

Temporal Differentiation of Attentional Processes

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Abstract

In this paper an analysis of the notion of attention is described that comprises a differentiation according to five stages of an attentional process related to action selection and performance. The first stage deals with the allocation of attention to external and internal stimuli, the second with examination and analysis, the third with decision making and action selection, the fourth with action preparation and performance, and the fifth with action assessment. The analysis involves temporal formalisation and validation based on data from a human operator executing a warfare task.

Introduction

In the literature on attention, an assumption often implicitly made is that attention is a single, homogeneous concept (e.g., Itti and Koch, 2001; Theeuwes, 1994). However, in recent years, an increasing amount of work is aimed at identifying different subprocesses of attention. For example, many researchers distinguish at least two types of attention, i.e. perceptual and decisional attention (e.g., Pashler, 1998). Some others even propose a larger number of functionally different subprocesses of attention (e.g., Laberge, 2002; Parasuraman, 1998). However, most of these studies describe the different subprocesses of attention in an informal manner. In contrast, the current paper explores the possibility of describing different subprocesses of attention in more detail, using formal techniques from areas such as Artificial Intelligence. According to this perspective, the following research question is formulated (in the context of a situation where multiple objects exist and where actions have to be undertaken with respect to these objects):

Is it possible to formally define a temporal differentiation of a number of subprocesses within an attentional process?

A first answer to this question could be affirmative in the sense that, for example, attention to examine a number of options, attention to prepare for a selected action, and attention to assess the effects of an action performed, seem different types of attention. This results in the hypothesis that such a differentiating definition indeed is possible.

Being able to distinguish between different types of attentional processes can be beneficial for a number of reasons. First of all, on a theoretical level, the attempt can be used to enhance the understanding of the attentional processes. But on a more practical level it can be beneficial as well. For example, in the domain of naval warfare, a

crucial but complex task is tactical picture compilation. In this task, the naval warfare officer has to compile a tactical picture of the situation in the field, based upon the information (s)he observes on a computer screen. Since the environment in these situations is often complex and dynamic, the warfare officer has to deal with a large number of tasks in parallel. Therefore, in practice (s)he is often supported by automation that takes over part of these tasks. However, a problem is how to determine an appropriate work division between human and system. Within a rapidly changing environment, such a work division cannot be fixed beforehand (Bainbridge, 1983; Campbell, Cannon-Bowers, Glenn, Zachary, Laughery, and Klein, 1997; Inagaki, 2003). A solution to this is to let the system determine such a task allocation at runtime: the system decides which of the tasks it takes over from the user, and which tasks it leaves to the user. This is a setting in which it can be very useful for the system to have information about the particular attentional state or process a user is in. For example, in case the user has just started to prepare for performing an action with respect to a certain track on the screen, it will be better to leave that track for him or her, whereas it is better to take over some of the tracks for which there is only attention of an examinational type or no attention at all.

To answer the above mentioned question on attentional process differentiation in a more systematic manner, in relation to a specific type of sense-reason-act cycle, in this paper five attentional subprocesses are distinguished and formally defined. These characterisations not only refer to state aspects, such as gaze directions, but also to temporal aspects for the time interval in which the state occurs. The temporal specifications identified have been validated in an empirical case study. This validation has been performed by representing the empirical data in a formal manner and by automatically checking the temporal specifications against this formally represented empirical data.

The structure of the paper reflects the research method used. First, at a conceptual level, different types of attentional processes were distinguished and an empirical case study was chosen. The empirical data were formally represented to enable automated analysis, and the different attentional processes were formalised in a temporal manner. Finally, validation of these specifications for the empirical material was performed in an automated manner using the TTL software environment (Bosse, Jonker, Meij, Sharpanskykh and Treur, 2006).

Distinguishing Attentional Processes

This section provides a (temporal) differentiation of an attentional process into a number of different types of subprocesses. The attentional process is considered in the context of a situation where multiple objects occur and where actions have to be undertaken with respect to (some of) these objects, for example as in the case study described below. To differentiate the process into subprocesses, a cycle *sense – examine – decide – prepare and execute action – assess action effect* is used. It will be discussed how different types of attention within these phases can be distinguished.

- *attention allocation*

This is a subprocess in which attention of a subject is drawn to an object by certain exogenous (stimuli from the environment) and endogenous (e.g., goals, expectations) factors, see, e.g., (Theeuwes, 1994). At the end of such an ‘attention catching’ process an attentional state for this object is reached in which gaze and internal focus are directed to this object. The informal temporal specification of this *attention allocation process* is as follows:

From time t_1 to t_2 attention has been allocated object O iff at t_1 a combination of external and internal triggers related to object O occurs, and at t_2 the mind focus and gaze are just directed to object O.

Note that in this paper validation only takes place with respect to gaze and not to mind focus, as the empirical data used have no reference to internal states.

- *examinational attention*

Within this subprocess, attention is shared between or divided over a number of different objects. Attention allocation is switched between these objects, for example, visible in the changing gaze. The informal temporal specification of this *examinational attentional process* is as follows:

During the time interval from t_1 to t_2 examinational attention occurs iff from t_1 to t_2 for a number of different objects attention is allocated alternatively to these objects.

- *decision making attention*

A next subprocess distinguished is one in which a decision is made on which object to select for an action on a certain object to be undertaken. Such a *decision making attentional process* may have a more inner-directed or introspective character, as the subject is concentrating on an internal mental process to reach a decision. Temporal specification of this attentional subprocess involves a criterion for the decision, which is based on the relevance of the choice made; it is informally defined as follows:

During the time interval from t_1 to t_2 decision making attention occurs iff at t_2 attention is allocated to an object, from which the relevance is higher than a certain threshold.

- *action preparation and execution attention*

Once a decision has been made for an action, an *action preparation and execution attentional process* occurs in which the subject concentrates on the object, but this time on the aspects relevant for action execution. The informal temporal specification is as follows:

During the time interval from t_1 to t_2 attention on action preparation and execution occurs iff from t_1 to t_2 the mind focus and gaze is on an object O and at t_2 an action a is performed for this object O.

- *action assessment attention*

Finally, after an action has been executed, a retrospective *action assessment attentional process* occurs in which the subject evaluates the outcome of the action. Here the subject focuses on aspects related to goal and effect of the action. For example, Wegner (2002) focuses on such a process in relation to the experience of conscious will and ownership of action. The informal temporal specification of this attentional process is as follows:

During the time interval from t_1 to t_2 action assessment attention occurs iff at t_1 an action a is performed for this an object O and from t_1 to t_2 the mind focus and gaze is on this object O and from t_2 they are not on O.

Case Study

The characterisations of the different attentional processes as presented above have been validated in a case study. This case study is based on a human participant executing a warfare officer-like task (cf. Bosse, van Maanen, Treur, 2006). The software Multitask (Clamann, Wright & Kaber, 2002) was altered in order to have it output the proper data to validate or reject the hypothesis stated in the introduction of this paper. This study did not yet deal with altering levels of automation (as was the subject of study in Clamann et al.’s work), and the software environment was momentarily only used for providing relevant data. Multitask was originally meant to be a low fidelity air traffic control (ATC) simulation. In this study it is considered to be an abstraction of the cognitive tasks concerning the compilation of the tactical picture, i.e., warfare officer-like task. A snapshot of the task is shown in Figure 1.

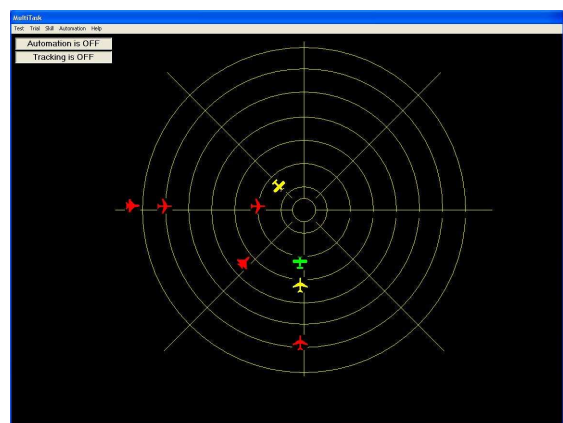


Figure 1: The interface of the used experimental environment based on MultiTask (Clamann et al., 2002).

In the case study, the participant (controller) had to manage an airspace by identifying aircrafts that all are approaching the centre of a radarscope. The centre contains a high value unit (HVU) and had to be protected. In order to do this, airplanes needed to be cleared and identified to be either hostile or friendly to the HVU. This task involves the following elements. Clearing involves six phases: (1) a *red*

colour indicates that the identity of the aircraft is still unknown, (2) *flashing red* indicates that the warfare officer is establishing a connection link, (3) *yellow* indicates that the connection was established, (4) *flashing yellow* indicates that the aircraft is being cleared, (5) *green* indicates that either the aircraft was attacked when hostile or left alone when friendly or neutral, and finally (6) the target is *removed* from the radarscope when it reaches the centre. Each phase takes a certain amount of time. In order to go from phase 1 to 2 and from phase 3 to 4, the participant has to click on the left and the right mouse button, respectively. Within the conducted experiment three different aircraft types were used: *military*, *commercial*, and *private*. The type of aircraft was not related to hostility. The different types merely resulted in different intervals of speed of the aircrafts. All of the above were environmental stimuli that resulted in constant change of the participant's attention.

The data that were collected consist of all locations, distances from the centre, speeds, types, and states (i.e., colour). Additionally, data from a Tobii x50 eye-tracker¹ were extracted while the participant was executing the task. All data were retrieved several times per second (10-50 Hz).

Empirical Data Representation

In order to analyse the results of the experiment conducted based on the above mentioned case study, the retrieved empirical data have been converted to a formal representation based on *traces*. Traces are time-indexed sequences of states. Here a *state* S is described by a truth assignment to the set of basic *state properties* (ground atoms) expressed using a state ontology Ont ; i.e., $S: At(Ont) \rightarrow \{true, false\}$. A state ontology Ont is formally specified as a sets of sorts, objects in sort, and functions and relations over sorts. The set of all possible states for state ontology Ont is denoted by $States(Ont)$. A trace γ is an assignment of states to time points; i.e., $\gamma: TIME \rightarrow States(Ont)$. To represent the empirical data of the case study, a state ontology based on the relations in Table 1 has been used.

Table 1: State ontology used to represent the data.

<code>gaze(x:COORD, y:COORD)</code>	The subject's gaze is currently directed at location (x,y)
<code>is_at_location(i:TRACK_NR, x:COORD, y:COORD)</code>	The track (aircraft) with number i is currently at location (x,y)
<code>mouse_click(x:COORD, y:COORD)</code>	The subject is clicking with the mouse on location (x,y)
<code>has_status(i:TRACK_NR, v:INT)</code>	Track i has status v ; e.g., 'red'. ²
<code>has_distance(i:TRACK_NR, v:INT)</code>	The distance between track i and the centre of the screen is v . ³
<code>has_type(i:TRACK_NR, v:INT)</code>	Track i has type v ; e.g., 'military'. ⁴
<code>has_speed(i:TRACK_NR, v:INT)</code>	The speed of track i is v . ⁵

¹ <http://www.tobii.se>.

² Here, 9 = "red", 8 = "yellow", 5 = "flashing red", 4 = "flashing yellow", 3 = "green", and 1 means that the track is currently not active.

³ This v is calculated using the formula $v=10-(d/550)$, where d (which is a number between 0 and 5500) is the actual distance in pixels from the centre of the screen; $v=1$ indicates that the track is currently not active.

⁴ Here 8 = "military plane", 6 = "commercial plane", 4 = "private plane", and 1 means that the track is currently not active.

Note that in the last four relations in Table 1, v is an integer between 0 and 10. The idea is that, the higher the value of v , the more salient the corresponding track (aircraft) is for within this task. For example, a red track is more salient than a yellow track (since red tracks need to be clicked on more often before they are cleared), but a yellow track is assumed to be more salient than a flashing red track (since it is not possible to click on flashing tracks; one has to wait until they stop flashing). Based on the above state ontology, states are created by filling in the relevant values for the state atoms at a particular time point. Traces are built up as time-indexed sequences of these states. An example of (part of) a trace that resulted from the experiment is visualised in Figure 2. Each time unit in this figure corresponds to 100 ms in real time.

Formalisation of the Attentional Processes

In this section, the different attentional subprocesses, as earlier described informally, are formalised as dynamic properties in the Temporal Trace Language TTL (Bosse et al., 2006). This predicate logical temporal language supports formal specification and analysis of dynamic properties, covering both qualitative and quantitative aspects. TTL is built on atoms referring to *states*, *time points* and *traces*, which are defined as explained in the previous section. In addition, *dynamic properties* are temporal statements that can be formulated with respect to traces based on the state ontology Ont in the following manner. Given a trace γ over state ontology Ont , the state in γ at time point t is denoted by $state(\gamma, t)$. These states can be related to state properties via the formally defined satisfaction relation denoted by the infix predicate \models , comparable to the Holds-predicate in the Situation Calculus: $state(\gamma, t) \models p$ denotes that state property p holds in trace γ at time t . Based on these statements, dynamic properties can be formulated in a formal manner in a sorted first-order predicate logic, using quantifiers over time and traces and the usual first-order logical connectives such as \neg , \wedge , \vee , \Rightarrow , \forall , \exists . A dedicated software environment has been developed for TTL, featuring both a Property Editor for building and editing TTL properties and a Checking Tool that enables formal verification of such properties against a set of (simulated or empirical) traces.

First, some useful predicates are defined that are used in the formalisation of the different attentional processes:

$$\begin{aligned} \text{gaze_near_track}(\gamma:\text{TRACE}, c:\text{TRACK}, t_1:\text{TIME}) \equiv \\ \exists x_1, y_1, x_2, y_2:\text{COORD} \\ \text{state}(\gamma, t_1) \models \text{gaze}(x_1, y_1) \ \& \\ \text{state}(\gamma, t_1) \models \text{is_at_location}(c, x_2, y_2) \ \& \\ |x_2 - x_1| \leq 1 \ \& \ |y_2 - y_1| \leq 1 \end{aligned}$$

$$\begin{aligned} \text{mouseclick_near_track}(\gamma:\text{TRACE}, c:\text{TRACK}, t_1:\text{TIME}) \equiv \\ \exists x_1, y_1, x_2, y_2:\text{COORD} \\ \text{state}(\gamma, t_1) \models \text{mouse_click}(x_1, y_1) \ \& \\ \text{state}(\gamma, t_1) \models \text{is_at_location}(c, x_2, y_2) \ \& \\ |x_2 - x_1| \leq 1 \ \& \ |y_2 - y_1| \leq 1 \end{aligned}$$

⁵ The variable v is calculated using the formula $v=s/100$, where d (which is a number between 100 and 1000) is the actual speed (in pixels per second). Furthermore, $v=1$ indicates that the track is currently not active.

$\text{action_execution}(\gamma:\text{TRACE}, c:\text{TRACK}, t2:\text{TIME}) \equiv$
 $\text{mouseclick_near_track}(\gamma, c, t2) \&$
 $\exists t1:\text{TIME } t1 < t2 \&$
 $\forall t3:\text{TIME } [t1 \leq t3 \leq t2 \Rightarrow \text{gaze_near_track}(\gamma, c, t3)]$

The reason for using `gaze_near_track` instead of something like `gaze_at_track` is that a certain error is allowed in order to handle noise in retrieved empirical data. Usually, the precise coordinates of the mouse clicks do not correspond exactly to the coordinates of the tracks and the gaze data. This is due to two reasons: 1) a certain degree of inaccuracy of the eye tracker, and 2) the fact that people often do not click exactly on the, for instance, centre of a track.

Based on these intermediate predicates, the five types of attentional (sub)processes as described earlier are presented below, both in semi-formal and in formal (TTL) notation:

A. Allocation of attention

From time $t1$ to $t2$ attention has been allocated to track c iff at $t2$ the gaze is directed to track c and between $t1$ and $t2$ the gaze has not been directed to any track.

$\text{has_attention_allocated_during}(\gamma:\text{TRACE}, c:\text{TRACK}, t1, t2:\text{TIME}) \equiv$
 $t1 < t2 \& \text{gaze_near_track}(\gamma, c, t2) \&$
 $\forall t3:\text{TIME}, c1:\text{TRACK}$
 $[t1 \leq t3 < t2 \Rightarrow \neg \text{gaze_near_track}(\gamma, c1, t3)]$

B. Examinational attention

During the time interval from $t1$ to $t2$ examinational attention occurs iff at least two different tracks $c1$ and $c2$ exist to which attention is allocated during the interval from $t1$ to $t2$ (resp. between $t3$ to $t4$ and between $t5$ and $t6$).

$\text{has_examinational_attention_during}(\gamma:\text{TRACE}, t1, t2:\text{TIME}) \equiv$
 $\exists t3, t4, t5, t6:\text{TIME } \exists c1, c2:\text{TRACK}$
 $t1 \leq t3 \leq t2 \& t1 \leq t4 \leq t2 \& t1 \leq t5 \leq t2 \& t1 \leq t6 \leq t2 \&$
 $c1 \neq c2 \&$
 $\text{has_attention_allocated_during}(\gamma, c1, t3, t4) \&$
 $\text{has_attention_allocated_during}(\gamma, c2, t5, t6)$

C. Attention on decision making and action selection

During the time interval from $t1$ to $t2$ decision making attention for c occurs iff from $t1$ to $t2$ attention is allocated to a track c , for which the saliency at time point $t1$ (based on features type, distance, colour and speed) is higher than a certain threshold th .

$\text{has_attention_on_action_selection_during}(\gamma:\text{TRACE}, c:\text{TRACK},$
 $t1, t2:\text{TIME}, th:\text{INTEGER}) \equiv$
 $t1 \leq t2 \&$
 $\exists p1, p2, p3, p4:\text{VALUE } \forall t3 [t1 \leq t3 \leq t2 \Rightarrow$
 $\text{state}(\gamma, t3) \models \text{has_type}(c, p1) \wedge \text{has_distance}(c, p2) \wedge$
 $\text{has_colour}(c, p3) \wedge \text{has_speed}(c, p4)] \&$
 $(0.1 * p1 + 0.5 * p2 + 0.8 * p3 + 0.5 * p4) / 1.9 > th \&$
 $\text{has_attention_allocated_during}(\gamma, c, t1, t2)$

D. Attention on action preparation and execution

During the time interval from $t1$ to $t2$ attention on action preparation and execution for c occurs iff from some $t4$ to $t1$ attention on decision making and action selection for c occurred and from some $t3$ to $t2$ attention on the execution of an action on c occurs.

$\text{has_attention_on_action_prep_and_execution_during}(\gamma:\text{TRACE},$
 $c:\text{TRACK}, t1, t2:\text{TIME}, th:\text{INTEGER}) \equiv$
 $t1 \leq t2 \&$
 $\exists t3:\text{TIME } [t3 \leq t1 \&$

$\text{has_attention_on_action_selection_during}(\gamma, c, t3, t1, th)] \&$
 $\forall t4:\text{TIME } [t1 \leq t4 \leq t2 \Rightarrow \text{gaze_near_track}(\gamma, c, t4) \&$
 $\text{action_execution}(\gamma, c, t2)$

E. Attention on action assessment

During the time interval from $t1$ to $t2$ action assessment attention for c occurs iff at $t1$ an action on c has been performed and from $t1$ to $t2$ the gaze is on c and at $t2$ the gaze is not at c anymore.

$\text{has_attention_on_action_assessment_during}(\gamma:\text{TRACE}, c:\text{TRACK},$
 $t1, t2:\text{TIME}) \equiv$
 $[t1 \leq t2 \&$
 $\text{action_execution}(\gamma, c, t1) \&$
 $\neg \text{gaze_near_track}(\gamma, c, t2) \&$
 $\forall t3:\text{TIME } [t1 \leq t3 < t2 \Rightarrow \text{gaze_near_track}(\gamma, c, t3)]$

All the above TTL properties can be checked in the Checking Tool. An example of how one could check such a property for certain parameters is the following:

$\text{check_action_selection} \equiv$
 $\forall \gamma:\text{TRACES}$
 $\exists t1, t2:\text{TIME } \exists c:\text{TRACK}$
 $\text{has_attention_on_action_selection_during}(\gamma, c, t1, t2, 5)$

This property states that the phase of decision making and action selection holds for track c , from time point $t1$ to time point $t2$, with a threshold of 5, for all loaded traces. This property either holds or does not. If so, the first instantiation of satisfying parameters are retrieved.

Validation

In order to check automatically whether (and when) the above properties are satisfied by the empirical traces, the TTL checker tool (Bosse et al., 2006) has been used. This software takes a set of traces and a TTL property as input, and checks whether the property holds for the traces. Using this tool, all properties as presented in the previous section indeed turned out to hold for the formal trace that was created on the basis of the empirical data. This confirms the hypothesis that a temporal differentiation of a number of attentional subprocesses can be found in empirical data, namely those that are defined in terms of the above properties.

In addition to stating whether TTL properties hold, the TTL checker also provides useful feedback about the exact instantiations of variables for which they hold. For example, suppose that the property `check_action_selection` holds for a certain trace, the checker will return specific values for time point $t1$ and $t2$ and for track c for which that property holds. This approach has been used to identify certain instances of attentional processes in the empirical trace that resulted from the experiment described earlier.

To illustrate, Figure 2 shows part of this trace.⁶ For this trace, the five properties as mentioned earlier hold for the following parameter values:

- `has_attention_allocated_during` holds for track $c=9$, for time points $t1=0$ and $t2=6$

⁶ Due to space limitations, in Figure 2 a mere selection of atoms has been made from the actual empirical trace, i.e., the time interval [65,85).

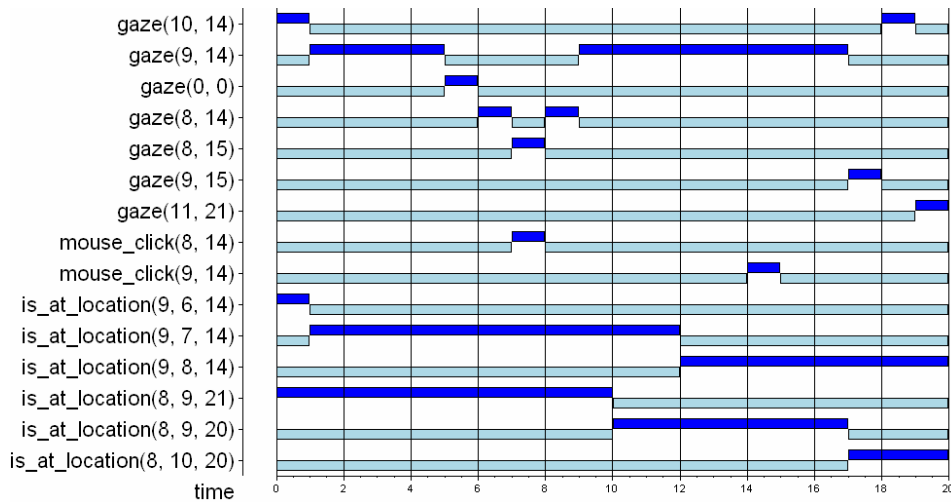


Figure 2: Visualisation of (part of) the empirical trace on the interval [65,85). The vertical axis depicts atoms that are either true or false. This is indicated, respectively, by dark or light boxes on the horizontal axis, in units of 10 ms.

- `has_examinational_attention_during` holds for tracks `c1=8` and `c2=9`, for time points `t1=0` and `t2=19`, because `has_attention_allocated_during` holds for track `c=9`, for time points `t1=0` and `t2=6` and for track `c1=8`, for time points `t1=18` to `t2=19` (note that for `t=17` the gaze is still on track `c=9`)
- `has_attention_on_action_selection_during` holds for track `c=9`, for time points `t1=1` and `t2=6`, and threshold value `th=4`. This is due to the fact that `has_type(9, 4)`, `has_distance(9, 3)`, `has_colour(9, 5)`, and `has_speed(9, 4)`, not shown in Figure 2, result in a combined saliency above `th=4`, for this time period
- `has_attention_on_action_prep_and_execution_during` holds for track `c=9`, for time points `t1=6` and `t2=7`, because `has_attention_on_action_selection_during` holds for track `c=9`, for time points 1 to 6, and `action_execution` holds at `t2=7`, and the gaze is near track `c=9` at time point 7
- `has_attention_on_action_assessment_during` holds for track `c=9`, for time points `t1=7` and `t2=9` (note that after `t2=9` the gaze is not on `c=9` anymore)

Furthermore, the TTL checker enables additional analyses, such as counting the number of times a property holds for a given trace, using a built-in operator for summation. Using this mechanism, one can calculate that the property `has_attention_allocated_during` holds three times for track 1, four times for track 7, one time for track 8, and two times for track 9, in the time interval [0,100) of the empirical trace. A similar calculation shows that `has_attention_on_action_prep_and_execution_during` holds only once, namely for track 9, for the same time interval. Comparison between such counts can be used to, for instance, indicate different task progresses or workload differences.

Discussion

In the literature on attention, various perspectives on the notion of attention can be found (e.g., Itti and Koch, 2001; Theeuwes, 1994). Although they identify various aspects that play a role in attentional processes, most authors still make the implicit assumption that attention is a single, homogeneous concept. However, this assumption makes it difficult to make distinctions between different types of attention that play a role in different phases in the attentional process (e.g., to distinguish between ‘global’ examinational attention that is aimed at several objects and ‘local’ focussed attention that is aimed at only one object). Therefore, the current paper addresses an analysis of the situation that occurs when this assumption is dropped, by explicitly involving the dynamics of attentional processes in the context of a situation where multiple objects occur and where actions have to be undertaken. Given this context, in this paper a number of attentional subprocesses have been identified within the process of attention, following the ideas of (Laberge, 2002; Parasuraman, 1998; Pashler, 1998). Each subprocess plays a specific role in the sense-reason-act cycle. These attentional subprocesses have first been described at a conceptual level, in an informal notation.

In order to obtain empirical data, an experiment has been conducted in which a human subject performs a warfare officer-like task in a simulated environment (cf. Bosse, van Maanen, and Treur, 2006). The data of the subject’s performance were logged, together with the data of an eye tracker that monitored the subject’s gaze during the experiment. After that, both types of data were represented in formal notation (based on a specific ontology), to obtain formalised traces of the empirical process.

Moreover, the semiformal specifications of each of the subprocesses have been formalised in the form of dynamic properties, using the temporal language TTL. Subsequently, these dynamic properties have been automatically checked against the formalised traces by means of the TTL checker (Bosse et al., 2006). The checks pointed out that the dynamic properties indeed held for the traces, which confirmed the existence of the predicted attentional subprocesses in the empirical data. Moreover, since the TTL checker allows the modeller to find out exactly for which time points the properties hold, the analysis method can also be used to indicate in detail which type of attentional subprocess occurs when. This has been done successfully for the data from the experiment.

As also indicated in the introduction, distinguishing between different types of attentional processes can be very useful, for example, in the domain of naval warfare. To determine (in a dynamical manner) an appropriate cooperation and work division between human and system, it has a high value for the quality of the interaction and cooperation between user and system if the system has information about the particular attentional state or process a user is in. For example, in case the user is already allocated to some task, it may be better to leave that task for him or her, and allocate tasks to the system for which there is less or no commitment from the user (yet).

Whereas the current paper is a first step towards a more precise definition of different attentional subprocesses, it is yet far from complete. For example, the attentional processes identified are all related to a certain object, whereas in principle it is also possible to have attention for an empty space (e.g., because one expects that a track will soon appear there). Moreover, the current model mainly addresses the exogenous aspect of attention (i.e., attention triggered by external stimuli), whereas it leaves the endogenous aspect (i.e., attention triggered by internal stimuli (Theeuwes, 1994), e.g. expectations) almost untouched. In future work, it will be explored whether such aspects of attention can be incorporated in the analysis method as well; e.g., (Castelfranchi and Lorini, 2003; Martinho and Paiva, 2006).

Another direction of future research is to validate the formal specification of attentional subprocesses against more data. This step would imply that more traces of attentional processes are acquired, and that the TTL properties mentioned earlier are checked against these traces. Since the TTL checker can take both empirical and computer (simulated) traces as input, it is also possible to check the properties against traces that result from simulation models. In this respect, an interesting challenge would be to generate traces using attention models in cognitive architectures such as ACT-R (Anderson, Matessa, and Lebiere, 1997) or EPIC (Kieras and Marshall, 2006) and compare them to the formal specification of attentional subprocesses being developed.

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