Evolving Action Selection and Selective Attention Without Actions, Attention, or Selection.

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Abstract

A minimal animat architecture, consisting only of a set of autonomous, direct, and continuously active sensorimotor links, is shown to support a full range of 'action selection' phenomena. A genetic algorithm is used to engineer the activation functions supported by these links. No 'actions' are 'selected' in this model, and the use of artificial evolution means that there is no artificial separation of the problems of 'link design' from 'link fusion'.

Implications are drawn for how the concepts of 'action selection' and 'selective attention' may relate to the idea of coherence between sensorimotor processes.

1. Introduction

In order to survive and prosper in a dynamic and complex world, animals and animats need to engage in a variety of different behaviours at different times, at least some of which will be mutually incompatible. The problem of how, at any given time, they come to be doing one thing rather than another, is traditionally known as the *action selection* problem (hereafter referred to as the AS problem). Approaches to this problem, both in ethology and in autonomous agents research, generally assume the need for internal arbitration mechanisms to select the most appropriate action or behaviour according to internal and external conditions (Tinbergen, 1950), (Tyrell, 1993).

This paper argues that internal arbitration between behaviours is *not* the right way to view the AS problem. Instead, a scheme based on the coherence between continuous and concurrent sensorimotor processes (or links) is recommended. This scheme is inspired by (Braitenberg, 1984), and has already been shown to be viable by (Lambrinos and Scheier, 1995), see also (Scheier and Pfeifer, 1995), (Steels, 1994).

A novel methodology is adopted in this paper, in which artificial evolution is used to shape the activation function employed by the sensorimotor links. This methodology allows a minimal internal architecture to support a full range of AS phenomena, and avoids some potential problems associated with hand-design (discussed in Section 2.3).

Section 2 rehearses the theoretical background for this approach. This is based on two shortcomings common to many AS models. First, a confusion between behavioural and mechanistic levels of description, and second, a disregard for perception.

Section 3 describes the animat model. The architecture of this animat consists merely of a set of evolved, direct, sensorimotor links, without any interconnections. The animat exists in a continuous simulated world in which it must avoid 'traps', whilst periodically visiting 'food' and 'water' sources. Section 3 also presents the results from this model,which are discussed in Section 4, with special emphasis laid on how the AS problem and the 'selective attention' problem are related. Finally, Sections 5 and 6 describe further research in this direction, including robotic experiments, much of which is underway, and set out the conclusions to be drawn from the present work.

2. Theoretical Background

2.1 Behaviour

This paper considers a behaviour to be a joint product of agent, environment, and observer. For example, 'swimming' requires more than 'limb movement' and 'immersion in water'. It also requires an observer to classify these interactions as 'swimming', since a different observer may classify the same set of interactions in a different way ('underwater yoga', perhaps).

2.2 Behaviour and Mechanism in Ethology and Animats

Ethology is the study of animal behaviour *in situ*, and therefore one widely held ethological perspective accepts that behaviours are the product of continuous agent-environment interactions. This can be a very valuable perspective, but its value, in ethology, is tempered by the way in which much ethological theory generally assumes that entire behaviours have internal correlates. For example (Tinbergen, 1950), (see also (Lorenz, 1985)), proposed an early solution to the AS problem in terms of a hierarchy of 'behaviour centres', animated by the flow of some unspecified 'activation energy'. In each case, these 'behaviours', such as feeding, fighting, and so on, were clearly assumed to have direct internal correlates. However, behaviours are, as argued in the previous section, the products of environment-agent-observer interactions and so the agent-side (internal) component of behaviour cannot be identical to the behaviour itself[1].

Many recent models of AS employing animats employ the same premises, and concentrate on designing internal architectures for animats which arbitrate between internal correlates of entire behaviours. For example, (Tyrell, 1993) extends Tinbergen's fixed, winner-take-all hierarchy of behaviour centres to a 'free-flow' hierarchy (one that does not obey a strict winner-take-all rule), demonstrating an improvement in the efficacy of the mediation between behaviours of the animat concerned. However, the constituents of his hierarchy are still entire behaviours, such as 'avoid hazard' and 'find food'.

In a different example, (Maes, 1991) argues that 'behaviour selection emerges in a distributed fashion by parallel local interactions among the behaviours and between behaviours and environment'. Whilst Maes brings to light the importance of agent-environment interactions, she too works from the assumption that behaviours can be *parts* of agents, instead of agent-environment-observer interactions.

Behaviours, and any apparent selection between behaviours, should therefore *not* be explained purely at a behavioural level, but at a more mechanistic level.

2.3 Perceptual Deprivation

As (Maes, 1994) points out, AS models in general 'have a narrow-minded conception of the relationship between perception and action'. This situation persists despite a now general acceptance that action and perception should be considered jointly, as a part of an ongoing cycle of agent-environment interaction, (Ballard, 1991). What an agent is perceiving, or 'attending to', is likely to strongly influence what behaviour is appropriate. And similarly, the kind of behaviour currently being engaged in, will itself influence what features of the environment are worthy of perception and attention (the relationship between AS and selective attention is discussed further in Section 4).

Ethological study, taking place in natural environments, is not ideal for investigating the role of perception in behavioural control. Animat perception, on the other hand, is readily accessible. Nevertheless, most AS models do not extend to a satisfying incorporation of perception. In (Maes, 1991) perceptual variables are constrained to hold only predicate values. And (Tyrell, 1993) writes :

> It was decided that the small amount of added realism [from considering the perception of the animat] was not worth the large amount of extra time it would have taken to include[2].

This paper contends that the role of perception is essential in any explanation of AS that goes beyond assuming internal arbitration between behaviours. It contends that a mechanistic level of explanation should be grounded in terms of sensorimotor interactions with an environment, which are then observationally classified into behaviours, and into 'selection' between behaviours.

2.4 Action Selection through Sensorimotor Coherence

The position taken in this paper is as follows. The control of multiple behaviours is best understood in terms of the coherence of autonomous, and continuously active, sensorimotor links, or processes[3]. Action selection (and selective attention) are misleading interpretations of the general problem of coherence between these processes.

(Lambrinos and Scheier, 1995) propose a similar perspective, and describe an experiment in which a Khepera mobile robot is able to achieve a successful balance between collecting pegs, bringing the pegs to a 'home base', and periodically visiting a 'charging area'. This balance is achieved through coordination between several hand-coded, continuously active, sensorimotor processes. This work is a valuable step forward, and has the virtue of being demonstrable in the real world.

The present research differs in the following ways. First, the task environment, although not real-world, is sufficiently flexible to allow the investigation of performance according to a list of AS *desiderata* (fully described in Section 3). Second, the use of artificial evolution to design the sensorimotor processes allows the distinction between behaviour and mechanism to be rendered completely explicit. In (Lambrinos and Scheier, 1995), the reliance on hand-coding requires the artificial separation of the problems of process design (what each individual process should do) and process fusion (how to combine these processes to deliver coherent behaviour). If these problems are separated, then each sensorimotor process can potentially be considered in terms

[1] Of course, ethologists in the field have no direct access to the internal state of the organisms they study, and so, in the past, have had little alternative but to impute arbitrary behavioural primitives (see (McFarland and Sibly, 1975)). Nevertheless, ethological theories certainly have great predictive and comparative value, and have largely underpinned our understanding of behavioural *function*.

[2] Indeed, Tyrell's simulated environment is a discrete 'grid' world. This immediately constrains any possible role for perception to the rather trivial.

[3] The difference between a 'link' and a 'process', as used here, is that a 'process' is employed as a general term for a sensorimotor connection which may include intermediate stages, and a 'link' is specific to the present model, in which the connection consists of just one single transfer function.

of an eventual behaviour to be subsequently 'fused', and indeed their processes carry the names 'go-to-station', 'home' and so on. Although there is no explicit arbitration between these processes (they are all autonomous and concurrently active) there is still a certain tension between their affirmation that behavioural and mechanistic levels should not be confused, and this potential influence of behavioural descriptions on the design of the internal mechanism. The use of artificial evolution avoids this problem by allowing process design and process fusion to proceed concurrently, providing no scope for any influence of behavioural description over internal mechanism.

3. An Animat Model

The animat consists solely of a set of direct, autonomous, sensorimotor links, with no interconnections or 'artificial neurons'. Artificial evolution is used to specify the activation functions supported by the links. All of these links are active all the time.

The purpose of this model is to illustrate how such a minimal architecture can satisfy the requirements generally expected from an AS mechanism. To assess the quality of the model, we consider a list of such requirements, originally collated by (Tyrell, 1993), and expanded by (Werner, 1994) (more comprehensive versions of this list, which is admittedly somewhat arbitrary, can be found in either of these publications). Explicit tests for these properties are performed wherever possible.

An effective AS mechanism should:

- Prioritise behaviour according to current needs: for example, head for food if hungry, but don't fall into traps on the way.
- Allow contiguous action sequences to be strung together.
- Exhibit opportunism; for example by diverting to a nearby food source even if water is needed more.
- Balance dithering and persistence; for example, by drinking until full and then eating until full instead of oscillating between food and drink.
- Interrupt current behaviour; for example, if a trap suddenly appears, the animat should change course to avoid it.
- Deal with all subproblems; the AS mechanism should cope effectively in all situations.
- Prefer consummatory over appetitive actions.
- Use all available information (both internal and external).
- Support real-valued sensors and produce directly usable outputs.
- Be extensible and support learning.
- Allow 'parallel actions' to be executed (for example, walking and talking).

3.1 The Animat and Environment

The architecture of this animat was inspired by (Braitenberg, 1984), and is illustrated in Fig 1. It possesses two wheels, and three types of sensor, with one of each sensor type each side (giving a total of six sensors). There are three links from each sensor to the wheel on the same side; thus a total of nine links on each side.

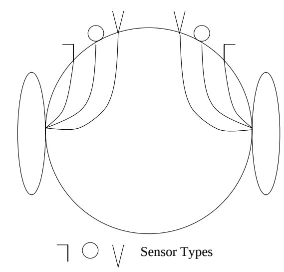

Figure 1 *Architecture of the animat: there are three sensor types, with each sensor connected directly to the wheel on the same side. Each illustrated connection actually comprises three genetically specified links, so the animat consists of 18 concurrent and direct transformations of sensory input into motor output.*

The animat also has two internal batteries which it must maintain at as high levels as possible. These levels diminish at a steady rate as long as the animat exists, and if both reach zero the animat 'dies'.

The links between the sensors and the motors simply transform the sensor input signal (ranged from 0-100) into a given output signal (ranged from -1 to 1) according to a transfer function (which can also be modified by battery level; see Section 3.2). The outputs from the links are combined at the wheels; the first 9 link outputs are summed, passed through a sigmoid function, and then scaled from -10 to 10 to set the left wheel speed. The links numbered from 9 to 18 are treated in a similar way to determine the right wheel speed.

The simulated environment is a continuous (in space, but not in time) unbounded area within which three types of object can exist, in addition to the animat. Each object is a circle, 16 units in radius (the animat is 5 units in radius, and all objects appear within a 200 by 200 unit area of the environment). The first object type (let us call this 'food') replenishes the animat's first battery level; the second type ('water') replenishes the second battery; and the third type ('trap') is dangerous, and will 'kill' the animat, if encountered. There are three instances each of food and water, and nine traps.

The three types of sensor respond to the distance from the nearest object of each type to the animat, with each sensor linearly ranging from 100 (at the source), to 0 (200 units or more distant). If an object is to the left of the animat, the relevant left sensor will respond with 20 percent greater activation (and *vice versa* if the object is to the right).

At the start of each trial, the objects and the animat are placed randomly within the environment (within a 200 by 200 unit range). The movement of the animat is then calculated on the basis of the changing wheel speeds (if both wheel speeds are set to +10, then the animat moves forward at a maximum speed of 2.8 units per time step). Each battery has a maximum (and intial) level of 200, which decreases by 1 each time step. If the animat encounters a food or water object, the appropriate battery level is restored to 200, and the object is replaced at a different random location. An encounter with a trap ends the trial.

3.2 Genetic Encoding Scheme

Each genotype consists of 83 integers in the range 0-99; thus 9 integers for each of the 9 links, and 1 each for the left wheel and right wheel sigmoid threshold values. Only 9 links need to be genetically specified since left/right symmetry is enforced. Figure 2 illustrates how the 9 integers for each link specify the shape of the activation function. The offset and thresholds are set by scaling[4] the 0-99 integer onto the range -100 to +100, with the restriction that the second threshold must follow the first. The gradients are set by scaling the integer to range from $-\pi/2$ to $\pi/2$, and then taking the tangent. The sigmoid thresholds are set by scaling on to a range from -3.0 to 3.0.

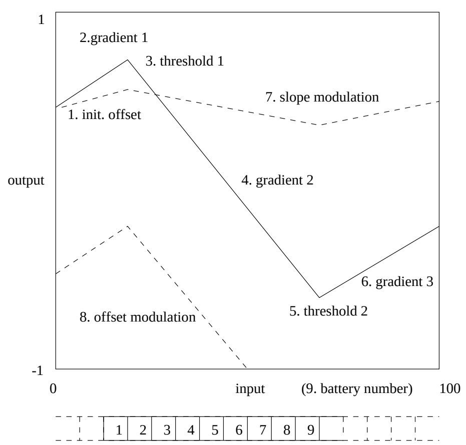

Figure 2 *Genetic encoding scheme: each sensorimotor link requires 9 integers to specify the various link parameters. The first 6 integers specify the basic shape of the activation function transforming the sensor input into an output signal, and the final 3 integers specify how this shape can be modified by a battery level. Each link can only be modified by a single battery (specified by integer 9), and the level of this battery can then influence both the overall gradient of the function (to a degree specified by integer 7), and the intial offset (to a degree specified by integer 8).*

The influence of the battery is slightly more complicated. If the ninth integer is even, then the function can be influenced by battery 1; if odd, then by battery 2. The relevant battery level ($\mathcal{B} \in (0:200)$) can affect two aspects of a function. First, through offset modulation ($\mathcal{O} \in (-1:1)$)):

$$out = out + ((\mathcal{B}/2) * \mathcal{O})$$

and second, through slope modulation ($\mathcal{S} \in (0:1)$) of the function:

$$out = out + (out * (((\mathcal{B} - 100)/100) * \mathcal{S}))$$

Note that there is no requirement that any given function, connecting a particular sensor type to a wheel, should be influenced by the battery corresponding to the object type that its sensor responds to.

3.3 The Genetic Algorithm

A distributed GA was employed, with a crossover rate of 0.5, and a per-bit mutation rate of 0.04. The population size was 100, and the fitness function simply rewarded high average battery level, calculated incrementally at each time step:

$$\mathcal{F} = (\mathcal{B}1 + \mathcal{B}2)/400.0$$

This function rewards animats that live long (by keeping at least one battery level above zero and avoiding traps), and that visit food and water sources as often as possible, up to a maximum lifespan of 800 time steps. It does *not* specify anything about what the animat should do in any particular situation.

Fit individuals evolved in about 200 generations (taking about 2 hours on a single user 143MHz Sun SparcStation). The results described in the next section are, however, drawn from the fittest individual of the 430th generation.

3.4 Results

The evolved animats displayed very effective AS behaviour. A sample trajectory is shown in Fig 3. The animat begins by navigating effectively through a series of food and water sources. At point 1, the threat of nearby traps is dealt with by backtracking and turning right towards some other food and water sources. At point 2, the animat displays opportunistic behaviour by visiting another nearby food source even though it had only just left a previous one. The animat then passes through another series of food and water sources before reaching its maximum lifetime of 800 timesteps.

Recalling the list of AS *desiderata*, the above example demonstrates the 'effective prioritisation of behaviour according to current needs', by generally heading towards the most needed type of source, without falling into any

[4] All scaling is linear.

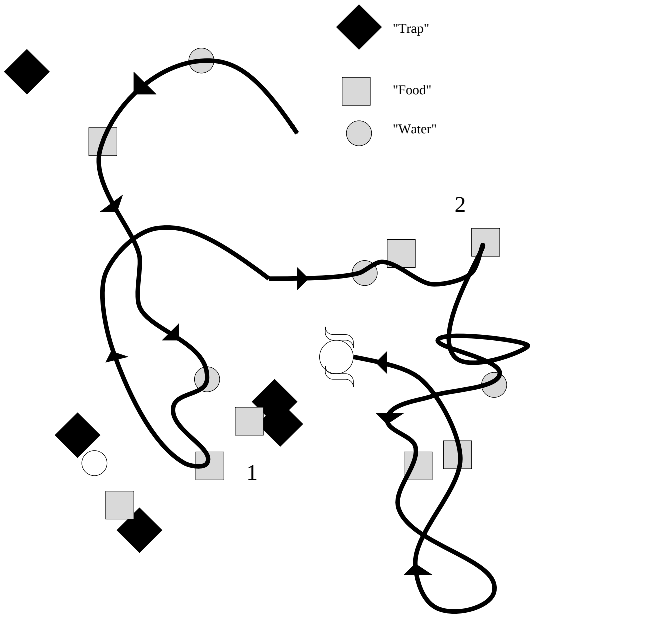

Figure 3 *A sample trajectory; animat passes through a series of food and water sources, backtracking to avoid traps at point 1, and displaying opportunistic behaviour at point 2.*

traps. The performance of 'contiguous action sequences' is illustrated by the way the animat moves smoothly from visiting one source to visiting another, and 'opportunistic behaviour' is also illustrated at point 2.

The following tests illustrate, more formally, that the evolved animat performs very well with respect to the requirements for effective AS:

A balance between dithering and persistence. In general, the animat would briefly slow down if equidistant between equally needed sources, before unequivocally plunging one way or the other. Fig 4 is a screen shot from a contrived situation in which the animat was placed equidistant from a cluster of 3 food sources (on the left), and a cluster of three water sources (on the right). Both battery levels were set at 100. The animat goes for the food first, and collects all three before returning for the water. The animat is therefore *persisting* at each task for an appropriate duration, rather than *dithering* between food and water collection.

Interrupts current behaviour if necessary. The animat was positioned at (0.0,0.0), with a food source at (100.0,0.0). Both battery levels were set at 150. As the animat approached the food source, and passed (30.0,0.0), a trap was suddenly introduced at (65.0,0.0). Fig 6a shows the trajectory of the animat as it changes course to successfully avoid the trap whilst still reaching the food. Fig 6b show the simple straight line trajectory traced by the animat if no trap is introduced, and Figs 6c and 6d illustrate the trajectory immediately before the trap appears, and immediately afterwards. The animat is clearly interrupting its direct navigation towards the food in order to avoid the trap.

Figure 4 *A balance between persistence and dithering; animat collects all 3 food sources (on left) before collecting all three water sources (on right). The animat does not 'dither' between the food and water sources.*

Furthermore, the degree of this interruption is dependent on the battery level. Twenty trials were performed at each of 10 starting battery levels, between 100 and 200. Fig 5 illustrates that with low battery levels, the animat could not avoid the trap, but as the battery level increased, the animat avoided the trap more often.[5] This phenomenon has been termed 'varying attention' (see (Maes, 1991) for an animat example); when needing food, the animat appears to 'pay less attention' to traps.

Opportunism. In addition to the instance of opportunism shown in Fig 3, a further controlled experiment was performed. The animat was positioned at (-100.0,0.0), with a food source at (-90.0,0.0), and a drink source at (30.0,0.0). An additional food source was placed with an x position of -20.0, and a y position varying from 0.0 to 30.0.

After collecting the first food source, the animat is more in need of water. However, should another food source be *en route*, the animat will opportunistically visit it (Fig 6e). If, however, the second food source is too far out of the way, it will be ignored (Fig 6f).

Twenty trials were performed at each of 8 different y positions of the second food source, and Fig 5 illustrates that as this source becomes increasingly out of the way, the animat diverts to it less frequently.

Prioritisation. The sample trajectory (Fig 3) illustrates that, in general, the animat will always head for the most needed source type. Figs 6g and 6h illustrates this more formally, with the animat starting between two sources, facing away from both. The animat has one battery level set to 150, and the other set to 100. If the sources are equidistant (Fig 6g), the animat will go for the most needed (the source to the left). But if that source is

[5] This test was especially difficult for the animat, there being only one food source in a direct line with a trap. In normal situations (see Fig 3), encounters with traps occurred rarely, if at all.

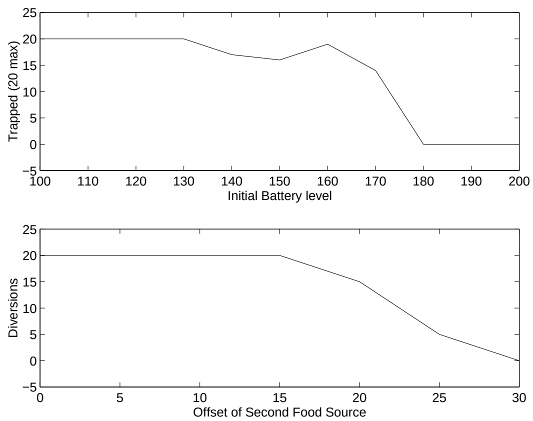

Figure 5 *Varying attention (top); the animat is more likely to fall into traps if it has a lower battery level. Opportunism (bottom); the animat will divert to collect a second food source en route to a water source, but does so less often as this second food source is placed increasingly out of the way.*

moved too far away (Fig 6h), then the animat will visit the source on the right instead. Thus the animat is striking a balance between prioritisation and opportunism.

Other Requirements. The remaining requirements for effective AS were not all applicable to this model, but are briefly discussed below:

– *Deals with all subproblems:* no particular subproblems arose other than evading traps, which the animat did very well.
– *Prefers consummatory over appetitive actions:* no distinction was made between the two in this model.
– *Uses all available information:* this is indeed the case, since all sensorimotor links are always influencing the motor output to some extent.
– *Has real valued sensors and produces directly usable outputs:* the animat consist of sensorimotor links and nothing else, so this is indeed true.
– *Allows parallel actions:* 'parallel actions' are undefined in this model.
– *Is easily extensible (perhaps through learning):* there is no reason why more sensors and effector types could not be added (perhaps to support 'parallel actions'), and 'learning' links could certainly be introduced.

4. Discussion

This model has illustrated that nothing more is required (under the conditions of this model) for effective AS behaviour than a set of independent sensorimotor links, and the influence of some internal state. In this model, a joint consideration of perception and action is paramount, and there is no arbitration between internally represented behaviours.

Fig 7 illustrates the shapes of the evolved activation functions for the links. All the links are influenced by one or other of the battery levels, even the links from the 'trap' sensors to the wheels. It is interesting to note that each set of three links is influenced by *both* batteries. That is, the 'food' sensorimotor links are not only influenced by the need for food, but also by the need for water. And the same applies for the 'water' sensorimotor links. This suggests the absence of any simple mapping from the behaviours 'get food', 'get water', and 'avoid trap' onto the sets of links. Indeed, there would be no reason to expect this to be the case. Thanks to the artificial evolution methodology, no distinction is made between 'link design' and 'link fusion', and so the internal mechanism need bear no relation to what may seem to be a sensible design strategy from an observer's point of view.

This work therefore advocates the position that action selection is not only not dependent upon internal arbitration, but also that it is not dependent on any kind of internalisation of behaviour at all. This has clear implications both for ethology and for animat research: theories of 'action selection' that assume the internalisation of behaviours may not be necessary, (and, as argued in Section 2, do suffer from some conceptual problems). Alternative perspectives that uphold the distinction between behaviour and mechanism, and that respect the inseparability of perception and action, are viable, and should be preferred. The relationship between the coherence of sensorimotor processes, and the observation of behaviours and behavioural 'selection' is one that invites further exploration in animat research.

It is also of interest that the overall behaviour of the animat could just as easily be described in terms of selective attention as in terms of AS. The animat appears to 'pay attention' to different features of the environment at different times, and indeed the term 'varying attention' given to the phenomenon recorded in Section 3.4 is perhaps a subtle recognition that the two problems are not different. Of course, in the present case the two problems are necessarily identical, since the presence of just a set of direct sensorimotor links precludes any distinctions being made between perception and action. All this is noteworthy since a substantial amount of work in cognitive science still considers selective attention in terms of a 'spotlight' designed to mediate between an external reality and an internal world model, with little consideration of the role of action (see, for example, (Treisman and Gelade, 1980))[6].

[6] This argument is in no way meant to invalidate this corpus of work. There is clearly an enormous gulf between the sensory apparatus of the present animat and the primate visual cortex, and psychology and neurology continue to contribute greatly to our understanding of the mechanisms involved in primate perception. All that is suggested here is that investigations into selective attention, in whatever

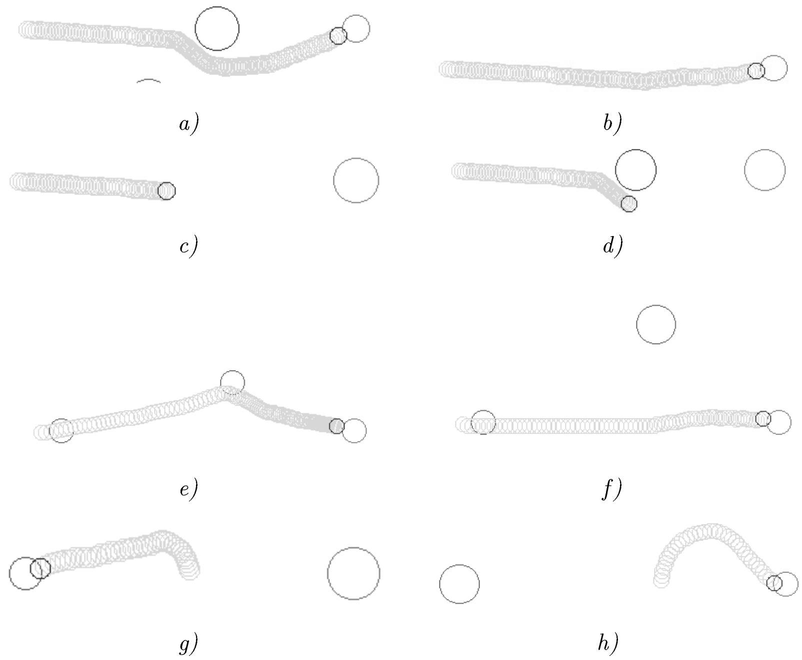

Figure 6 *Action selection tests; consumed sources appear as smaller circles; a) a trap suddenly appears, and the animat interrupts its progress towards the food in order to avoid it. b) with no trap, the animat progresses directly to the food source. c) trajectory of the animat at the point just before the trap appears... d)..and just after the trap appears. e) animat passes through a first food source, and will divert to a second food source (en route to water) if the diversion is not too far. f) if the second food source is too far away, the animat will proceed from the first food source to the water source. g) animat starts between two equidistant sources, and will head towards one needed most. h) if the 'most needed source' is too far away, then the animat will proceed to the other source.*

5. Further Work

A current project is to extend this methodology to real robots in real situations, with sensors that can no longer respond directly to the distance from a given object type. Artificial evolution will still be used to design the internal mechanism of the robots, since as the robots and the task demands become increasingly complex, the actual nature of appropriate sensorimotor processes is likely to be of considerable interest, as a way of understanding more about the relationship between behaviour and mechanism. If the sensorimotor processes are hand-designed, then this is harder to study.

6. Conclusions

This work has shown that a full range of action selection phenomena can be elicited from a minimal internal architecture, with neither explicit arbitration between internally represented behaviours, nor the hand-design of sensorimotor processes. The model is designed to make this theoretical point, and is not touted as the 'best' way of controlling behaviour in autonomous agents, even though it performs more than adequately in its context.

The novel methodology, of evolving the shape of each activation function, allows the design of each sensorimotor link to proceed concurrently with the fusion of all the processes into a coherent global behaviour. This avoids the potential influences of behavioural descriptions on internal mechanism that may arise in hand-designed architectures, where process design and process fusion are considered separately. Therefore it also allows the relationship between behaviour and mechanism to be the object of study.

Action selection behaviour is shown to emerge from coherence between autonomous, direct, and continuously active sensorimotor links. It is argued that just as the term 'action selection' is misleading through the disregard of perception, so the term 'selective attention' is misleading through the neglect of action.

domain, could benefit from a more detailed consideration of the role of action.

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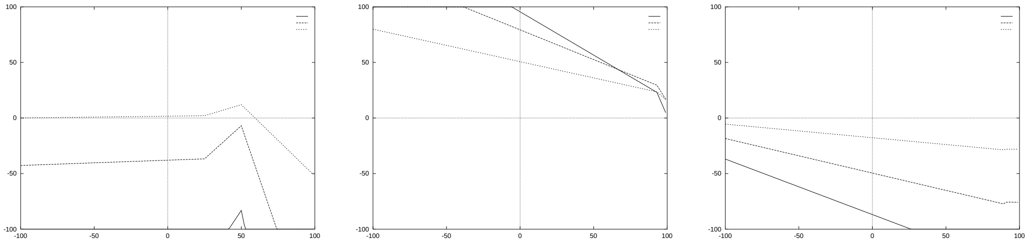
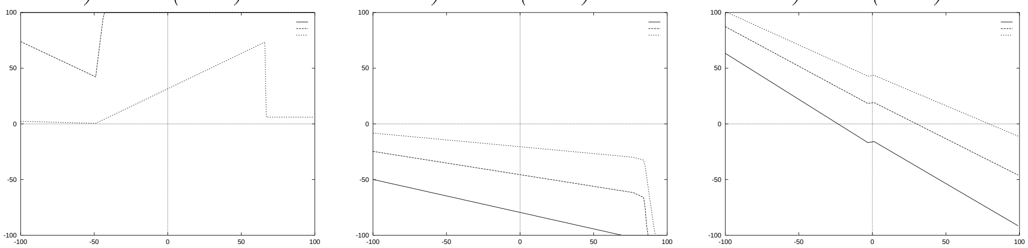
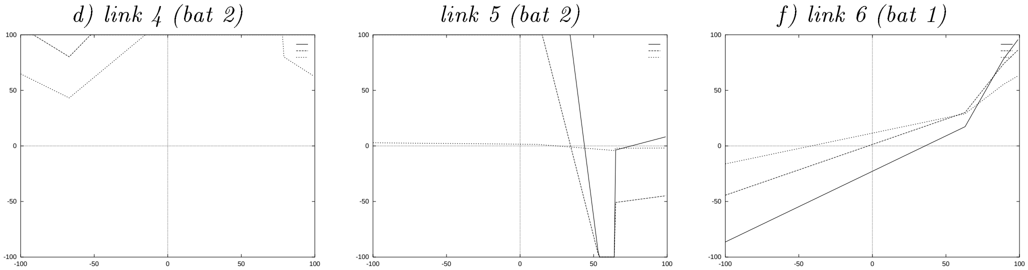


a) link 1 (bat 1) *b) link 2 (bat 2)* *c) link 3(bat 2)*



d) link 4 (bat 2) *link 5 (bat 2)* *f) link 6 (bat 1)*



d) link 7 (bat 1) *link 8 (bat 2)* *f) link 9 (bat 1)*

Figure 7 *Evolved activation functions; links 1-3 connect the 'food' sensors to the wheel, links 4-6 the 'water' sensors, and links 7-9 the 'trap' sensors. All axes are scaled from -100 to 100 (input along the x axis, and output along the y axis). The three lines on each graph represent the activation function at battery levels of 200,100 and 0, and the battery which influences the function is shown in parentheses. All these links are active all the time. Note that each set of three links is influenced by BOTH batteries, and contains a mix of excitatory and inhibitory outputs.*

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