Arousal and Awareness in a Humanoid Robot

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Abstract. We describe how an arousal system that controls the levels of awareness can be implemented in a robot. The different levels of awareness correspond to different states of consciousness and we argue that an artificial arousal system modeled after its biological counterpart has a useful function in controlling the cognitive processing of a brain-like cognitive architecture. The level of awareness depends on arousal that in turn is controlled by novel or emotionally charged stimuli as well as by a circadian clock. Arousal is also modulated during cognitive tasks to control the randomness of decision processes and to select between exploration and exploitation.

Keywords: arousal · locus coeruleus · exploration-exploitation · gain control.

1 Introduction

Why is the study of consciousness relevant for robotics? In our view, there are processes that reflect the level of awareness in humans that can play an important role in the control of a robot. These processes are commonly associated with different conscious states. However, our interest in these processes is not primarily that they are correlated with different conscious states, but rather that they are useful as control mechanisms in their own right. We believe that this gives a solid basis for studying consciousness in AI systems since the different mechanisms are motivated by their functional role rather than by subjective notions of awareness or conscious experience.

The present paper presents an overview of the arousal system for a humanoid robot. This arousal mechanism, which is is roughly modeled after its biological counterpart, determines the level of awareness and controls processing in a memory system that supports many cognitive operations. The arousal system decides how information is processed in memory, how thoughts are focused or allowed to wander, and sets the balance between exploration and exploitation. The level of arousal can be considered one of several meta-parameters that control processing in a natural or artificial cognitive system [8].

A central componenent of the robot control architecture is a biologically motivated memory system. We have argued elsewhere that a conscious robot needs to maintain an inner world to support various cognitive functions. This inner world is based on a combination of episodic, semantic and working memory structures [3]. The basis for the model is an autoassociative network with latching dynamics [16, 6] that binds together stimuli with locations and learns episodic sequences. Our implemented system support tasks such as the A-not-B test, delayed matching to sample, episodic recall, and vicarious trial and error [3].

In the memory system, memories correspond to attractor states of the network and perception and recall is the process of finding the attractor state most consistent with the input. The latching dynamics make attractors semi-stable. This causes the memory state to jump from attractor to attractor in an episodic manner unless the state is explicitly locked in the current attractor. As a consequence, learned episodes can later be recalled as episodic memory transitions. In addition, the memory system supports semantic transitions where a stimulus associates to other similar stimuli [13].

A critical parameter of the memory system is its gain that controls whether the system stays in an attractor or is allowed to transition to other memory states. With a very high gain, the memory system will be locked in an attractor. With lower gain, it will start to transition through learned episodic sequences. If the gain is lowered even more, the randomness of the state transitions will increase as a results of noise which can produce novel transitions from combination of old episodes [3]. These mechanisms supports memory paths that range from focused recall to completely random state transitions. A central claim of this paper is that gain control is a fundamental function of the arousal system which goes hand in hand with different levels of awareness.

In the brain, the level of awareness is controller by the ascending reticular activating system. It consists of a number of nuclei that can control processing in the whole of the brain, including wakefulness and sleep. Here we will focus on the locus coeruleus (LC), which is the primary nucleus for the control of wakefulness though its noradrenargic projections to cortical, subcortical, cerebellar and brainstem circuits of the brain. A high LC activity is associated with heightened attention. During sleep, the LC is almost completely turned off. We have earlier developed a computational model that is able to explain how the LC is activated by novel or emotionally charged stimuli [14]. This model forms the basis for the system described here. The LC activation is also influenced by a circadian oscillator in the hypothalamus that tracks the 24 hour day-night cycle [11]. This makes the LC more susceptible to stimulation during the day than during night.

It has been suggested that the level of noradrenaline functions as gain modulation in cortical processing by controlling the randomness of decision processes [1, 7, 9]. This can be seen as a choice between exploration and exploitation, where a lower arousal causes a more random choice, or exploration, while a higher level of arousal, causes exploitation of learned information. The concept of gain modulation is related to Hebb's idea of an optimal level of arousal [12] and the related Yerkes-Dodsons law [22]. The LC also controls muscle tone. There is thus a connection between mentally increasing focus or trying harder to physically using more force. Whether this is a good strategy or not depends on the problem.

Simple problems benefit from an increased focus while harder problems require the mind to evaluate different alternatives. This is parallel to physical obstacles, where simple situations can benefit from increased force, while harder situation require active problem solving. Interestingly, the LC also influences the size of the pupil which makes pupil dilation a useful index of increased noradrenergic activity [4].

2 Levels of Awareness

Different levels of awareness all have roles to play in cognitive processing, ranging from intense focus to drowsiness and sleep. This is a continuous scale, but we here focus on some qualitatively different levels of awareness. All these states have useful functions in the control of a robot.

Focus At the highest level of arousal, the attentional and memory systems are a focused on a single stimulus or memory state. During manual actions, this is the relevant level of arousal as it allows the visual system to lock on to a stimulus without being distracted by irrelevant stimuli [18].

Although intense focus could sound like an ideal state, this is not always the case. The problem is that it locks the current memory state and if it is not the correct one, it will be hard to move away from it. This can be seen, for example, during the tip-of-the-tongue phenomenon [5] where we fail to recall a word even though we in fact know it. Thinking more intensely about the word does not help recall and we are better off giving up. Once the mind is allowed to wander, the correct word will very likely be recalled. This shows that the level of arousal must be decreased for novel memories to become activated. Interestingly, it has been shown that when people give up on a task, arousal is lowered in this way as can be seen in their pupils [23].

Planning and Problem Solving To find novel combinations of episodic sequences, as is necessary during problem solving, it is required that arousal is kept at a high, but not too high level. Focused exploration of alternatives is combined with unfocused mind wandering to generate new alternatives. When the robot fails to move forward in a task, the arousal is decreased to allow novel solutions to emerge. These solutions are either tested in the environment or evaluated in memory. The process is similar to simulated annealing where noise is introduced in an artificial neural network to allow its memory state to jump to a novel solution [15]. Once a new solution is found, the arousal is increased again to allow the execution of the corresponding behavior. This increase in arousal is caused by an evaluative mechanisms that increases emotion and consequently also LC activity.

Planning is similar to problem solving in many ways, but need not be concerned with an immediate problem. When planning, the system can be viewed as stringing together behaviours and episode-fragments in memory to compose a plausible path from the present context to some desired goal state. The exploration is hence goal-directed and more focused than the mind wandering, daydreaming state described below. However, depending on the general arousal level of the system, planning may degenerate into daydreaming, or oscillate between the two. During planning, the memory system will produce the kind of forward sweeps seen during vicarious trial and error in animals [19]. This can be seen as internal simulation of an action sequence that later may be used in the real world.

Daydreaming During daydreaming or mind wandering the arousal is lower compared to planning. The memory transitions of the robot mirror the state in which the default network dominates access to working memory [17]. This state is entered if the system is cognitively unoccupied, and can be viewed as a way of exploring novel avenues through memory, not necessarily linked to specific goals. Like planning, it has a strong episodic component, and allows internal rehearsal of alternative behavioural sequences linked to common situations. This type of mechanism has previously been used for example in reinforcement learning in the DYNA-architecture, where behaviors are rehearsed from memory as well as in the environment [21].

Drowsiness Drowsiness is associated with a very low level of arousal. In terms of gain control, it allows the memory state to drift freely without any goal direction or focus. This is a transitional state that can be linked to the sleep-wake cycle, at the transition stage to sleep. However, it can also be used to simulate the propensity to seek novelty or change task if the current task does not yield sufficient reward. The same can happen if the task is too energy-draining compared to the level of reward, or the level of perceived progress towards a goal. Drowsiness might also be entered into if the robot is understimulated. That is, the activation of its perceptual system is below some threshold. For example, the robot may be presented with a static or blank scene or it may be required to not move for a too long period of time. In humans and animals, a lack of stimulation from proprioceptors and other signals from the peripheral system associated with sitting or laying for extended periods of time tend to induce drowsiness and lethargy [10].

Drowsiness can end up in a sleep state, but because it also motivates action, it can also cause the robot to do something novel to increase arousal. Which direction the arousal will take depends on contextual factors such as the availability of objects in the environment that can stimulate actions. We have earlier modeled how novel or emotional stimuli can increase arousal through the activation of a simulated LC [14], thus causing states associated with increased awareness in the robot.

Sleep At the lowest level of arousal we find sleep. The obvious use for a sleep-like state in a robot is that it serves energy conservation. However, sleep is not equivalent to being turned off. The sleeping robot can quickly become aroused and move to an active attentive state if something unexpected happens. This implies that rudimentary sensory processing must also occur during sleep, but perhaps at a lower resolution or at a lower rate to save energy. As in the brain, the sleep-cycle is also controlled by a clock, which determines at what time it is appropriate to sleep, and allows the robot to quickly go back to sleep again after being woken up by something unexpected.

In general, monitoring of the environment during sleep depends on passive attention to the environment. Such attention is controlled by processes of habituation that form a model of the environment that can detect unexpected disturbances [2]. For the robot, we implement this as adaptive background mixture models for each of its sensory modalities that learn the normal variation of the background input [20]. Similar methods are used for visual, auditory and tactile inputs.

3 Discussion

Having a system that dynamically transitions between arousal states similar to those found in animals allows the study of aspects of consciousness that may be hard or time consuming to study in biological systems. It may also allow insights into the phenomenon of consciousness as such, by accessing it indirectly through arousal, rather than attempting to tackle it directly. Thus, the infamous "hard" problem of consciousness may perhaps be chipped away at without becoming stuck in the traditional debates surrounding this issue.

Closer to everyday concerns, perhaps, are the requirements of artificial systems to conserve and optimize energy use when not connected to a continuous energy supply. We argue that modelling arousal levels in general, and the LC noradrenergic system in particular affords a biologically plausible way of managing energy expenditure, as well as a highly interesting avenue for studying dynamic cognitive behaviour with a high level of experimental control. Moreover, a robot with a biologically plausible arousal system may allow insight into human maladaptive conditions associated with the noradrenergic system. This includes depression and anxiety disorders, attention deficit disorders, schizophreniaand narcolepsy.

To summarize, we have outlined the function of a biologically motivated arousal system for a humanoid robot. This central system controls how the memory system transitions from one state to the next to recall episodic memories or to produce novel states and transitions based on earlier experiences. The level of arousal is closely connected to level of awareness and acts as a speed control for thought.

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