A Bottom-Up Investigation of Emotional Modulation in Competitive Scenarios

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Abstract. In this paper, we take an incremental, bottom-up approach to investigate plausible mechanisms underlying emotional modulation of behavior selection and their adaptive value in autonomous robots. We focus in particular on achieving adaptive behavior selection in competitive robotic scenarios through modulation of perception, drawing on the notion of biological hormones. We discuss results from testing our architectures in two different competitive robotic scenarios.

1 Introduction

One of the main problems for autonomous robots is behavior selection or "what to do next" [12]. Motivation-based architectures [12,4,17,2] integrate a combination of internal and external factors to select the appropriate behavior and satisfy the robot's needs in real time. However, these architectures are not always sufficiently adaptive to rapid environmental changes. Previous work [5] postulated the use of second-order mechanisms, akin to some of the functions of emotions in biological systems, that act on other elements in the architecture for improved performance in dynamic, unpredictable, and dangerous environments. In that architecture and others that have followed a similar approach, the adaptive functions of emotions are predefined by the designer. While this nowadays widespread design practice can produce efficient behavior selection, it leaves unanswered the question of which are the underlying mechanisms and how they integrate and interact with other elements to achieve adaptive behavior. In the work presented here, we take an incremental approach to investigate plausible mechanisms underlying emotional modulation of behavior selection and their adaptive value. We are particularly interested in how such modulation can achieve different functionalities from the same architecture by interacting with other elements, rather than including emotions as additional components. In this paper, we focus on discussing how behavior selection can be made adaptive (i.e., its output biased) to different environmental situations (two different competitive robotic scenarios) by modulating different sensory channels—perception of external and internal stimuli. Drawing on the notion of biological hormones,

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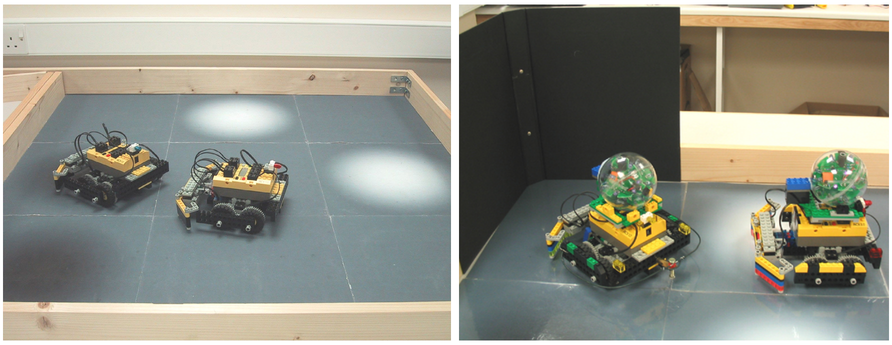

Fig. 1. Experimental setups used to carry out the studies: a Competitive Two-Resource Problem scenario (left), and a "prey-predator" scenario showing the prey robot inside the nest and the predator outside (right)

we have modeled two of the functionalities ascribed to them in order to improve the adaptation of motivation-based architectures to different problems. To achieve different functionalities from the same architecture, we have taken inspiration from neuroscience models of hormonal control [9,10], in particular regarding the following ideas: (a) Sensory inputs enhance the release of hormones that act at different levels of the nervous system; (b) they act as gain-setting sensitization processes that bias the output of the organism in particular directions; and (c) after modulation, the organism responds to particular sensory stimuli with an altered output appropriate to the new situation. We have tested our "hormone-like" mechanisms in two dynamic and unpredictable competitive robotic scenarios depicted in Figure 1, and show how they improve adaptation and performance using quantitative indicators based on the notion of viability. Finally, we analyze the results in terms of interesting behavioral phenomena that emerge from the interaction of these artificial hormones with the rest of architectural elements and the environment, and that resemble "emotional" behavior in biological systems confronted to similar situations.

2 Behavior Selection Architecture

Following [5], in our architecture behavior selection results from the interactions of a number of elements integrated through an artificial physiology and in interaction with the environment.

The physiology consists of (1) survival-related, homeostatically controlled essential variables and (2) hormones. *Essential variables* are abstractions representing the level of internal resources that the robot needs in order to survive. They must be kept within a range of permissible values for the robot to remain viable or "alive," thus defining a physiological space [14] or viability zone [1,13] within which survival (continued existence) is guaranteed, whereas transgression of these boundaries leads to "death." *Hormones* can be seen as second-order control mechanisms that affect the behavior of other elements of the arhitecture.

Motivations are abstractions representing tendencies to act in particular ways as a function of internal and external factors [18]. Internal factors are mainly (but not only) physiological deficits ($0 \leq d_i \leq 1$) or bodily needs—traditionally known as "drives"—that set urges to action to maintain the state of the controlled physiological variables within the viability zone. External factors are environmental stimuli, commonly termed "incentive cues" in Ethology, ($0 \leq c_i \leq 1$) that allow to satisfy bodily needs through behavior execution. In our implementation, each motivation performs homeostatic control of one physiological variable. We have used the equation proposed in [2] to combine cue and physiological deficit when computing motivational intensities:

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

In addition to physiological deficits (d_i) and incentive cues (c_i), this equation introduces a weighting factor ($0 \leq \alpha \leq 1$) that affects the relevance given to the external cue.

Behaviors are coarse-grained subsystems (embedding simpler actions) that implement behavioral competencies similar to [12,5]. Following a classical distinction in ethology [15], motivated behavior can be consummatory—"goal-achieving" and needing the presence of an incentive stimulus to be executed—or appetitive—"goal-directed" search for a particular incentive stimulus. In addition to modifying the external environment, the execution of a behavior has an impact on (increases or decreases) the level of specific physiological variables. Therefore, behaviors take part in the homeostatic control to maintain the state of the physiological variables within the viability zone.

Behavior Selection is performed in a continuous loop consisting of three main steps: (1) The deficit of the physiological variables (internal needs) and the intensity of the external stimuli are calculated; (2) motivational intensities are computed combining (perception of) deficits and external stimuli ponderated by the weight α, following equation 1; (3) the behavior that (best) satisfies the motivation with the highest intensity is executed, modifying the physiology and possibly the position of the robot relative to external stimuli in the environment.

3 Competition for Resources

In previous work [2] we analyzed different motivation-based behavior selection architectures within a static Two-Resource Problem (TRP), in which a single robot must maintain appropriate levels of two internal variables by consuming two resources available in the external environment. The TRP constitutes the minimal scenario to test behavior selection mechanisms, and it has become a standard testbed for behavior selection both in animals—see e.g., [17]—and autonomous agents and robots—e.g., [4,7,3]. Its simplicity, although not devoid of problems, favors a systematic analysis of results. The particular implementation of the TRP in [2] used a Lego Mindstorms robot (see Figure 1, left, for a similar arena, although the TRP uses only one robot), with the need to maintain temperature and energy levels by consuming heat (white gradients on the floor of the arena) and food (black gradients), respectively. The robot had two motivations: m_{cold} to increase temperature, which can be satisfied by executing the consummatory behavior b_{warmup}, and $m_{fatigue}$ to increase energy, which can be achieved by executing the consummatory behavior b_{feed}. In addition, the robot had a reflex obstacle avoidance behavior b_{avoid}, and the appetitive behavior b_{search}. The execution of all behaviors affects both essential variables[1].

To measure results in TRP, we used different performance indicators based on the notion of viability, in particular: *Life Span*, defined as the time that the robot survived in each run ($LS = t_{life}/t_{run}$); *Overall Comfort*, the average level of satisfaction of the physiological variables during a run ($OvC = \sum_{i=1}^{t_{life}}(1 - \overline{d_i})/t_{life}$); and *Physiological Balance*, the homogeneity with which physiological needs are satisfied during a run ($PhB = \sum_{i=1}^{t_{life}}(1 - \sigma^2(d_i))/t_{life}$). We also noted that, when doing behavior selection in TRP, the robot executed regular cycles of activities rather than isolated behaviors, and those activity cycles were reflected in the physiological space of the robot, as shown in Figure 2: from the initial state, the robot would start looking for a given resource, e.g. heat (arrow noted as A in the figure), then consume it until satiated (B), then start looking for the other resource (C), consume it until satiated (D), and start all over again. The position of the cycles in the physiological can be changed: the same cycle (i.e., with the same shape and duration of each activity) would be executed closer to the ideal state, therefore preserving viability "better", or father away from it (and therefore in a "less viable" way) depending on the value of α, the parameter that weighed the significance of external stimuli in equation 1, as depicted on Figure 2 (right). The regular shape of those activity cycles reflects the fact that behavior selection in TRP was static and highly predictable.

The Competitive Two-Resource Problem[2] (CTRP) is an extension of this problem that consists in the introduction of two robots in the same environment simultaneously performing their own TRP, as depicted in Figure 1 (left). The robots do not explicitly communicate or compete; however, the fact that they have to use the same resources to satisfy their needs introduces competition for those resources, as both robots might need access to the same resource at the same time. Therefore, new forms of environmental complexity—availability and accessibility of resources—appear due to the interaction between robots, breaking the predictability and symmetry of TRP. The question that needs to be examined here is to what extent the architecture used for the TRP can solve the CTRP.

[1] At each execution cycle, b_{warmup} increases temperature by 0.3 units while decreasing energy by 0.1 units, b_{feed} increases energy by 0.3 units while decreasing temperature by 0.1 units, and b_{avoid} and b_{search} decrease each variable by 0.2 units.

[2] We refer the reader to [3] for an in-depth technical quantitative analysis of this scenario, while here we focus on a qualitative discussion of the adaptive value of hormonal modulation and its significance from the point of view of emotion.

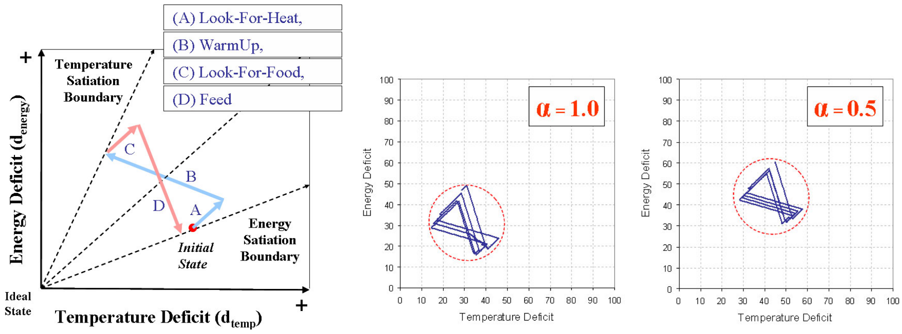

Fig. 2. Activity cycles in TRP. Left: cycle as reflected in the physiological space. Right: position of cycles in the physiological space as a function of α.

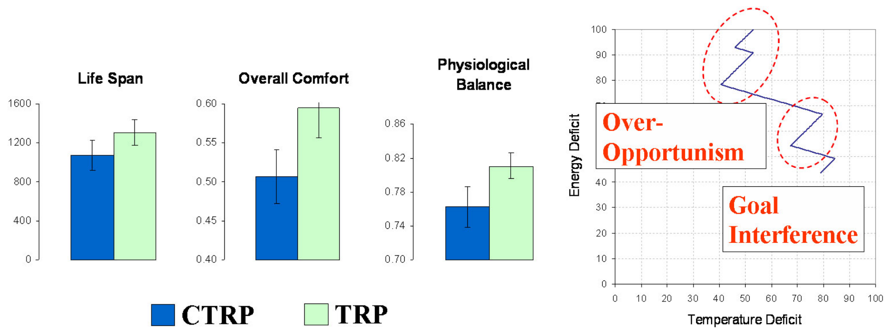

Fig. 3. Decreased performance in the CTRP, as measured by viability indicators (left) and activity cycles (right)

Analysis showed that the new forms of complexity dramatically decrease the performance of that behavior selection architecture, as clearly reflected by the different viability indicators and the activity cycles depicted in Figure 3. In particular, analysis of the activity cycles shows that the cycles easily loose the regularity and symmetry they showed in TRP, as illustrated in Figure 3 (right), and that the robot very often dies from two problems that the behavior selection mechanism used within the TRP presents when used in the CTRP. First, the robot can fall in a pathological sequence of opportunistic activities—consuming the same resource—that eventually can drive it to death due to over-opportunism. Second, when one robot is located on top of a resource—i.e., consuming it—the other robot might bump into it and push it out of the resource. This will result in the interruption of the ongoing consummatory activity and to death due to goal interference.

The next step in our incremental design approach is to analyze what needs to be added to the architecture to be able to solve those problems. A solution to the "over-opportunism" problem requires shifting attention away from less needed resources when the robot is in a high risk of death (RoD), that we define as the inverse of the distance between physiological state (d_{temper}, d_{energy}) and lethal boundaries. A solution to the "goal interference" problem requires that the robot in need of an occupied resource does not avoid the "intruder" as if it were a mere obstacle. Both problems can be solved by altered perception of external stimuli, i.e., by modulation of exteroception.

3.1 Modulation of Exteroception

Rather than adding more structural elements to our architecture, our solution consists in trying to achieve additional functionality from the same architecture. A single "hormone-like" modulatory mechanism can alter perception in both cases, with a twofold effect. First, by acting on the parameter α of equation 1—i.e., by biasing the relevance given to external cues—the hormone reduces the perception of both incentive cues, therefore reducing opportunistic activities when there is any risk of death. Second, by cancelling the perception of obstacles $s_{obstacle}$ (carried out using the bumper sensor), and hence the avoidance reflex behavior, when the robot is facing the competitor, the hormone potentiates the competition skills of the robot by enhancing its capacity to push the other robot out the resources and not to be interrupted. To achieve this twofold functionality, the concentration of hormone will be a function of the risk of death (RoD) and the perception of the competitor, given by $0 \leq s_{competitor} \leq 1$. Hormone concentration is computed as:

$$c_g = RoD + s_{competitor} \tag{2}$$

The relation between hormone concentration and the cancellation of the perception of incentive cues and obstacles is as follows. To achieve the first functionality, the cancellation of α is directly proportional to the increment in hormone concentration, i.e., when RoD increases, α decreases: $\alpha = min(1 - c_g, 0)$ The second functionality is obtained by cancelling the perception of $s_{obstacle}$—i.e., bumpers—when the competitor is in front of the robot. For this mechanism to be efficient, two conditions must be fulfilled to make a coherent pushing of the other robot. First, the robot must avoid getting engaged in fights when it has high RoD. Second, it must only bump blindly into the other robot, not against the walls of the arena. To produce that effect the cancellation of the bumpers must be at hormonal levels $c_g \simeq 1$ and $c_g \simeq 2$.

It is worth noting that the motivation-based behavior selection architecture has suffered no modification; the only difference with respect to the TRP is the fact that now one of its parameters (α, cfr. equation 1) is modulated by the hormonal feedback mechanism.

3.2 Experiments and Results

We tested the robots for a total of 16 runs of 1200 steps (approximately 5 minutes) each, one step representing a loop of the behavior selection mechanism that takes $260ms$ in the 16MHz onboard microcontroller. As shown in Figure 4,

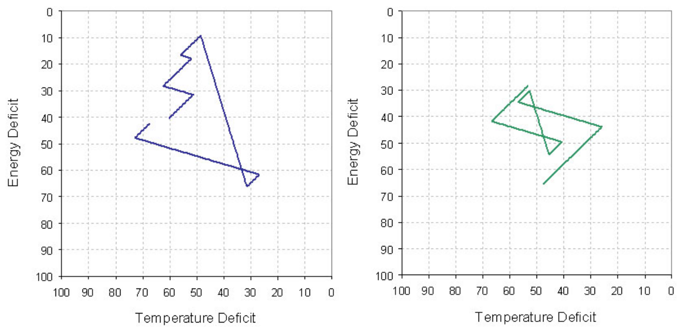

Fig. 4. Activity cycles in CTRP in unmodulated architecture (left) and with modulation of exteroception (right)

the robot with hormone-like mechanism recovers the stability and viability of activity cycles. We refer the reader to [3] for a detailed quantitative analysis, while we focus here on various interesting functionalities that emerged as a result of modulating the exteroception of the robot. The first functionality is to stop consuming resources when the robot detects its competitor approaching. This could be interpreted by an external observer as abandonment of a situation (waiting for the other robot at the resource) in which competing is disadvantageous. Instead, the robot will leave the resource and go straightforward towards the competitor until it reaches it; at that moment, two things can happen. If there is some level of RoD, the bumpers of the robot will not be cancelled and it will avoid the competitor, showing a behavior that an observer could interpret as “fear” after evaluating the competitor. On the contrary, if there is no RoD, the hormonal system will cancel the bumpers and the robot will push the competitor unconditionally—as if it showed some sort of “aggression” against it. If we study the whole picture as external observers, such behavioral phenomena could well be interpreted as some sort of “protection of resources”.

4 Prey-Predator Scenario

The previous scenario involved no active interaction between the two robots. It therefore seems natural to ask whether an active relation between the robots would introduce additional complexity, and how the previous behavior selection architecture would cope with it. We thus designed a prey-predator scenario (Figure 1, right) that we call the Hazardous 3-Resource Problem (H3RP). In H3RP, a “predator” robot actively chases and can damage a “prey” robot by hitting a home-made contact sensor in the form of a ring. To make this interaction possible, we had to introduce new elements in the environment—a nest in one of the corners of the arena, in which the prey can “hide” and recover from damage—and in the architecture of the prey, namely: (a) a third physiological variable, integrity, which is a metaphor of the essential need any organism has to keep its tissue—the boundary between the organism and its environment—intact and that is unpredictably reduced by the attacks of the predator; (b) a new motivation m_{damage} to decrease the integrity deficit; and (c) an appropriate consummatory behavior $b_{recover}$ to satisfy the new need.

Initial experiments showed very quickly that a purely motivation-based behavior selection mechanism does not perform well within the new framework, since the prey invariably died as a consequence of predator attack (see the right graph of Figure 6 for quantitative results of additional experiments). The main cause seemed to be the inability of the prey to react timely to the attack of the predator, which was perceived in close proximity only. In other words, the behavior selection mechanism paid low attention to the new motivation to recover integrity, even when the predator is in sight. The probability to lose integrity rises when the predator is around, therefore it would be advantageous for the prey robot to "anticipate" that loss and start "preparing in advance" to recover integrity.

In the animal world, exposure to predators triggers what has been termed "predator-induced stress" or "predator-stress" for short, characterized by high levels of corticoids or "stress hormones" and a number of responses related to increased attention to and avoidance of the predator. Such reactions occur not only in the presence of a predator. Prey animals use unconditioned and conditioned predator cues to assess risk of predation, and they even seem to be able to perceive risks in the absence of such cues [6]. An example of the latter is the phenomenon known as "risk of permanence"—maintained levels of vigilance after predator's disappearance. Risk of predation strongly influences prey decision-making (for example, when and where to feed, vigilance, or the use of nest), which in this circumstances can be considered as a mechanism to allow an animal to manage predator-induced stress [11]. Risk of predation has been proposed to increase the animal's level of "apprehension," i.e. the reduction in attention to other activities (e.g. foraging) as a result of increasing the time spent executing defense-related activities such as vigilance or refuge use [8].

4.1 Modulation of Interoception

We have again applied "hormonal" modulation to our behavior selection architecture to achieve such "anticipatory" behavior, this time exploiting the temporal dynamics of hormonal decay to produce long-term modulatory effects triggered by short-term exposure to a stimulus [10].

To achieve this, a simple solution consists in using one of the existing sensors of the prey robot to detect the predator from a distance. Given the morphology of the robot, this sensor must be the same as that used to locate the nest. The problem of using that sensor is that it is fixed, pointing forwards. Since the predator does not pass in front of the prey very often and only does it for very brief periods, the additional stimulus ($s_{predator}$) will be too weak to make any difference. However, long-term hormonal modulation acts as a mechanism for predation risk assessment in the absence of predator cues. Hormone concerntration makes the system more sensitive to integrity deficit after the detection of the predator. Hormonal secretion follows the detection of the stimulus $s_{predator}$ and increases the *perceived* integrity deficit. Due to the hormone's temporal dynamics, modulation will be acting in the system long time after the predator has disappeared. Hormone concentration modifies again one of the sensory inputs of the architecture—interoceptive in this case—biasing behavior selection.

We have modeled hormonal temporal dynamics—release and dissipation—using an artificial endocrine system similar to that proposed in [16] and described by equations 3 and 4. A gland g releases hormone as a function of the intensity of the external stimulus predator ($s_{predator}$) at a constant releasing rate β_g:

$$r_g = \beta_g \cdot s_{predator} \tag{3}$$

Hormone concentration[3] suffers two opposite forces over time: it increases with the release of hormone by the gland, and dissipates or decays over time at a constant rate γ_g:

$$c(t+1)_g = max[(c(t)_g \cdot \gamma_g) + r_g, 100] \tag{4}$$

In this implementation, the hormone increases the perception of the integrity deficit ($d_{integrity}$), i.e., the higher the hormone concentration, the higher the reading of the $d_{integrity}$ interoceptor:

$$d^{new}_{integrity} = max(d_{integrity} + \delta_g \cdot c_g, 1) \tag{5}$$

Factor δ_g determines how susceptible to hormonal modulation the interoceptor ($d_{integrity}$) is. We use $\delta_g = 0.005$, which implies that the level of perceived $d_{integrity}$ is increased by 0.5 when hormonal concentration is maximum ($c_g = 100$). In other words, although the level of integrity is at its ideal value ($d_{integrity} = 0$), the interoceptor will perceive a level of 0.5 if hormone concentration is maximum. Note that there is a constraint to avoid the level of integrity deficit to be perceived beyond the maximum possible value ($d_{integrity} = 1$).

4.2 Experiments and Results

We tested the robot for 16 runs of 1600 steps each, i.e., each architecture (non-modulated and modulated) was tested for almost two hours in H3RP.

The prey robot presented higher viability levels in terms of life span, at the cost of overall comfort, when equipped with the modulatory mechanism, as shown in Figure 5. Long-term hormonal modulation acts as a mechanism for predation risk assessment in the absence of predator cues. It can be regarded as increasing the level of "apprehension" of the prey robot after short-term predator exposure, and this is reflected in an increment of the motivation to recover and of the execution time of recover-related (consummatory and appetitive) activities—the robot spends more time looking for the nest and recovering integrity in it—at the cost of other activities, namely feed and warmup, as reflected in Figure 6

[3] We constrained hormonal concentration to a maximum of $c_g = 100$ in order to keep more control on the hormone's dynamics and thus facilitate the analysis of results.

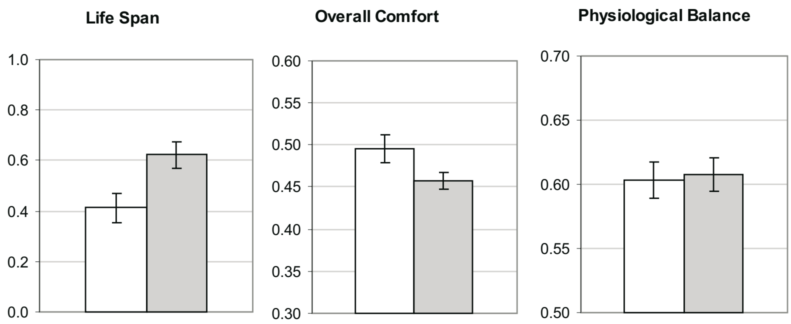

Fig. 5. Average performance of non-modulated (light bars) and modulated (dark bars) architecutres in terms of LifeSpan, Physiological Balance, and Overall Comfort. Bars show standard error of the mean.

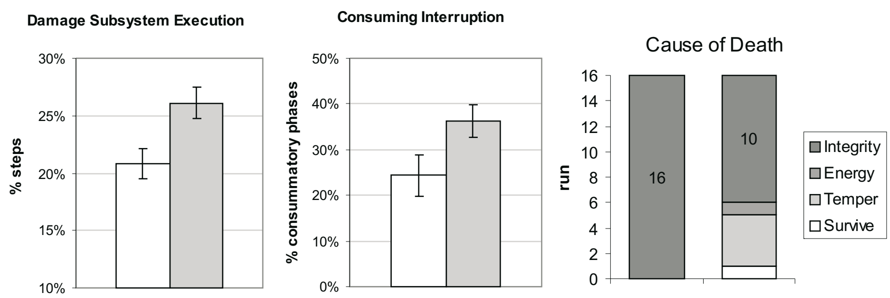

Fig. 6. Comparison between non-modulated (bars on the left of each graph) and modulated (bars on the right) architectures in terms of execution time of recover subsystem (left), average number of interruptions of consummatory feed and warmup behaviors (center), and causes of death in the 16 runs (right). Bars show standard mean error.

(left). This increment in the execution time of recover-related activities is statistically highly significant. Another important phenomenon is the interruption of ongoing consummatory feeding or warming-up activities (Figure 6, center). When the robot is under the effect of the hormone it will abandon the resource and go to the nest before the motivation has been satiated. The prey robot, when equipped with the hormonal mechanism, presents statistically higher levels of interruption of ongoing feeding or warming-up activities. Finally, analysis of the causes of death (Figure 6, right) shows substantial differences with respect to the non-modulated architecture.

5 Conclusion

We have discussed a bottom-up study of plausible mechanisms underlying emotional modulation of behavior selection and their adaptive value, in particular

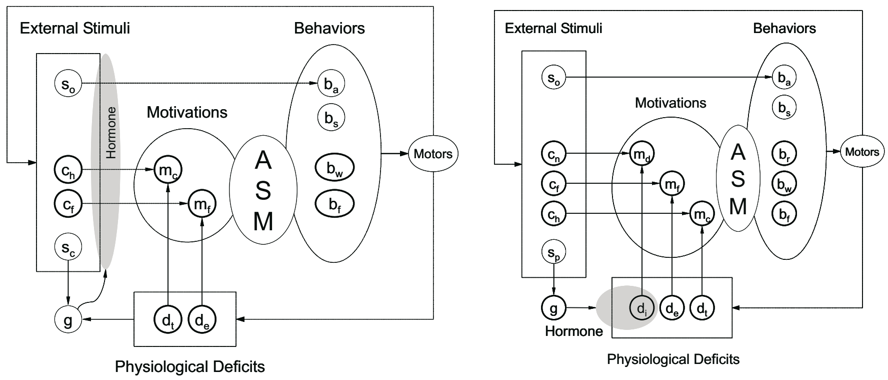

Fig. 7. Hormonal modulation of exteroception (left) and of interoception (right)

how such modulation applied to a motivation-based architecture can achieve different functionalities found in biological emotions, to face different emotionally-relevant problems posed by different competitive scenarios. We have considered a first scenario in which obtaining resources in competition with others is the main survival-related problem, and a second scenario in which the attack of a predator constitutes the main threat. Drawing on the notion of biological hormones, we have focused on achieving adaptive behavior selection in these different competitive robotic scenarios by modulating perception of external stimuli in the first case, and of internal stimuli in the second, as depicted in Figure 7. In addition to improving behavior selection performance and adaptation, modulation has given rise to some emergent behavioral phenomena that could be interpreted by an external observer as "emotional," such as aggressive/defensive behavior in the first, "fleeing" and "apprehension" in the second. We suggest that such modulatory mechanisms provide a more principled integration of different behavior selection elements and functions, in addition to improving the adaptation of a robot to changing environments. The type of adaptation fostered by such mechanisms is different from other mechanism such as learning or evolution, for which "past solutions" are "overwritten" by new ones.

Current and future work includes the integration in the same architecture of both types of hormonal modulation presented here, to face a more complex prey-predator problem requiring interactions among both mechanisms. We will also continue our incremental study of plausible modulatory mechanisms underlying emotions by changing and complexifying the environment to give rise to other behavior selection problems.

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