Time Production and Representation in a Conceptual and Computational Cognitive Model

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Abstract

Time perception and inferences there from are of critical importance to many autonomous agents. But time is not perceived directly by any sensory organ. We argue that time is constructed by cognitive processes. Here we present a model for time perception that concentrates on succession and duration, and that generates these concepts and others, such as continuity, immediate present duration, and lengths of time. These concepts are grounded through the perceptual process itself. We also address event representation, event hierarchy and expectations, as issues intimately related with time. The LIDA cognitive model is used to illustrate these ideas.

Keywords: time - time perception – cognitive architecture – event - duration

1. Introduction

Time perception is unlike other modes of perception such as motion, color or sound. We can see images, listen to sounds, or touch objects. Our senses enable us to perceive events of the real world. But time is different. We do not have a sense for time. Moreover, we perceive all other senses *over* time. We perceive change in our sensations, but even if we could cease sensing the world for a period, we would still have the perception of time. The concept of time is integral to the cognitive process. Here we will argue that, instead of asking "How can time be perceived?", we should ask "How is a sense of time produced by a cognitive system?". In other words, we contend that *time is something that the cognitive process constructs*.

There are many perspectives on how to model cognitive time and time perception. Williams James presented one of the first in the nineteenth century (James, 1890) which is still relevant today. Most cognitive models of time concentrate on the duration of events (Michon, 1990), and some others on different aspects of time such as sequence (Block, 1990). But few focus on an integral view of time perception and representation. The pulse accumulator model and the scalar expectancy theory are well known psychological models of time perception (Buhusi & Meck, 2005) (Gibbon, Church, & Meck, 1984). These models are based on a pacemaker that generates pulses at regular intervals. An accumulator stores these pulses when a time duration estimation is required. Then the pulses stored in the accumulator are compared to the pulses stored in a reference memory. These models address only the duration aspect of time. Other authors such as Boltz (Boltz), and Zakay et. al. (1994) have studied how event structure may influence perception of event duration. They addressed the judgment of event duration both using retrospective and prospective techniques. They considered also the event structure and the complexity of the event as modifiers of the precision of the judgment of duration. Most of these works study the perception of duration of events in the range of tens of seconds or more. For this work, we centered our attention to time perception in the range of few seconds and we addressed a broader scope of time, not only duration. Nevertheless, the *event* section addresses representation of high-level events although their duration is not specifically discussed.

Taatgen and others presented a model of time perception that addresses event duration for the ACT-R model (2004). Similarly, Cassenti and Reifers developed a different version based on the same model (2005). From a more philosophical point of view, Dainton proposed a model that addresses these integral perspectives (2000). In neuroscience, time perception refers mostly to the perception of event duration (Ivry & Schlerf, 2008). Eagleman's research addresses time perception from a broader perspective, comprising duration, perception time scale, and sequence (2008). Here we take a quite abstract view of time production and its representation in an autonomous agent, be it human, animal or artificial.

An autonomous agent can be defined as "A system embedded in, and part of, an environment that senses its environment acts on it over time in pursuit of its own agenda so that its actions affect its future sensing"(Franklin & Graesser, 1997). We humans are good examples of autonomous agents, as are most animals, some mobile autonomous robots and some computer viruses. Time is an important variable for an autonomous agent. It is referenced three times in the above definition. All sensory stimuli are sensed over time, and actions can generate changes in the *future* sensing. Finally, the term "agenda" implies that the agent has plans for the future. To be able to plan and foresee the result of an action, or group of actions, is a desired ability for many autonomous agents. The ability to estimate the duration of these actions, or to perform time related logical inferences, is also valuable. Moreover, for living organisms in general, and for animals in particular, survival is a critical goal. Thus the perception of time, its representation, interpretation, and manipulation, are crucial abilities for many autonomous agents.

From a cognitive point of view, time presents three major aspects that are focused on here: succession, duration, and temporal perspective (Block, 1990). Succession refers to the sequence of events from which an agent can perceive time order and succession. Duration addresses the length of time that an event persists, or the time between events. Finally, temporal perspective deals with the separation of experiences into the categories of past, present, and future.

In this work, we present a model for time perception that concentrates on succession and duration. It generates these concepts and others, such as continuity, immediate present duration, and length of time. We also address event hierarchy and expectations as subjects intimately related with time and temporal perspective. In sum, we propose a model that addresses time perception broadly.

This theoretical model for time can be implemented in any sufficiently comprehensive cognitive architecture. We briefly introduce one such architecture in the next section. Then we discuss primitive events and some of the more important aspects of time: event duration, succession of events (time order) and time scale perception. After that, we present the Immediate Present Train model, and its implementation in the LIDA model, the Conscious Content. We complete our discussion by describing the use of this Conscious Contents Queue to create time related concepts and representation of events and expectations. Finally we compare our model with some others and suggest further research directions.

2. The LIDA Model and its Architecture

The LIDA model (Baars & Franklin, 2009; Franklin & Patterson, 2006; Ramamurthy, Baars, D'Mello, & Franklin, 2006) is a comprehensive, conceptual and computational model covering a large portion of human cognition[1]. Based primarily on Global Workspace Theory (Baars, 1988, 2002), the model implements and fleshes out a number of psychological and neuropsychological theories.[2]

The LIDA computational architecture is derived from the LIDA cognitive model. The LIDA model and its ensuing architecture are grounded in the LIDA cognitive cycle. Every autonomous agent (Franklin & Graesser, 1997), be it human, animal, or artificial, must frequently sample (sense) its environment and select an appropriate response (action). More sophisticated agents, such as humans, process (make sense of) the input from such sampling in order to facilitate their decision making. The agent's "life" can be viewed as consisting of a continual iteration of these cognitive cycles. Each cycle constitutes a unit of sensing, attending and acting. A cognitive cycle can be thought of as a moment of cognition, a cognitive "moment."

We will now briefly describe what the LIDA model hypothesizes as the rich inner structure of the LIDA cognitive cycle. More detailed descriptions are available elsewhere (Baars & Franklin, 2003; Franklin, Baars, Ramamurthy, & Ventura, 2005; Wallach, Franklin, & Allen, 2010). During each cognitive cycle the LIDA agent first makes sense of its current situation as best as it can *by updating its representation of its current situation, both external and internal*. By a competitive process, as specified by Global Workspace Theory, it then decides what portion of the represented situation is most in need of attention. Broadcasting this portion, the current contents of consciousness[3], enables the agent to chose an appropriate action and execute it, completing the cycle.

[1] "Cognition" is used here in a particularly broad sense, so as to include perception, feelings and emotions.

[2] The LIDA model derives from and extends IDA, a US Navy project to model and implement an Intelligent Distribution Agent (Franklin, Kelemen, & McCauley, 1998). LIDA stands for Learning IDA, but the LIDA model and its architecture are more general, and not bounded by the original IDA aims.

[3] Here "consciousness" refers to functional consciousness (Franklin, 2003). We take no position on the need for, or possibility of, phenomenal consciousness.

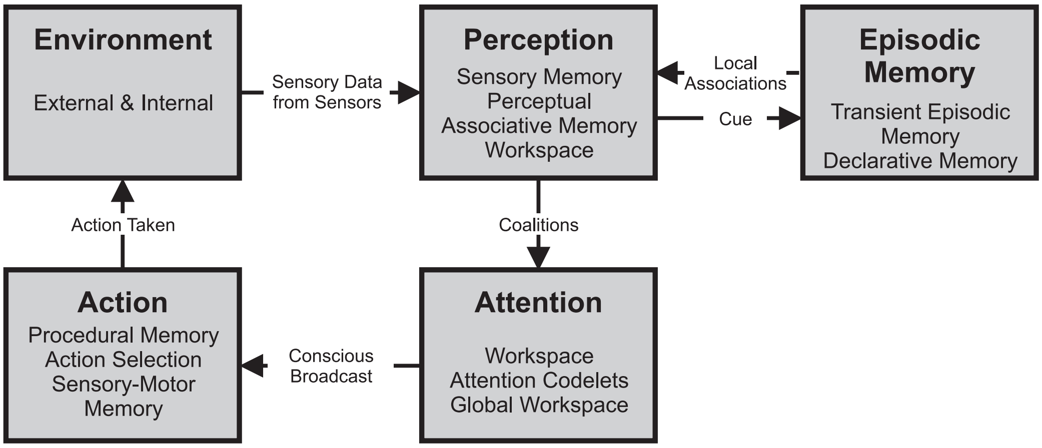

Figure 1. Simplified LIDA Cognitive Cycle Diagram

Thus, the LIDA cognitive cycle can be subdivided into three phases, the understanding phase, the attention (consciousness) phase, and the action selection phase. Figures 1 and 2 should help the reader follow the description. It starts in the upper left corner and proceeds roughly clockwise. Beginning the understanding phase, incoming stimuli activate low-level feature detectors in Sensory Memory, whose processes serve to preprocess the incoming sensory data. The output is sent to Perceptual Associative Memory where higher-level feature detectors feed into more abstract entities such as objects, categories, actions, feelings, events, etc. The nodes in this long-term perceptual memory whose activations rise over threshold form the current percept. This resulting percept moves to the short-term, preconscious Workspace whose job it is to make sense of the current situation. The percept cues both Transient Episodic Memory and Declarative Memory producing local associations from these short-term and long-term episodic memories. These local associations are combined with the percept to generate a current situational model, the agent's understanding of what is going on right now.

Attention Codelets[4] begin the attention phase by forming coalitions of selected portions of the current situational model and moving them to the Global Workspace. A competition in the Global Workspace then selects the most salient, the most relevant, the most important, the most urgent coalition whose contents become the content of consciousness. These conscious contents are then broadcast globally, initiating the action selection phase. The action selection phase of LIDA's cognitive cycle is also a learning phase in which several processes operate in parallel (see Figure 1). New entities and associations, and the reinforcement of old ones, occur as the conscious broadcast reaches Perceptual Associative Memory. Events from the conscious broadcast are encoded as new memories in Transient Episodic Memory. Possible action schemes, together with their contexts and expected results, are learned into Procedural Memory from the conscious broadcast. Older schemes are reinforced. In parallel with all this learning, and using the conscious contents, possible action schemes are recruited from long-term Procedural Memory. Each scheme consists of an action, its context and its expected

[4] A codelet is a small piece of code that performs a specific task in an independent way. It could be interpreted as a small part of a bigger process, similar to an ant in an ant colony.

result. A copy of each recruited scheme is instantiated with its variables bound and sent to Action Selection, where it competes to be the behavior selected for this cognitive cycle. The selected behavior triggers Sensory-Motor Memory to produce a suitable algorithm for the execution of the behavior. Its execution completes the cognitive cycle.

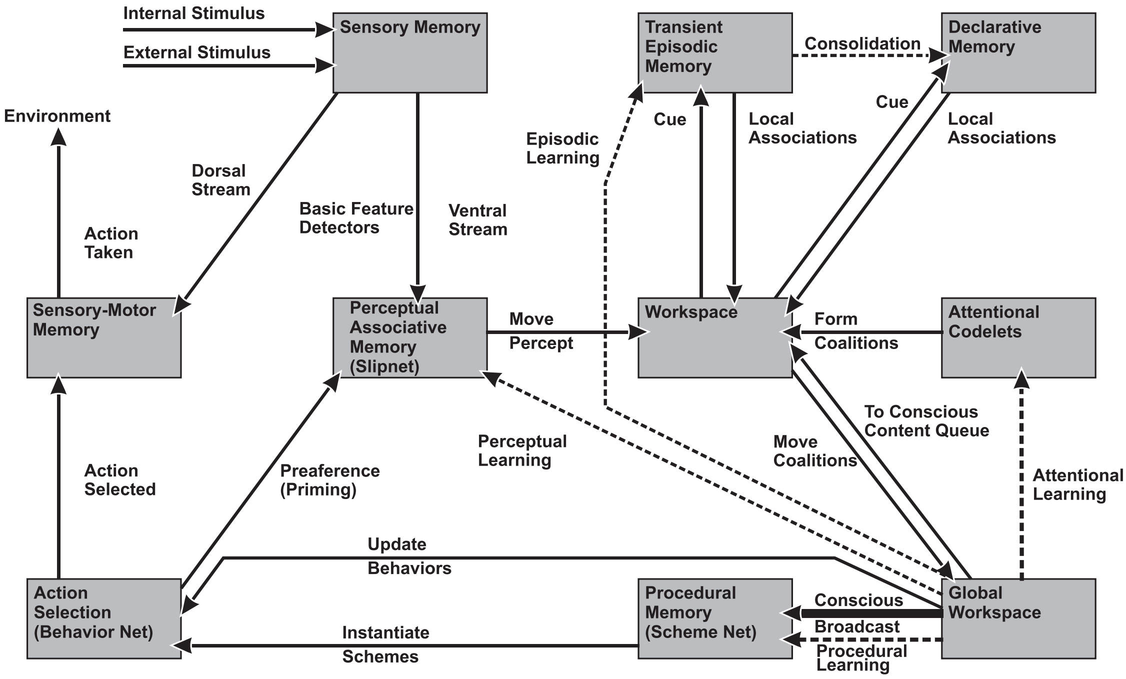

Figure 2. The LIDA Cognitive Cycle Diagram. its Modules and Processes

The Workspace requires further explanation. It is a short-term memory whose main function is to be a “playground” where the representation of the current situation of the agent is built. Its internal structure is composed of various input buffers and three main submodules: the current situational model, the scratchpad and the Conscious Contents Queue. This last, a major subject of this paper, will be discussed in detail later. The current situational model is where structures representing the actual current internal and external events are stored. Structure building codelets are responsible for the creation of these structures using elements from the various submodules of the Workspace. The scratchpad is an auxiliary space in the Workspace where structure building codelets can construct possible structures prior to moving them to the current situational model.

2.1 Primitive events

Here an event is thought of as a parameterized action in the sense of Allbeck and Badler (2003). A primitive event is the shortest event that an agent is capable of producing “in one shot.” More complex events are thought to be composed of sequences of primitive events. In the LIDA model, an instant or primitive event lasts one cognitive cycle phase (see previous section).

An action takes place in space and time (e.g., rain falls). An event consists of an action together with one or more objects that parameterize it, i.e., they play specific thematic roles a la Fillmore (1968). In the event described by “John throws the ball to Bill,” the action “throw” is parameterized by the object “John” playing the agent role, the object “ball” playing the object role, and the object “Bill” playing the patient role.

Events in the world must be represented perceptually in order to be understood. An internal event is similar to a real event, but is generated internally by the system, e.g., imagining a unicorn, or a remembered event. A change in a goal, or an action that modifies the internal state, might also be examples of internal events. Thus a primitive event can be internal to the agent or external in the environment.

3. Time Production

What follows is a discussion of two of the principal aspects of time from a cognitive point of view: succession and duration. In the first we explore a sequence of events and their temporal order. Both succession and duration are critical for time perception, time representation, and in determining how long our sense of the “immediate present” lasts.

3.1 *Duration*

Consider a person whose episodic memories last at most five minutes. The patient HM is the canonical example of a person who cannot form *any* new episodic memories (Schmolck, Kensinger, Corkin, & Squire, 2002). Our hypothetical person is like HM, but has no episodic memories that are more than five minutes old. In terms of the LIDA model, this hypothetical person has a transient episodic memory with a lifetime of at most five minutes. As a consequence of this short memory span, this person would only know of, and be able to recall, events from the last five minutes of their experience.

Now imagine a hypothetical person who congenitally lacks any episodic memory at all. This person would still have their preconscious working memory, which we hypothesize contains the contents of consciousness of the last few seconds. Their lack of episodic memory would prevent them from recalling past events. However, since this person retains the contents of the consciousness of the last few seconds, they could still perceive the duration of brief events and other time-related aspects.

Now, taking this example to an extreme, consider this same hypothetical person who additionally cannot retain any recent content of consciousness in their preconscious working memory while still lacking any episodic memory. Now, not only would “the past” lose its meaning to that person, event duration would lose its meaning as well.

Memory is what gives time its meaning. In order to measure the duration of an event, it is necessary to have memory. This idea was first presented by Saint Augustine in his *Confessions* (Warner, 1963). He argued that past and future are non-existent so they can have any property, and that the present has no duration (Section 4 for a discussion of this point). How are we able to measure the duration of an event or an interval? He concluded that what is measured is in the memory.

Memory is a necessary ingredient to be able to perceive time. What is stored in this memory, and how much memory, are the concerns of the following sections.

3.2 *Sequence: Succession and Time Order*

The idea of succession is well illustrated in a paragraph from Williams James:

> If the present thought is of A B C D E F G, the next one will be of B C D E F G H, and the one after that of C D E F G H I -- the lingerings of the past dropping successively way, and the incomings of the future making up the loss. These lingerings of old objects, these incomings of new, are the germs of memory and expectation, the retrospective and the prospective sense of time. They give that continuity to consciousness without which it could not be called a stream. (James, 1890 pg. 606)

The succession of events is an inherent property of our time perception. Memory is necessary, and the order of these events is fundamental. A good analogy is to imagine past events as a reel of a movie. Each frame can be considered as an event. If all the frames are cut apart and mixed up, much of the information is lost.

Let us consider the hypothetical person with limited memory suggested in the Duration section. Suppose he has no episodic memory at all, but only has memory for events from the last few tens of seconds. His or her ongoing perception would consist almost entirely of a stream of consciousness, the *time stream*. In terms of the LIDA model, such a person would have a buffer in his workspace that retains recent conscious broadcasts. We have termed this buffer the *Conscious Contents Queue*. A person like this with no episodic memory could still perceive the continuity of an event and could follow what James calls the "The Stream of Thought" (James, 1890 Chapter XI). However, he could not remember any episodes. A 'river' or a 'stream' are the metaphors by which it is most naturally described. *In talking of it hereafter, let us call it the stream of thought, of consciousness, or of subjective life*. (James, 1890 pg. 239)

Again, if this person additionally lost all memory of recent consciousness, the notion of duration of events vanishes, and event order would lose its meaning as well. Having no memory of recent consciousness would eliminate the notion of time. Retaining the sequence of the most recent conscious broadcasts creates an order for primitive events, and this order gives time meaning. In the LIDA model, this order is retained briefly in the Conscious Contents Queue in the workspace.

3.3 *Time Scale in Time Perception*

Time perception is relative to the length of time it takes to discriminate one instant in time from the next. In humans there are limits on the shortest and longest length of time that we can react to and directly perceive a change in. Even in the time of William James there were experiments that explored these sorts of concepts:

> In music, Wundt and his pupil Dietze have both tried to determine experimentally the *maximal extent of our immediate distinct consciousness for successive impressions* (notes of a melody). Wundt found that twelve impressions could be distinguished clearly as a united cluster, provided they were caught in a certain rhythm by the mind, and succeeded each other at intervals not smaller than 0.3 and not larger than 0.5 of a second. This makes the total time distinctly apprehended to be equal to from 3.6 to 6 seconds. (James, 1890 pg. 612)

Similar results were found by Block who hypothesizes:

> …the psychological present is limited to about 5 s and suggested that this limit is related to the dynamic functioning of the short-term store. (Block, 1990)

The continuity of movies (motion pictures) illustrate that time can be too short to be perceived. Movies are a succession of static images, frames that are presented to us one by one each during a short time interval. However, we are unable to distinguish a frame as an individual event. These events occur in a shorter time span than the minimum one that we can perceive consciously.

We can sum up the concept of time perception as follows: there is an upper and lower limit on the length of time intervals that we can perceive directly. Events that last for a shorter time than the lower limit will be indistinguishable from one another, while those that last longer than the upper limit must be recognized by a cognitive system indirectly, using higher level cognition processes.

4. Immediate Present Train

Williams James developed the concept of the “Specious Present,” which was first proposed by E. R. Clay (James, 1890). He argued that what is perceived as present has duration. The last few seconds of our consciousness are perceived as a “whole” present.

> I make the fanciful hypothesis merely to set off our real nature by the contrast. Our feelings are not thus contracted, and our consciousness never shrinks to the dimensions of a glow-worm spark. *The knowledge of some other part of the stream, past or future, near or remote, is always mixed in with our knowledge of the present thing.* (James, 1890 pg. 606)

Both aspects of time, order (sequence) and duration, must be preserved for events in the specious present. In order to understand the specious present we use the analogy of the immediate present train. This is an analogical model that combines the specious present, time duration, sequence, and time scale in time perception. The present can be considered analogous to a train. The length of each car in this train represents the smallest time that can be consciously perceived. The length of the train denotes the duration of the present, i.e. the specious present. Each car of this train holds the content of the last conscious event. For example, suppose the most recent conscious events were A then B then C then D. A would be the oldest event in this group and D the most recent. The cars of the train hold these events in reverse order. At the beginning of the train is the event D, and at the back the event A. One instant before a new conscious event E is stored in the first car. Event D, previously in the first car, now is in the second. Event C passes to the third and so on.

The whole train comprises what we experience as the present. This is what makes it possible to represent events that are not simultaneous (they are in different cars) as being “present” (they are still in the train). Example: Bill throws the ball. The ball moves. Bob catches the ball. Consequently more than one event can be perceived as being in the “specious present” even though they were not simultaneous.

It is important to clarify that changes faster than the lower limit of time perception can still be perceived directly as change or motion, but not as separate events, and that the representation of these events can have representations of their change, or movement as a special case of change. So the representation of the event in some car of the immediate present train can contain a component representing this change or movement.

This analogical model elucidates the duration of events and their order, and is also compatible with our limits of shortest and longest time event perception.

5. Time in LIDA

5.1 *Conscious Contents Queue*

The Conscious Contents Queue represents the "Immediate Present Train" and James' *Specious Present* (James, 1890 pg. 609). It is 2 or 3 seconds long. However, this is not a critical value, and durations as long as 10 seconds could also be considered. It can be thought of as a queue in which each element is the contents of a conscious broadcast (see figure 3). Each position in this queue represents a "car" in the Immediate Present Train".

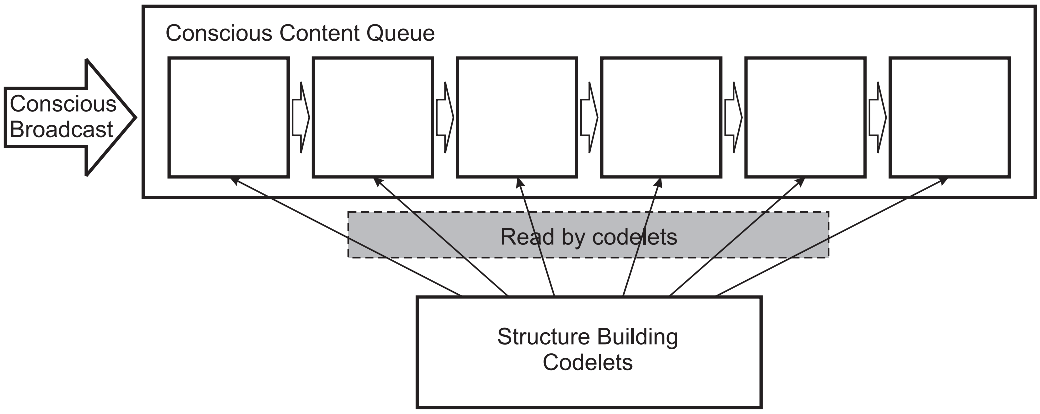

Figure 3. Conscious Contents Queue

The Conscious Contents Queue is a submodule of the Workspace in the LIDA architecture. This permits structure building codelets to work directly with its content, a fundamental requirement as we shall see in the next sections.

With each new conscious broadcast, the current contents of consciousness is added as an element to the queue, and the previous elements of the queue pass to the next position (toward the "end" of the queue). We decided to call this module "queue" to reinforce the ideas of order and natural movement to the "back" that the term "queue" implies. However, its behavior has the particularity that structure building codelets can directly access any position in the queue. Queues typically can be accessed only at their ends (see figure 4).

Elements in the first positions (the most recent elements) will typically have more activation than older elements (at the end of the queue) since elements decay. An element toward the end of the queue may completely decay before later elements that had more activation, leaving one less element in the queue. The Conscious Contents Queue is not of fixed length.

The Conscious Contents Queue and the LIDA cognitive cycle determine the time scale of which the agent is directly aware. The LIDA cognitive cycle can be divided into three phases: the interpreting phase, the selective attention phase, and the action selection and learning phase. Each of these takes approximately 100 ms to complete. They can cascade roughly in parallel, overlapping in the execution of three consecutive cycles. In this way, a cycle takes roughly 300 ms to complete, but LIDA has a throughput of approximately one cycle completed each 100ms. While the cycle t_0 is running the last phase (action selection and learning), the cycle t_1 is executing the selective attention phase, and the cycle t_2 is executing its interpreting phase. Thus, each broadcast roughly corresponds to a 100ms time period, the duration of a phase of the cognitive cycle.

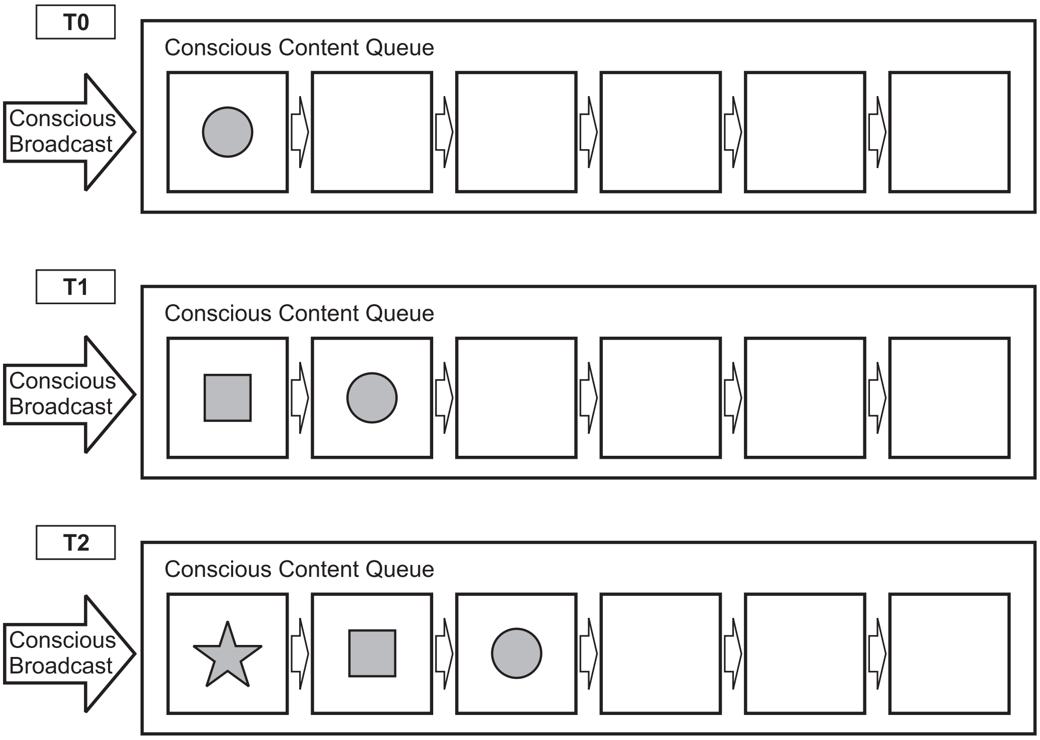

Figure 4. Behavior of the conscious contents queue after the broadcast of three cognitive cycles.

In the LIDA architecture the lower limit of time perception would be determined by the length of the interpreting phase of a cognitive cycle and would coincide with the duration assigned to one position in the Conscious Contents Queue. The upper limit would be determined by the number of positions retained in this queue. This limit should be a function of the duration of time that each position represents, e.g. ~100ms for primitive events, and how long positions in the queue last before they decay. This fact is fundamental for the creation of time related concepts, or nodes, by LIDA. This issue is discussed in the next section.

Changes occurring on timescales faster than a cognitive cycle phase (~100ms), can still be perceived directly. A common example of this is the direct perception of a moving object. The movement itself is represented by a node that enters the Workspace linked with the node representing the object. It could be chosen to be broadcast as conscious content. In this way, the Conscious Contents Queue holds the recent contents of consciousness, but not as static “pictures.” Rather it stores the change and movement associated with its elements.

Lifetimes of representations in the Conscious Contents Queue are typically longer than those of representations in the current situational model. This is due to the fact that the decay rate differs between these two components of LIDA's Workspace. In the Conscious Contents Queue the decay rate is slower than in the current situational model, so representations remain active for a longer time. Also, the current situational model can sometimes be rapidly overwritten.

The Conscious Contents Queue contains the conscious contents of recent broadcasts. The elements of each broadcast may have varying activations. Since elements decay in the Conscious Contents Queue and may have different initial activations, some elements, and likely even entire broadcasts, would disappear from this queue. Only the most salient elements of the broadcasts in older positions would be preserved. This behavior implies that positions of the queue, especially at the end, do not have a uniform length. So perception of the duration of events using this queue becomes inexact. This is not a problem at all; indeed it reflects a characteristic of the human estimation of event duration.

The content of the broadcast also is sent to the Transient Episodic Memory during each cognitive cycle. The main difference between the Conscious Contents Queue and the Transient Episodic Memory is that the former is contained in the Workspace and permits direct access to any of its positions by structure building codelets. The Transient Episodic Memory, on the other hand, does not permit such direct access, but requires a cue in order to recall information. These two memories are then complementary. Transient Episodic Memory stores events for a longer period but does not allow direct access to them. The Conscious Contents Queue stores the events for a short period, and allows direct access to its content.

The Conscious Contents Queue is an implementation of the immediate present train in the framework of the LIDA architecture. The next sections explore how this module permits us to perceive time and supports time related concepts.

5.2 *Time Representation using Perceptual Associative Memory and Workspace Nodes*

The LIDA model must be able to represent time without using time for that purpose. There would be nodes both in the workspace and in the perceptual associative memory that represent time.

Perceptual Associative Memory contains various kinds of nodes, for example feature detector nodes, object nodes, category nodes, feeling nodes, action nodes, etc. Each of these represents something that the system is able to "understand". The simplest nodes are feature detectors, many of which are activated directly from sensory memory. Abstract nodes like object or category nodes are more complex. The "meaning" of these nodes is derived from activation passing along the links between the nodes and their feature detectors. Those abstract nodes need to gain activation through their links in order to reach the Workspace as part of the percept.

Perceptual Associative Memory nodes reach the Workspace as part of a percept, and may become part of a structure, built by structure-building codelets, that constitutes the agent's model of its current situation.

Nodes in LIDA's Perceptual Associative Memory are not amodal symbols (Barsalou, 1999, 2008). All these nodes are ultimately grounded in sensory feature detectors. Objects are grounded exclusively in sensory feature detectors but some additional mechanism is needed to ground the notions of time and time representations. We argue that representations of time are grounded in the order and duration of perceptual events. The use of the Conscious Contents Queue enables the generation of grounded nodes related to time. These nodes are not grounded only in feature detectors, but are produced by structure building codelets using material from the Conscious Contents Queue.

We distinguish two kinds of time nodes: short-term and long-term. Short-term time nodes represent durations shorter than the duration of the Conscious Contents Queue, which is on the order of a few seconds. Long-term time nodes are inferred indirectly and represent periods on the order of tens of seconds, minutes, hours, or even longer. Since the time intervals represented by these time nodes are inexact, their implementation should reflect this.

Short-term time representations are produced by structure-building codelets using representations in the Workspace particularly from the Conscious Contents Queue. We hypothesize that the Conscious Contents Queue of the workspace retains on the order of thirty of the most recent conscious broadcasts. This means it roughly holds the conscious contents broadcast during the last three seconds.

One element can be broadcast consecutively several times. So this element is "conscious" during an interval. Moreover, many elements can comprise the content of a single broadcast. Nodes representing change of these elements, for example movement, can also be attached in the Workspace, permitting smooth transitions from one conscious content to another. Part of the "when" pathway of the right parietal lobe is thought by neuroscientists to play an important role in direct movement perception (Battelli, Pascual-Leone, & Cavanagh, 2007). In humans, functional imaging studies have demonstrated a homologue of the macaque motion complex, MT+, believed to intersect both the middle temporal lobe (MT) and medial superior temporal lobe (MST), in the ascending limb of the inferior temporal sulcus (Dukelow et al., 2001).

Codelets can use the contents of the Conscious Contents Queue to ascertain temporal events. For example, a codelet could detect that some consecutive positions in the Conscious Contents Queue contain an apple element. Then that codelet might create a representation of the apple being present for a period of time, for example, for one second. The resulting representation could be then added to the agent's current situational model. Changes occurring over time scales on the order of a few seconds may be recognized in this way.

This process is responsible for the production of a time node. Such time nodes are comparable to distance nodes. How is LIDA able to understand distance? Processes detect different lengths in Sensory Memory (e.g. 1cm, 1m, 10m) producing nodes in Perceptual Associative Memory. Then an abstract node "Distance" categorizing them could be constructed. After that, LIDA could create new nodes representing larger distances, even distances that can not be captured by sensors or represented in Sensory Memory (e.g., 10 m, 1000 km, a light year).

In the same way, codelets working on the Conscious Contents Queue can detect and produce nodes for time periods of a few seconds in length. Then the abstract node “Time duration” could appear categorizing them, and an even more abstract node for “Time” could also be generated. Finally long-term nodes for periods of, 1hour, 1 day, 1 year, a century, could be created.

Codelets can also provide a mechanism for temporal reasoning. They can detect similarities, changes, and even cause-effect relations between elements in the Conscious Contents Queue, and in the current situational model or scratchpad. Let’s look at the following example.

> "… the successive ideas are not yet the idea of succession, because succession *in* thought is not the thought *of* succession. If idea A follows idea B, consciousness simply exchanges one for another. That B *comes after* A is for our consciousness a non-existent fact; for this *after* is given neither in B nor in A; and no third idea has been supposed. *The thinking of the sequence of B upon A is another kind of thinking from that which brought forth A and then brought forth B*; and this first kind of thinking is absent so long as merely the thinking of A and the thinking of B are there..." (James, 1890 pg. 629)

In this quote, James is discussing an example where the idea of “B followed by A” “pops” into consciousness. James continued by saying:

> In short, when we look at the matter sharply, we come to this antithesis, that if A and B are to be represented *as occurring in succession* they must be simultaneously represented; if we are to think of them as one after the other, we must *think* them both at once." (James, 1890 pg. 629)

The agent could have a structure-building codelet that detects A in one position of the Conscious Contents Queue and B in some later position. This codelet could then produce the representation “A before B” and put it in the scratchpad or current situational model. Then this representation “A before B” could be broadcast. (see figure 5).

In general, the contents of the Conscious Contents Queue can be combined with other elements in the Workspace forming structures in the scratchpad. These structures could then be added to the current situational model.

Another way in which time enters into the LIDA model is during the encoding of episodic memories, which occurs with each conscious broadcast. The comparison of episodic memories may also lead to the creation of new (new to the agent) long-term time representations. This is not recognition of a time period. Rather, it is more like a logical inference. For example, suppose there are two episodic memories: “it rained yesterday morning” and “it rained yesterday at dinner,” and it is inferred that “it rained all day”. Expanding on this idea, it should be possible and useful for various structure-building codelets to use some combination of local associations (cued retrievals from episodic memories), conscious broadcasts, and/or percepts to add new long-term time representations to existing events or other representational structures. It seems that this process of using workspace contents to determine the duration of events (both current and past) would use inexact nodes of time e.g. something like “a few seconds” or “about an hour”.

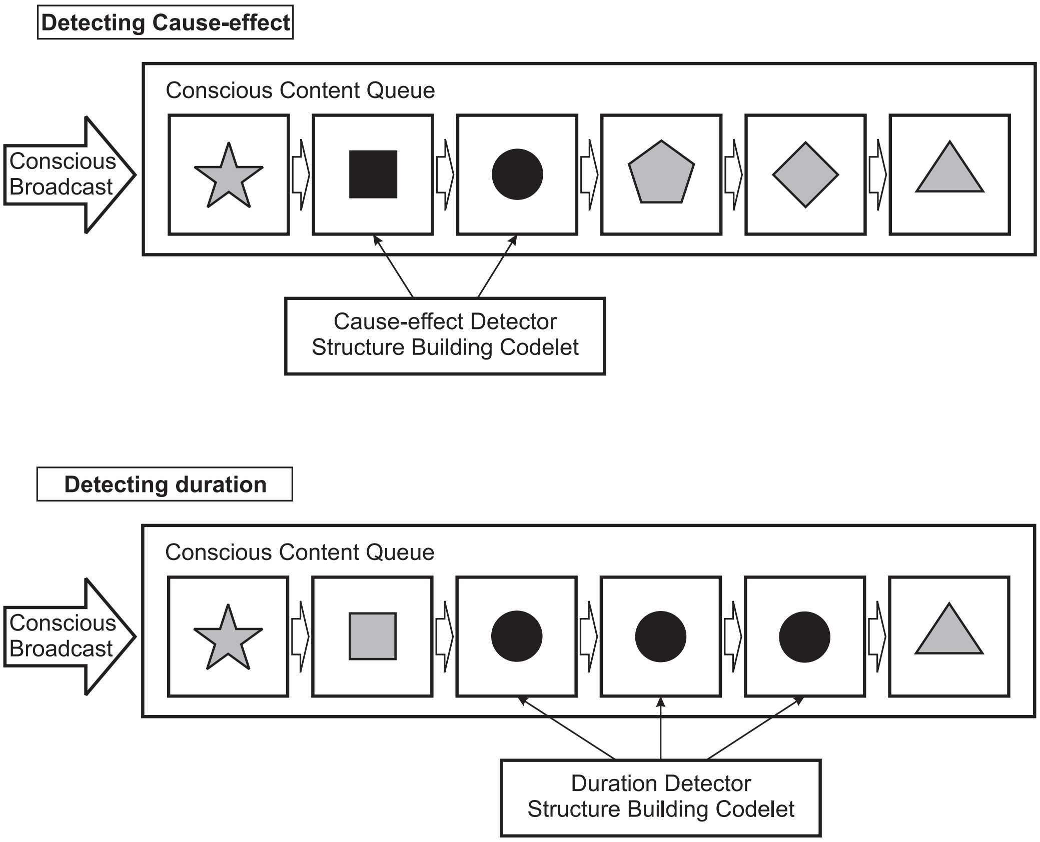

Figure 5. Conscious contents queue in action.

A Cause-effect Detector structure building codelet can inspect the queue and detect that "square" is in a latter position than "circle," and can produce a representation of "circle before square" in the Workspace. Another structure building codelet, a Duration Detector, can check the queue for sequences of repetitions. Since each position in the queue roughly represents the same duration of time, counting the number of consecutive positions where the same element appears, the sequence represents a measure of duration of this element. The structure building codelet can create a representation of the duration of this element in the Workspace.

The Conscious Contents Queue supports the creation of grounded, time related concepts, and the detection and use of them, to describe events in the current situational model. With this scaffolding, other ways to detect time concepts are possible, like comparisons of episodic memory contents or reasoning about time.

5.3 *Events*

An event is defined as a succession of more primitive events that are related in some way. Examples of events are opening a door or crossing the street. In LIDA, these events can be composed of a sequence of conscious broadcasts of portions of the structure in the current situational model. Naturally, there are differences between each broadcast.

> By 'event' we mean a segment of time at a given location that is conceived by an observer to have a beginning and an end. In particular we focus on the events that make up everyday life on the timescale of a few seconds to tens of minutes –

> things like opening an envelope, pouring coffee into a cup, changing the diaper of a baby or calling a friend on the phone. (Kurby & Zacks, 2008)

It is possible to construct sequences of events in this way having different timescales.

> Events can be identified at a range of temporal grains, from brief (fine-grained) to extended (coarse-grained). In goal directed human activity it is natural to think of such events as being hierarchically organized, with groups of fine grained events clustering into larger units… (Kurby & Zacks, 2008)

Here a simple event, or just an event, is what Kurby and Zacks refers to as a fine grained event, and a high-level event is what they call a coarse grained event.

High-level events are combinations of simple events. Events can form a complex hierarchy, at the lowest level they are composed of primitive events and at higher levels of longer and more abstract events.

An example of high-level event is: go to the supermarket. It could be divided into simple events: park the car, get a cart, find the milk, the meat, etc., checkout, put everything in the trunk, and return home.

In each cognitive cycle the current situational model is altered by the addition of new nodes and/or by a change in relative node salience. During each cycle, part of the current situational model, sometimes all of it, is broadcast. So the Conscious Contents Queue holds a sequence of contents of recent broadcasts. In this way, the agent could have a complex situational structure, but have only a small part present in the current situational model. But, it can easily recall other parts of the structure from the Conscious Contents Queue or from transient episodic memory.

Episodic memory adds a "timer" to the event in order to maintain both sequence and long time reference (Aimone, Wiles, & Gage, 2009; McCall, Franklin & Friedlander, 2010). It is speculated that this timer can more accurately discriminate recent events than older ones. We call this process a logarithmic timer. Logarithmic timers link together events that occur almost simultaneously and permit the agent to discern which event was first and which one was second in both episodic memories.

The contents of the current situational model are often changed by being overwritten. The overwriting of representations in the current situational model occurs when the entire situation changes, for example when one turns one's head quickly and is suddenly viewing a new scene; the current situation can change dramatically. Such situational changes should produce an event boundary (Kurby & Zacks, 2008). When the current situation changes more gradually, the activations of the representations in the current situational model decay. In this case there is not an event boundary, and older elements would decay away. Such elements can still be remembered from the Conscious Contents Queue, or from transient episodic memory if the elements have persisted in consciousness long enough.

5.4 *Expectations*

The structure in the current situational model can have nodes that represent expectations based on perceptual associative memory or episodic memory (Barsalou, 1999) (Ploghaus, Becerra, Borras, & Borsook, 2003) (Negatu, D'Mello, & Franklin, 2007). These nodes are linked to other nodes by an “expectation” link. These nodes do not represent a real perceptual event but an expected event, an event that is supposed to occur in the future. For example, if a real perceptual event, such as lightning, is activated in the current situational model, a node representing thunder might be added to the current situational model also and is linked to the lightning node by an “expectation” link. These expectations could be originated by relations in the perceptual associative memory, by local associations from episodic memory or by processes implemented by structure building codelets.

Expectations can be generated by relations in Perceptual Associative Memory (PAM) when some nodes in the PAM are activated due to features from Sensory. These nodes spread their activation to other nodes in PAM. There could be nodes linked with “expectation” links to the activated nodes. If these linked nodes that represent expectations are sufficiently activated, they may enter the Workspace. This may be how thunder is expected due to its relation to lightning. This case can arise during a single cognitive cycle if the node linked with the “expectation” link gains enough activation in one cognitive cycle, or over multiple cycles otherwise.

Other expectations are generated from episodic memories. The content in the workspace cues the episodic memories, and the retrieved local associations could lead to an expectation. Take for example, the magician’s illusion of “a woman in a box.” A woman enters a box. Then the magician rotates it many times and finally opens the box and the woman has disappeared. Another example is when we park the car in the supermarket parking lot. But, sometimes the car is not where we expected. Another example is when we listen to a song that we know. We expect some phrase or word. The same can happen with just the music; we expect a specific sequence of chords.

Finally, the last case of expectation analyzed here is an expectation generated by a process. For example, a ball is rolled and is hidden by a wall in part of its trajectory. Finally it appears at the other end of the wall. A node representing the time when the ball should appear and an “expectation” link can be generated by a process that calculates this time based in the trajectory and speed of the ball and the length of the wall. The position where it should appear could be another example of this kind of expectation.

Nodes that represented expectations can be added to the current situation model by structure-building codelets. These various processes that generate of expectations can be accomplished during a single cognitive cycle or over multiple cycles.

If new elements that enter the Workspace do not fit expectations, or if the environment has changed considerably, the current situational model structure may be overwritten and a new one takes control.

> When perceptual or conceptual features of the activity change, prediction becomes more difficult and errors in prediction increase transiently. At such points, people update memory representations of ‘what is happening now’. The processing cascade of detecting a transient increase in error and updating memory is perceived as the subjective experience that a new event has begun. (Kurby & Zacks, 2008)

Neuroscientists are beginning to understand the neural underpinnings of expectation (anticipation) (Hollerman & Schultz, 1998).

5.5 *Time in Imagination*

Suppose you see a baby who is learning to walk. The baby is walking in the park. Then, the baby walks to the edge of a hole. You can imagine the baby falling before it occurs. But your image seems to you in normal time, not accelerated as in a Chaplin movie. So the system must have a way to represent that possibility of the baby falling and the corresponding feeling of concern.

This example shows that the Workspace needs a place (or module) where structure-building codelets might "project" a sequence of events and forecast a future "current situation". In the same way, the agent can recall an event from declarative memory and project it into this module. In the LIDA model, the construction of hypothetical structures takes place in the current situational model, produced by structure building codelets.

Such a sequence could come as a local association, or as a sequence of them. Structure building codelets would "project" it into the current situational model.

The scratch pad may contain a planned or imagined representation that has a temporal order e.g. the falling baby. However, this sort of temporal order, being the result of structure building codelets, should not determine the system's sense of time. The order and sense of time is determined by the order of the conscious broadcasts stored in the Conscious Contents Queue. This temporal order may include broadcasts of imaginary contents.

In outlining an architectural framework for cognition, Sloman postulates three types of action selection or decision making processes: the reactive processes, the deliberative processes, and the meta-management processes (Sloman, 1999). It's the deliberative processes that will concern us here.

We humans, when faced with a goal or problem often imagine possible plans for achieving the goal or for solving the problem (Franklin, 2000). These trial plans or solutions typically take the form of scenarios of various kinds; say the steps to a solution, the route to a destination, or a single image scenario as a possible solution to a design problem. The essence of deliberation consists of the creation such scenarios and the choosing among them, discarding some, acting on others. This ability to mentally try out plans or solutions without acting upon them allows us to often avoid actions that may be ineffective or even dangerous. This internal virtual reality has been, perhaps, a major factor in our success as a species.

Deliberation involves the imagination, or recall, of a situation and the anticipation of the consequences of possible actions, or simply of the action of time. Again, time is an important variable in this process.

6. Comparisons and Further Directions

The Immediate Present Train and its implementation in the LIDA model, address several aspects of time perception. Other models, like the pulse accumulator model, focus on event's duration only. Moreover, even considering only this aspect, the Immediate Present Train allows the agent to keep track of more than one event duration at the same time. This is because various structure building codelets can detect durations of different events using the data in the Conscious Contents Queue.

On the other hand, the Immediate Present Train is thought to hold only the last few seconds of the agent's conscious content. So, to estimate durations longer than that, another kind of mechanism is necessary and the pulse accumulator model could be used to model this behavior.

The strength of the Immediate Present Train comes from the broad scope of time perception aspects that it addresses. In particular it addresses the grounding of time related concepts, and allows the agent to represent them. This goes beyond the estimation of an event's duration because this model enables the agent to "understand" these concepts and reason about them.

There is still plenty of work to do. Some simple experiments like presenting an agent one figure for a random duration (chosen among a set of durations) and then asking the agent to detect the duration of this event. Sequences of events can be tested in a similar way. Two figures, A and B, are shown in sequence. Nodes denoting "A then B" and "B then A" should be predefined in the system. Then, more complex experiments that test the learning of new nodes capabilities of the agent can be performed. Some of these experiments can be contrasted with human participants doing the same tasks, and the accuracy of the model can be tested.

The integration of these capabilities in LIDA finally should allow the agent to produce better internal models of the current situation, and to predict future events more accurately, enabling it to choose actions more effectively.

7. Conclusions

Time is a difficult concept to apprehend. The detection and perception of time-related aspects of events can be invaluable capabilities for agents that have it. This work presents a system that addresses the principal characteristics of time perception: duration, sequentially, and time scale. The Conscious Contents Queue, a submodule of the Workspace in the LIDA model, implements the Immediate Present Train and Williams James' specious present. A principal virtue of the Conscious Contents Queue, and its structure building codelet processes, is that they ground time related nodes, enabling the agent to interpret time concepts and to reason with them. This architecture permits the construction of representations of events, including both primitive and higher level events, and their time related attributes. This construction, in turn, permits the agent to understand situations and how they change over time, for example, comprehending cause and effect relationships. In the same way, this model can reason about the future, creating expectations that represent possible future states based in the actual situation. Producing expectations is often crucial for the agent, for example, to facilitate learning (Adcock, Thangavel, Whitfield-Gabrieli, Knutson, & Gabrieli, 2006; Zaghloul et al., 2009)

Even though these are the bare bones of time perception, many time related processes have been explained and incorporated into the LIDA model. This work opens the door to more sophisticated processes like deliberation and metacognition.

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