Emotion in Decisions of Life and Death - Its Role in Brain-Body-Environment Interactions for Predator and Prey

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Abstract

Taking inspiration from the biological world, in our work we are attempting to create and examine artificial predator-prey relationships using two LEGO robots. We do so to explore the possible adaptive value of emotion-like states for action selection in this context. However, we also aim to study and consider these concepts together at different levels of abstraction. For example, in terms of individual agents' brain-body-environment interactions, as well as the (emergent) predator-prey relationships resulting from these. Here, we discuss some of the background concepts and motivations driving the design of our implementation and experiments. First, we explain why we think the predator-prey relationship is so interesting. Narrowing our focus to emotion-based architectures, this is followed by a review of existing literature, comparing different types and highlighting the novel aspects of our own. We conclude with our proposed contributions to the literature and thus, ultimately, the design and creation of artificial life.

Introduction

In our work we are, broadly speaking, interested in seeing what existing ideas about emotion in biological agents can do for the creation of more adaptive artificial agents. Concentrating on ideas about the role of emotion in rational decision-making, we are especially concerned with how such ideas might help us address the problem of action selection using emotion-based architectures. Action selection referring to the problem all agents (biological and artificial) must necessarily face of "what to do next" [Bryson (2007)], we are further interested in (and advocate) studying it within the context of (biological and artificial) predator-prey relationships.

By focusing on this type of relationship, besides enabling us to better explore and develop our ideas about the role of emotion for adaptive behaviour in dynamic environments, we suggest it allows us to obtain more detailed insights due to and regarding specific aspects or characteristics of this type of environment. This includes those requiring some kind of appropriate risk assessment (such as perception of danger) and, in turn, risk-taking. Consequently, one of our main aims is to consider in greater depth how action selection mechanisms might be developed so as to be adaptive in such situations. That is, where an agent's decisions are literally those of "life and death".

Considering relatively recent ideas about the importance of the body for intelligent and adaptive behaviour [Pfeifer and Scheier (1999); Pfeifer and Bongard (2006)], we explore the link between action selection and emotion in terms of brain-body-environment interactions. Asking whether we should stop focusing so much on abstracting away features of body, in favour of developing emotion-based architectures oriented more towards ideas such as those inherent to the notions of internal robotics [Parisi (2004)] and morphological computation i.e. those explicitly giving agent body a more proactive role in the generation of behaviour.

To do this, and because we are interested in identifying factors (particularly those relating to the concepts of embodiment and embeddedness) that might affect such interactions, we have developed robots that both model and provide a means for studying the (different types of) relationship between a single predator and prey agent. Specifically, we use an implementation of a predator-prey type scenario previously developed to study action selection: the Hazardous Three Resource Problem (H3RP) [Avila-García and Cañamero (2005)].

Here though, we set aside the more technical details of our experiments and implementation. Firstly, for a more general consideration and outline of our ideas as to why the predator-prey relationship is so interesting and relevant to the problem of action selection (also detailing our main research interests and questions). Secondly, to review the literature so as to compare more general features of our work, robots and implemented emotion-based architecture with those of other researchers. And finally, to detail the ways in which we hope our work will make its own contribution to the existing literature, for both the problem of action selection and role of emotion in adaptive systems.

The Predator-Prey Relationship and Problem of Action Selection in the Literature

The relationship between predator and prey is one that should be of particular interest to those studying action selection. Indeed, it is of interest across and within many disciplines. While there are many aspects of this scenario to interest researchers, what often stands out is the fact it is a relationship between two agents. Moreover, it is a relationship characterised by a dependency of one agent (the predator) on another (the prey) for its continued survival. This results in interactions between agents that will determine the success of each agent, with a push-pull effect. Where one wins, the other will likely suffer some corresponding cost or loss.

Looking at the literature, research has explored this scenario from various perspectives. From the level of the individual over a lifetime [Kelly et al. (1999)] to populations across generations [Nolfi and Floreano (1998); Buason et al. (2005)]. Yet the way this relationship has most often been studied is through the development of action selection mechanisms for the prey that will result in it fleeing whenever it sees a predator. In effect, making this the more or less automatically optimal or decided choice of action, regardless of the task currently being performed.

Strangely, researchers have also commonly continued to focus on one type of agent only (predator or prey) with the action selection problem of the other agent being of secondary to no interest. We regard this as possibly leading to a more superficial look at, or treatment of, the action selection problem for artificial predators and prey. A perspective which may lead to less rich, or realistic, solutions than might be the case or useful in real life and real time.

For example, this emphasis does not take into account or allow for the possibility that in fact there may be times in which the more adaptive behaviour would be for the prey to "take the risk" of being attacked by its predator. Or, indeed, the case that there are some, if not many, environments in which life must constantly be risked in order to achieve long-term survival. Perhaps in favour of satisfying some other survival need or task. Looking towards ethological studies for evidence and inspiration, researchers illustrate this could also be true of biological organisms.

For instance, Cooper Jr (2000) found a species of lizard will tolerate predators to come closer before they decide to "flee" under certain conditions, including when they were eating food. Though it could be argued this might also reflect the possibility that the lizard's attention is more directed on feeding than awareness of or perception of the predator. More interestingly, it could be that some kind of economic model allows for "risk-taking" or a kind of "cost-benefit" analysis in terms of risk assessment that is adaptive for agents. Then too, this could lead to a role for emotion-like states as quick, real-time assessors of risk in relation to certain stimuli.

Our Interest in the Predator-Prey Relationship

The predator-prey relationship may be of interest for action selection researchers for many other reasons. However, for us, among the most interesting are:

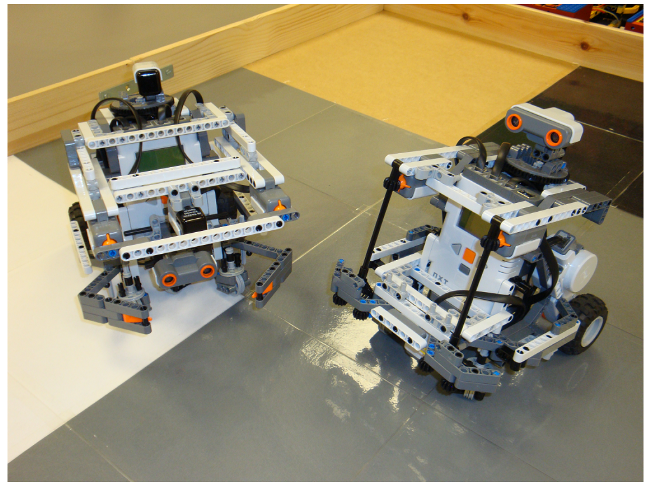

Figure 1: Our Implementation: Predator (left) and Prey (right) robots developed for early experiments [O'Bryne et al. (2009)]. These agents have been built using two LEGO NXTs. Our initial experiments have focused on developing different "brains" for our agents (emotion-based architectures); looking at the results in terms of adaptive value (production of adaptive behaviour) in different "bodies" and "environments" (by connecting architectures to the environment in different ways, such as using different physical sensors; and varying properties of the partner robot i.e. predator or prey agent)

- Adding a predator (or prey) to a given agent's environment is a way of making that environment dynamic. It leads to to changes over time that the agent must respond to adaptively and often increases environmental complexity. Thus, in terms of action selection, it can act as a good test for how well an individual agent (or the action selection mechanism implemented within it) can cope with increases in the dynamics of their environment. Importantly, the typical nature of these are usually such that each agent has to make quick decisions in order to make adaptive ones. This leads to a trade-off, where if the agent hesitates or ponders too long, all could be lost anyway (game over, especially for the prey).

- It allows us to study action selection at a higher or more general level, within the context of two agents in a very unique relationship. Typically, one in which, where one agent wins, the other will invariably lose. This may affect the demands for (and guide the design of) the agents and action selection mechanisms themselves, especially as the relationship is characterised by a dependency of one on the other i.e. predator is dependent on prey. Admittedly, prey might also be said to be dependent on predator. For instance, at the population level, to avoid over-population. Yet such dependency is likely to be much more indirect. This thereby makes the balance of opportunity cost and stakes for each agent in any interaction unequal. Where predator loses a meal, prey loses its life.

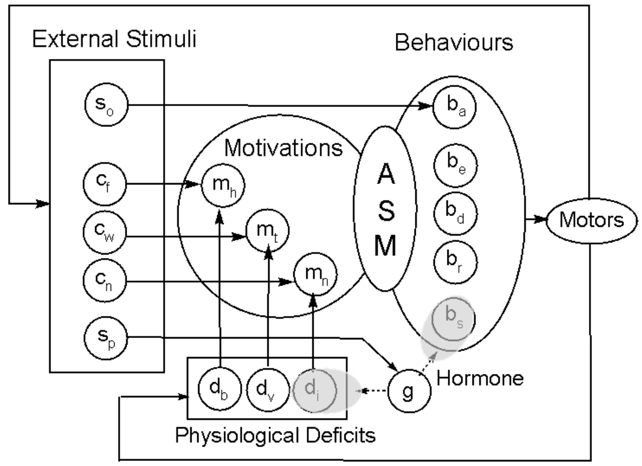

Figure 2: Overview of our developed architecture ("brain") for a prey agent: internal "body" is represented through physiological variables, deficits of which act as drives which, combined with the presence/absence of external stimuli, are used to calculate motivational and behavioural intensity. For example, calculations of motivational intensity for a motivation representing hunger will take into account both physiological deficits such as blood sugar and the presence/absence of food in the environment. In our experiments we vary external "body" using different physical sensors. Emotion-like states are modelled by the addition of a gland (g); releasing a "hormone" in the presence of a specific stimulus (in this case the predator) which affects both perception of internal physiological deficits, increasing calculations of motivational intensity, and the behaviour selected in terms of physical response (speed or tempo of behaviour is increased if hormone is present)

- It provides us with (if nothing else a wealth of biological) inspiration for building action selection mechanisms both a) capable of dealing with situations of high and immediate risk (used by prey) and b) capable of adapting to another agent's behaviour (environmental dynamics) for the agent's own advantage (used by prey and predator). It is also a problem that may call for compromises, increasingly specialised or more adaptive behaviours and, more specifically for us, interesting trade-offs. Namely, between the basic choices for the prey of whether it should flee or not, and for the predator of whether it should attack/hunt or not. Somehow, these agents must be able to effectively weigh up and make these decisions in the limited time available.

- It allows us to focus on the interactions that result between (the action selection mechanisms of) two agents with different sensory abilities, brains, bodies, motivations, possibly emotions (especially at the time of interaction) and behavioural repertoires. Starting our own "arms race" between such agents, we can develop and fine-tune features of these agents to enable one to gain an advantage over the other. This could not only produce and drive the production of increasingly more adaptive agents, but also lead to a better understanding of the (different types of) predator-prey relationship(s), as well as the circumstances when certain components of action selection mechanisms might be most adaptive.

- It allows us to look in more detail at the requirements for adaptive behaviour in this context. For example, it allows us to ask whether a predator needs more "brain power" than its prey in order to be able to catch it, or simply different types of behaviours and abilities. Similarly, it allows us to explore those ways in which we might increase or examine the adaptive value of predator and prey action selection mechanisms. This could include the use of methods across disciplines. For instance, we might analyse developed prey agents' behaviour in a similar way to Cooper's lizards: in terms of the assessments of risk or cost-benefit analyses that he suggests can be used to explain their behaviour.

Our Research

Driven by these interests, we have been using our robotic predator and prey to develop and explore the adaptive value of emotion for emotion-based architectures (see Figures 1 and 2). Both to gain insights as well as explore (test) links between concepts of emotion, action selection, adaptive value, dynamic environments, the brain-body-environment and predator-prey relationship. Adopting a bottom-up approach, we introduce emotion-like states using a mechanism that simulates the effects of neuromodulation (albeit at a more abstract level than that of the neuron). What is particularly attractive about this mechanism is it can be used as secondary controller to an existing architecture.

Broadly, we look to see under what conditions our emotion-based architectures (especially those implementing our chosen mechanism) prove adaptive for agents. We believe a systematic study, in the context of the H3RP, will increase our understanding of the adaptive value and potential of this mechanism. Not only in terms of action selection, but in terms of predator-prey scenarios. Our mechanism was chosen primarily because neuromodulation has previously been noted as a possible "substrate of emotion". And it is within this general framework that we formulate our more concrete experimental research question(s).

Experimentally, this has led to an attempt to identify factors affecting the adaptive value of the mechanism simulating neuromodulation. Both as a proposed substrate of emotion and biasor of action selection, in the predator-prey scenario. However, we are interested not only in what this will tell us about the possible adaptive value of emotion, but also its likely link to and dependence on properties of a given body and environment (implementation or task[s]) [O'Bryne et al. (2009)].

More specifically, we ask how changes in the physical (e.g. sensory-perceptual and motor-behavioural) abilities of predator and prey agents interact to affect the balance or dynamics of their relationship. The abilities we aim to study have primarily included the distance into the agent's environment information about stimuli can be obtained. We are not only interested in such relationships in terms of the advantage of one over the other in given encounters i.e. who "wins", but more importantly the behavioural interactions and adaptive value of the mechanism simulating neuromodulation.

In the context of brain-body-environment interactions [Chiel and Beer (1997)] we think such questions are interesting. Not only are we explicitly exploring the importance of certain specific aspects of body in producing adaptive behaviour. But we are also considering their importance for the successful integration of emotion and emergence of specific, adaptive behaviours within a predator-prey situation. Looking not only at what kind of role emotion might play with regards to brain-body-environment interactions, but also how the presence of another agent (prey or predator) might concurrently affect and direct this relationship or interactions.

To put this another way, we ask what will happen to the dynamics of a predator-prey relationship when sensory capabilities, including perceptual distances, are varied. We want to know what will happen in terms of physical and behavioural advantage, as well as the consequent adaptive value, of a mechanism simulating neuromodulation (as a biasor of action selection).

A Comparison with other Emotion-Based Architectures

To give an idea of where we place our work and architectures in relation to that of others, as well as to give an overview of related literature, it might be useful to conduct a quick

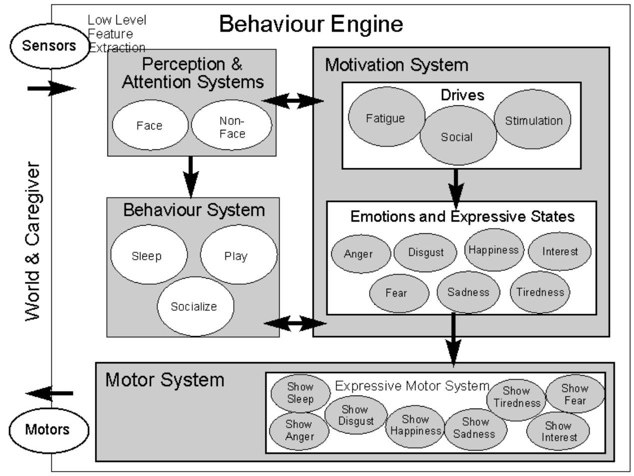

Figure 3: Illustration and overview of Breazeal's architecture for Kismet: Incorporating ideas about different types of emotions and connecting them to different motor responses (emotional expressions) [Breazeal and Scassellati (2000)]

comparison of different types of emotion-based architectures. Specifically, those which have also been implemented in robots. Here we look to do so in order to effectively, albeit briefly, contrast our work with that of three other researchers: Breazeal, Arkin and Avila-García.

We chose each of these researchers and their architectures for different reasons: Breazeal [Breazeal and Scassellati (2000)] provides us with a "classic" architecture for comparison, Arkin [Moshkina et al. (2009)] with a relatively recent addition (TAME being the "state of the art" in the history of his work) and Avila-García's work [Avila-García (2004)] is in many ways closest to our own. Such similarity makes it important for us to identify the ways in which our approach and architectures differ.

So as to get more of an overview of the differences between them, we will look at these researchers' research in reasonably broad terms, using some simple criteria. We do so here in the context of how each of these researchers treat or incorporate ideas about emotion in their architectures; what their primary motivations are, including the problem or domain of interest studied; and what they consider adaptive action selection to be (i.e. their measures of adaptive value).

Function and Integration of Emotion

Illustrations of the types of architecture produced by each researcher, including our own, are produced in Figures 2-5. First, we should look at how each one sees "emotion" in this context i.e. their ideas as to the function and integration of emotion for action selection mechanisms. As can be seen from Figure 3, Breazeal's architecture explicitly introduces emotions as a subset of motivations. Ideas about the function of emotion as being communicative are incorpo-

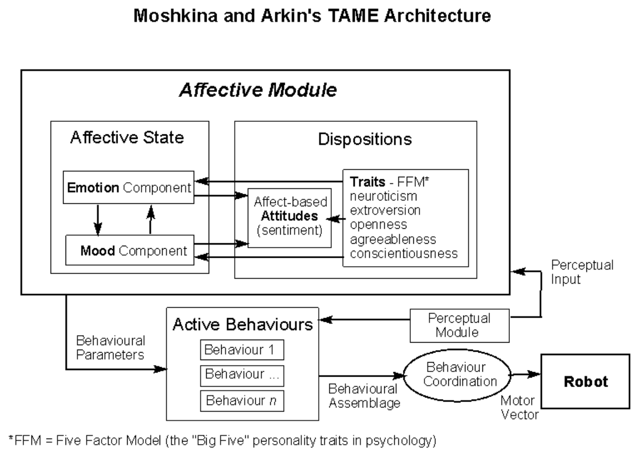

Figure 4: Illustration and overview of Moshkina and Arkin's TAME Architecture: Incorporating ideas about and explicitly modelling personality and emotion using concepts connecting Traits, Attitudes, Moods and Emotions - each of these varying in their temporal effects and influence on each other [Moshkina et al. (2009)]

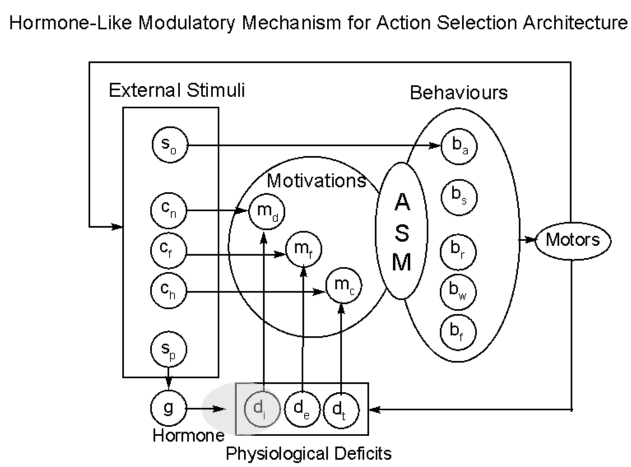

Figure 5: Illustration and overview of Avila-García's hormone-like modulation of an action selection architecture: Emotion-like states are modelled by the addition of a gland (g); releasing a "hormone" in the presence of a specific stimulus (in the case of his predator-prey scenario, the H3RP, the predator) which affects both perception of internal physiological deficits, increasing calculations of motivational intensity: concentration decays over time [Avila-García (2004)]

rated through the modelling of emotional expressions (the "actions" selected by her implemented robot Kismet) and internal "emotions" are used to activate a robot's physical expression at any given time.

Contrastingly, from Figure 4, we see that lately Arkin has been contributing towards the development of a different kind of architecture. The TAME architecture introduces and incorporates emotions in a more "sophisticated" model, where emotion is treated as one of a number of affective phenomena to be explicitly modelled (traits, attitudes, moods and emotions). Similarly to Kismet, the robots (AIBO and Nao) in which TAME has been implemented have used emotion in a communicative context. This is in contrast to some of his earlier architectures, looking "up the food chain", which were generally based on the ideas of his earliest architecture (AuRA) and also looked at other possible functions of emotion (non-communicative) for individual, autonomous agents.

With more relevance for our own work, Figure 5 presents one of Avila-García's architectures. This is where we most closely align ourselves with regards to the function and integration of emotion. This is because, in his architecture, Avila-García does not explicitly label any one component as "emotion" (something we also advocate). Instead, we both prefer a more bottom-up approach: trying to model one of the suggested neural "substrates of emotion". Namely, neuromodulation [Fellous (1999)]. We do this in order to examine the emergent properties of a system, which may consequently resemble the "emotion-like" behaviours of real-life adaptive agents.

Thus, we have both attempted to simulate the effects of neuromodulation for the benefit (adaptively) of action selection mechanisms. In addition, at a level of abstraction which has resulted in the development of hormone-like mechanisms ("hormone-release" occurring in the presence of relevant external stimuli) which affect action selection over time. In particular, Avila-García examined different ways in which such a mechanism can act as a biasor of action selection, modulator of perception (both interoception and exteroception) and "second-order controller" for existing architectures (in this case a motivation-based one).

However, one way in which our currently developed architecture differs, is that we try to integrate this kind of mechanism more pervasively or intricately with the rest of our architecture. As Figure 2 shows, we have linked our hormone-like mechanism not only to calculations of motivational intensity, but also the intensity of behavioural response. To give an example, in recent experiments, this has translated into an implementation of a prey agent that, when its "hormone level" increases, so too does its physical speed. Thus, we use this "substrate" not only to modulate perception, but to influence behaviour more dynamically and physically, in terms of factors such as time.

We think this has the advantage of effectively making "short-cuts" or more direct links between a perceived external stimulus and physical response or readiness of action, which may especially help in the problem of allocation of limited "energy" resources. Moreover, we go further to consider the interactions between two agents (and their architectures) rather than looking at one individually (though this is not explicitly illustrated in Figure 2).

Problem or Domain of Interest

Next, we would like to turn to and compare the particular areas or "problems" that these architectures, or their implementations, have been designed to study or solve. We attempt to do so here with regards to each researcher's particular contribution to the study of action selection, reflected in the implementations each researcher has developed, as well as the particular context (environment/scenario/task) it has looked at the role of emotion or emotion-like states in. In this way, we can also examine some of the features of action selection that each focuses on.

Whilst each architecture can itself be considered a contribution to the action selection literature, and all have been implemented in robots which is especially appealing, they have each been implemented for quite different purposes and in quite different environments: Kismet to model social interactions between infant and caregiver (thus human-robot interactions); Arkin's TAME to model affect more sophisticatedly for human-robot interaction; Avila-García's to test the properties of architectures across different types of environment/scenarios (only one of which includes a predator-prey type scenario); and ours to study action selection within a very particular context and relationship (predator-prey) in order to examine brain-body-environment interactions.

First, in more general terms, we can say that the primary implementations of both Breazeal's and Arkin's architectures have been in the area and interests of human-robot interaction. The robot head Kismet is Breazeal's result and TAME has been implemented in both Sony's AIBO dog and the humanoid Nao. While this is of course an extremely relevant and interesting area for the study of the role of emotion (particularly with regards to communicative functions and interactions) what sets such architectures apart for us is that they are designed to say as much, if not more, about our own emotions and interpretation of other agents' (robots) behaviours. That is to say, they may reveal more about us and less about the adaptive value of emotion for the robot.

We regard this as bringing a dimension to their work that we currently prefer to leave out of our own, in favour of focusing our study more exclusively on artificial agents. One of the advantages of a synthetic approach is that we can study the interactions resulting between two agents we already know the exact internal workings of. Introducing a human participant negates this as we do not know the exact workings of such an agent. Thus, we are less concerned with their impact on our own (human) behaviours and perceptions of them as agents (though of course we may always inadvertently introduce our own bias as researchers if we are not careful in how we study them).

Avila-García similarly goes a different way to Breazeal and Arkin. He implements his architectures across different scenarios, also using LEGO robots (Taurus and Sador being examples of these). However, he focuses instead on developing ways to quantitatively and qualitatively measure these implementations as individual adaptive systems, to identify their specific properties in different contexts. He considers other agents solely with regards to how they may add to the environmental dynamics, and possibly environmental complexity (rather than as an agent in a partnership or some kind of artificial ecology, which can affect and be affected by other agents).

By not focusing on one particular problem, Avila-García was able to look at the properties of architectures, in particular arbitration mechanisms, across different scenarios. He developed several types of scenario for the study of action selection, including a robotic two-resource problem; competitive two-resource problem; and hazardous three-resource problem (H3RP). Yet, even in his predator-prey type scenario (the H3RP) action selection did not involve situations of such high risk as might be expected of such a relationship. This was due to his development of a more "parasitic" type of predator-prey relationship (allowing his agents some leeway in choosing to change activity).

This does not mean that we do not want to, or do not aim to contribute towards developing ideas that may also be of use to these other domains of interest. More, we think by focusing on our particular scenario now (that of predator-prey) we will be able to bring something particularly special or unique to the problems of these other architectures later. Currently, for instance, all three of these other architectures, when you consider the implementations, do not seem capable of producing adaptive behaviour in situations where both the two-way relationship between two agents is accounted for, and the right decision or action selection is vital for agent survival i.e. studying both agents in high risk situations.

What is primarily different about our own motivation then, is with regards to the kinds of decision and environmental demands we want our architecture to deal with. This includes situations where there may not be enough time or flexibility to allow for mistakes or trial-and-error learning; instead requiring split-second judgements. More to the point, we want to study the predator-prey scenario for a much more in-depth look at this kind of relationship, where a predator is not just an environmental dynamic.

For example, if a robot were to identify another agent as a predator, we would like to see our robot's emotion-based architecture capable of using its "fear" to better make those split-second decisions that will direct action selection towards the agent's own survival. This could involve some means of "fleeing" the scene, but might even involve our prey robot staying to "brave" it out or "defend" its position or resources. More, we also want the robot predator to be able to adapt to such behaviour, somehow weighing up the situation in the limited time available to better direct action selection.

Finally, another difference can be seen in the type of intelligence or adaptive behaviour studied. For example, Breazeal and Arkin can be said to study action selection and emotion more focused on ideas of human-level intelligence and emotions (though Arkin has in fact previously developed ones he suggests demonstrate a lower, more insect-like intelligence). Once more in common with Avila-García, in contrast we attempt to create simpler creatures for study. For example, considering these concepts more in terms of animal-like mechanisms of adaptive behaviour and intelligence.

While Arkin has previously studied architectures aiming towards insect-level intelligence (incorporating and developing ideas about motivation and emotion), in "moving up the food chain" [Arkin (2005)] it does appear he left a somewhat expansive gap between the level of insect and that of animals. Using our bottom-up approach, this is where we would like our work to fit. Between the reactive architecture he attributes to an insect; and the more deliberative architectures he chooses for those interacting with humans.

Measures (of Adaptive Value)

Finally, we can also compare researchers in terms of the level of analysis and criteria each expects will be used to measure the adaptive value of their architectures in a given implementation. Without going into unnecessary detail, perhaps due to their interest in human-robot interaction, in this respect both Breazeal and Arkin can be said to have focused on the use of both internally and externally-derived measures i.e. measuring, for different purposes, both external effects of their robots' action selection on human response; and the internal parameters of the system or architecture over time. When involving observations, this is often a lengthy process with regards to analysis, but has the benefit of allowing us to directly study interactions between humans and robots.

Conversely, Avila-García's architectures were studied placing focus mainly on the use of more internally-derived and summarative measures. He developed measures of analysis that consider the viability of agents over an individual life span (presumably choosing this as the correct level of analysis to study adaptive value). But, just as interestingly, Avila-García also considered and suggested action selection be studied in terms of activity cycles rather than separate decisions. Similarly, we would like to consider how analysis of behaviour over time might bring us more insights into our architecture's behaviour in different predator-prey scenarios.

In our work though, perhaps more in common with Breazeal and Arkin, we try to combine the use of both externally *and* internally-derived measures for studying the performance of our agents. We also attempt to go further, for a more comparative look. One of our primary concerns is thus to ask at what level of study we will find out most or understand our systems best. Especially with regards to what one might consider adaptive value to be (and in terms of brain-body-environment interactions). In this way we again seek to bridge the gap between these architectures, this time in respect of the level their researchers have proposed we analyse them at.

One source of inspiration for us in this endeavour again comes from another discipline: ethology. Though dynamic systems theory has developed tools to study the interactions of dynamic systems, we use the analogy of animal-like behaviour to suggest that the ethologists have already developed many tools to be used in the analysis of our animat agents. In particular, many of these methods allow us to combine both considerations of internal and external data (as derived or collected from experiments).

Contributions

Having considered our own research using such criteria, the contributions we therefore hope our work will make, especially towards the literature on action selection and emotion (or affect) include:

For "Affective" Action Selection:

- Further development of our architectures and implementation. In initial experiments, we divided perception into proximal and distal types (combinations of which making further sub-problems or versions of the H3RP). This enables and hopefully justifies direct comparison, especially in terms of the interactions of different physical properties of predator and prey, with previous findings using the same framework (such as Avila-García's). At the same time, it introduces a new dimension for study (an aspect of embodiment, in this case perceptual field or "sensory ability"). Such a comparison will, for example, enable us to identify aspects of the original scenario that may be crucial for the success of our proposed emotion-like mechanism.

- A more systematic study of the predator-prey type relationship than has been conducted yet in the action selection literature with regards to affect. For instance, looking to see the *minimal* conditions under which our chosen mechanism (or emotion in general) might be adaptive. Both with regards to the capabilities of our agents' "brains" and "bodies", as well as features of the environment: varying both abilities of predator and prey. For, while others have looked at the role of emotion in the predator-prey scenario, they do not necessarily know or have not necessarily taken into consideration how their mechanisms or emotion-based architectures might work, or be developed to work, in increasingly more dynamic environments. Or with different types of embodiment.

- An analysis of costs and benefits of both emotions and decisions in the predator-prey relationship. Looking at neuromodulatory effects as the basis for emotion, when used in different ways for agents (such as aggression for predator, fear for prey). But, in addition, also looking at action selection mechanisms more in terms of trade-offs. So, examining mechanisms as assessors of risk or opportunity cost: quick or rough-and-ready filters for behaviour and representations of the importance and limited nature of time. Looking at action selection in terms of a trade-off, between the time taken to decide and time taken for environmental circumstances to change adversely, temporally-adaptive responses may follow.

For Analysis of Adaptive Systems:

- A comparison and evaluation of measures of adaptive value (both quantitative and qualitative) that might be adopted. From internal measures of viability from examination of an individual agent, to Markov Models constructed from external observational data (by adopting the idea of activity cycles, thereby looking to analyse temporal behaviour of agents rather than simple life span etc).

- An analysis of the action selection problem in terms of the brain-body-environment relationship. Taking a broader look at action selection, so as to be asking whether we should actually be looking at the architecture alone in isolation, or whether we find out more by considering elements together. For example, considering both architecture and body, predator and prey, together, rather than individually. Moreover, looking at how (more realistic) two-way interactions may affect the performance of architectures and where emotion might fit in the relationship.

For System Design:

- A demonstration of how we might manipulate or adjust parameters so as to better "fine-tune" our mechanism and increase its value for adaptive action selection in this context (of the H3RP and predator-prey relationship). In particular, looking at how we might benefit from further distributing control and neuromodulatory influence across both agent architecture and agent body (as generators of brain-body-environment interactions).

We suggest that together these contributions will enable us to make an altogether much more comprehensive, perhaps even synergistic, contribution to the literature regarding action selection. Not only linking concepts such as action selection and emotion to the predator-prey relationship and brain-body-environment interactions; but, in turn, highlighting their more general contributions to the more intelligent design or creation of artificial life.

Acknowledgements

Funded by UH Studentship

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