimension of the red blob.

In Figure 7 we plotted a fragment of the percept (i.e., red blob area perceived by ESCAPE behaviour) of one of our experiments. Such percept is sampled according to the corresponding internal clock. Let us highlight that, while the internal clock is inactive, the robot does not update its perceptual input, which remains constant until the next activation of the clock. Moreover, let us notice how the frequency of activation of the clock is modified following the trend of the input percept.
In Figure 8 we plotted some results for the case study described above. The first plots (see 8.a and 8.b) refers to the subsumption implementation of the behaviours, while the second ones refers to a parallel architecture (see 8.c and 8.d). The first plot of each of the two cases represents the percept of the ESCAPE behaviour, the corresponding internal clock, while the last part of each plot represents the internal clock of the FIND_FOOD behaviour that depends on time. As soon as this value increases more than the value of the ESCAPE clock, the robot will start to move towards the food. The result of the combination of these two emotional states, elicited by the risk of starvation and the risk of predation, is an oscillating movement that will lead, eventually, to reach the position of the food (see Figure 8.b and 8.d).

Let us notice that the emergent behaviour in both the two approaches, represented by the changing of the position of the robot towards the food, is comparable, in the sense that both the approaches, when the behaviours are controlled by internal clocks, will lead to the same oscillating pattern towards the food. The only substantial difference between the two approaches happens when the hunger is low: in fact, while in the subsumption architecture the robot will move in the opposite direction of the food (and the threat), in the parallel architecture the robot is not moving.

Let us now discuss the case of a subsumption implementation. The emotional modulation of behaviours, in this case, implies the possibility of adaptation to particular contextual conditions that, in an architecture without AIRMs, will not be allowed by the nature of the subsumption itself. The bigger elicitation of the FIND_FOOD behaviour, respect to the ESCAPE behaviour, produces an emergent behaviour that is opposite to the behaviour induced by the subsumption. Such emergent behaviour is similar, in fact, to the emergent behaviour of the implementation without subsumption. From this similarity we can foresee that even without any subsumption, which provides itself a sort of action selection mechanism, an emotional modulation of the behaviour activity, at least for simple conflicting cases, may help in modelling a coordination of actions starting from the need of an urgent response.
Figure 8. Subsumption (a)(b) and parallel (c)(d) testing of behaviours. For each case, the plots show the changing of the input (red area) (a)(c), the changing of the two clocks (ESCAPE and FIND_FOOD) and of the position of the robot towards the food at each time unit (b)(d).
In Figure 9 we compared the emergent behaviour of parallel architectures, implemented on the same robot, changing the initial maximum value for the period of the ESCAPE behaviour. Let us highlight that the emergent behaviours of the robot do not seem to depend on this initial value. The explanation of this circumstance, in this particular case study, is that, while approaching the food, the clock of the ESCAPE behaviour frequently changes its value, also for the presence of a possible threat. This oscillation pattern makes the robot unable to return to the initial value of the ESCAPE period that keeps oscillating between the minimum value and a constant average value. In this case, it seems that the maximum value of the ESCAPE period does have no effect on the emergent behaviour. Anyway, we want our robot to react in useful time to a moving obstacle (i.e., the predator). In fact, while the AIRM is able to dynamically adapt to the changing of the surrounding area (e.g., changing the period from the preferred value to a more frequent sampling), such change may only happen according to the sampling rate of the clock. A bigger value of the period implies a coarser monitoring of the environment that, especially for behaviour designed to maintain the survival of the robot, is undesirable. In future work we intend to introduce learning mechanisms for the settings of proper preferred values for the periods according to the environment and the robot needs.

Finally, in Figure 10 we plotted the changing of the perceived red area and, accordingly, the changing of the clock period of the ESCAPE behaviour and the changing of the robot position when the red object starts to move (see Figure 5.c). Let us remark that when the period reaches its minimum value, the module of the velocity is bigger in order to escape. This plot shows that, even if the emergent behaviour of the robot makes the system try to reach the food position, the robot, through the AIRMs behaviour adaptation, is able to react to the moving object and safely escape. In fact, the emotional modulation of the behaviour will imply a more frequent activation of the ESCAPE behaviour and a focusing of attention on the predator.
5 Discussion

In this paper, we started to explore the feasibility of designing robotic architectures based on modulation of behaviour activities by means of adaptive periodic releasers in the case of conflicting behaviours. The emergent properties of such architecture can be related to a substrate for emotional processes, intended as a bottom-up influence on perceptual capabilities as well as a modification in the action readiness. The embedding of rhythmic controlled releasers, within RS’s behaviour, allows the realization of flexible/adaptive behaviour which can realize timed activation of the behaviour as well as modulation of its performance according to internal states and sensorial information. In this way, each behaviour can react and adapt to environmental and internal changes in useful time.

This architecture was inspired by different works in several areas of research, like, for example, ethology, biology and neuroscience. From a neuro-anatomical point of view, Ewert and von Seelen [34] suggested a filter-type model of prey\predator discriminator in amphibians, by considering the spike traces of tectum, pretectum and thalamus. They claimed that the higher the frequency, the better the associated response. These evidences seem to support our model but it is hazardous, for now, to assert that there is a genuine agreement. A deeper analysis of data coming from neuro-anatomy of several types of animals could confirm or disconfirm this hypothesis. Moreover, from the early days of perception research, without reaching a consensus, discrete psychological phenomena have been linked to brain oscillations, in particular the alpha rhythm [35] and to the gamma rhythm [36]. Such oscillations play some role in perception, attention [37, 38], cognition and behaviour. Finally, attentional processes have been linked to emotional regulation and self-regulation [39], as well as inhibitory control [40].

In robotic systems, other authors dealt with this kind of problems. Among others, one of the first and successful approaches, which connected motivational
capabilities to releasing of behaviours, is ALLIANCE [41]. The main characteristic of this architecture is the connection of a subsumption system to a motivational layer able to inhibit or release lower levels. The motivational layer is influenced by the internal state of the robot, by the perception of the external environment and by the communication with the other robot in a multi-robot coordination problem. The motivational layer is driven by motivational variables, such as impatience and acquiescence, which, once they reach specific thresholds, can achieve adaptive action selection and switching among tasks.

A further work that links the concept of releasing of behaviours to emotions is [42]. In this architecture, relevant systems, such as perceptions, behaviours, emotions and drives, are represented as independent modules, modelled as distributed networks, directly connected to other relevant units. Releasers, which also correspond to computational units, elaborate sensory data and identify special conditions which provide excitatory or inhibitory input to the systems they are associated with. The general form of the response or activation of each basic system is a non-linear function of its input, and it is proportional to the output of its releasers and to the strengths, or weights, of their connections. For example, within the drive system, a releaser may have the purpose to maintain a controlled variable within a specific range. This variable is measured through some of the agent’s sensors and compared to a desired value. If its value does not match the set point, an error signal is produced that is fed to the appropriate drive, and it is combined with error signals from other relevant control systems, with a non-linear combination. The emotional systems, in particular, have the capacity of learning releasers. Learned releasers, that represent emotional memories, have been modelled with an associative network. These learned releasers have the ability to act as biasing mechanisms during the action-selection process of self-interested and non-conflicting behaviours that can issue motor actions simultaneously.

Other authors introduced, as in our work, a schema representation of behaviours. For example, in [8] the Authors presented a parallel architecture focused on the concept of activity level of each schema which determines the priority of its thread of execution. The activity level of schemas is set according to three parameters: absolute relevance, contextual relevance and predictive success. The absolute relevance represents how much a schema is relevant by default and the contextual relevance represents how much the schema is relevant in the current situation, such as is mainly influenced by the motivational state. Finally, the predictive success incorporated a predictive component. While this paper focused on the role of anticipatory processes, it has many issues in common with our approach. For example, in [8], a more active perceptual schema can process the visual input more quickly and a more active motor schema can send more commands to the motor controller. However, while in our approach such effects are obtained through rhythmic activation of behaviours, in [8] the variables are elaborated through a fuzzy based command fusion mechanism. Moreover, as in our work, there is no explicit action selection, since all the active schemas send their commands to the actuators, although with different fire rate.
Finally, traditional emotion based architectures emphasize the role of emotion for behaviour switching. In this sense, the role of emotion is fundamental in order to prioritize goals or behaviours and focusing attention. Behaviour-based robotic, usually, resolves conflicts by using a subsumption architecture or by implementing some other arbitration mechanisms in order to switch between tasks, selecting the action. For example, in [6] the authors presented a schema theoretic model for a praying mantis in which behaviours are driven by motivational variables such as hunger, and emotional variables, such as fear, and sex-drive. In this approach, the action selection module takes into account only the motivational/emotional variables with the highest value. While hunger and sex drive are time depending functions, fear is the only variable that depends on the perception of the predator. When the predator is in the field of view of the prey, this variable is set to a predefined high value. As in our example, when the hunger is too high the robot will move towards the food even though there is a predator in sight. On the contrary, in our work we started to analyze emergent action selection mechanisms as a combination of multiple conflicting goals. There can be, in fact, situations in which the robot needs to temporarily overlook one goal to accomplish another (i.e., short-term and long-term goal), or situations in which the robot needs not to give up on important tasks (i.e., safety) even when they may be in conflict with the current one. In the latter cases an action selection mechanism, as well as a controller for perceptual activities, does not have to work only as a mere switch between behaviours, but has to include the possibility of a combination of different behaviours. Moreover, the activities of different behaviours, through periodic releasers, can be modelled as parallel activities with different time scales.

In conclusion, let us notice that while the risk of starvation may have a linear model of development, emotions, such as “fear”, are not a linear succession of events [7]. In our approach we presented a model of emotional behaviour that does not depend only on linear time dependent functions, but is directly connected to the changing rate of the surrounding environment. However, while for a simple case study our architecture was able, by means of asynchronous computation, to act like an action selection mechanism and to adapt to its context, one of the problems of more complex parallels architectures comes from the possibility of arising interferences between different processes. Since emotions and motivation are not independent processes, future work we will move forward in the direction of studying how these adaptive periodical activations of behaviours may influence and constrain each other.

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Notes
1. This is only a technical solution in order to have integer values for halving or further reducing the period.
References


