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TEMPORAL AWARENESS IN ATC: LITERATURE REVIEW AND A PROPOSED MODEL

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Air traffic control (ATC) offers a paradigmatic example of a dynamic multi-task environment, placing both considerable and unique demands on the human controllers' cognitive faculties. In particular, the notion of temporal awareness, which is argued here to be fundamental to both controller workload management and task performance, brings together many of the most central components of human information processing system. The temporal dimension of ATC offers thus both a rich task environment for the study of temporal awareness and the associated cognitive processes as well as affords their quantitative measurement for modeling purposes. This paper makes a case for focused research of temporal awareness in ATC and presents a framework for development of time-based controller performance metrics and testing of cognitive models of temporal awareness.

Introduction

Successful control of complex systems implies that the users have a 'mental model' of the system, allowing them to predict its behavior and the consequences of their inputs to it (e.g., Conant, & Ashby, 1970; Norman, 1983; Rouse & Morris, 1986). The necessity of prediction in the control of even the simplest devices or in the performance of the most mundane everyday tasks is obvious, and bespeaks of the congenital role of temporal aspects of mental models in human behavior and performance (Rosen, 1985). Time can hence be seen as an integral dimension of mental models as well as an inherent component and constraint in nearly every human activity.

Human performance in controlling dynamic systems has a reasonably long history in psychological and engineering research (e.g., tracking studies), but time as a focal point in human performance studies has only recently gained in importance. It is apparent that operators do not merely react to information presented to them on panels and meters, but act on the basis of their understanding of the context of the information and the specific task they are performing (Hollnagel, 1988). The difficulties humans have in the control of dynamic situations and systems are well documented (e.g., Waganaar & Sagaria, 1975; Wickens & Hollands, 2000) as are the often catastrophic consequences of these complications in many high-risk sectors (De Keyser, 1995). Examples of such occurrences include air traffic controllers who 'lose the picture' of the traffic under their responsibility, pilots who 'fall behind' their aircraft, and control room operators who become overwhelmed by unanticipated events. Many operator errors can also be classified as temporal (Decortis, De Keyser, Cacciabue, & Volta, 1991; De Keyser, 1995). Consequently, there are several examples of the benefits of computer aiding in predicting the future states of the system in air traffic control (ATC) (Wickens, Mavor, & McGee, 1997; Wickens, Mavor, Parasuraman, & McGee, 1998), process control (Woods & Roth, 1988), and aircraft cockpits (Wiener & Curry, 1980).

The intricacies of control of complex and dynamic systems are particularly well illustrated in the nation's ATC system. Temporal demands are congenital to ATC; the task environment is inherently dynamic and the work often force-paced, with limited opportunities to shed tasks at times of increased workload. The importance of an up-to-date mental model of the traffic situation to the controller is self-evident (a.k.a. controllers' 'picture'; Mogford, 1997; Whitfield, & Jackson, 1982), as are the temporal demands of the controllers' task. Air traffic controllers typically must keep track of multiple simultaneously unfolding events in the airspace under their responsibility and juggle several tasks requiring simultaneous attention and action, often under severe time pressure. The notions of controller mental workload and SA are furthermore central in the modernization efforts of the National Airspace System (NAS) in the U.S. (Wickens et al., 1998)

In addition to the importance of temporal performance of air traffic controllers, time offers a useful domain for research of a multitude of human factors aspects. In addition to the relevance of time to anticipatory behavior in control of dynamic systems, time offers attractive methods for the measurement of covert mental models. Time has a long history as a means to investigate cognitive processes, timing data are relatively easy to obtain under both experimental and naturalistic conditions, and time is a variable that is common to the human, the task, and the environment. Time offers thus a common unit of measurement of human performance in the context of the task, and can be used to infer the goodness of the temporal dimension of the operator's mental model of the task or system being controlled.

In this paper I present a conceptual framework for study of temporal awareness as it pertains to ATC, detail the parameters of a possible model, and suggest relationships between the model parameters and between the model and other cognitive constructs. Some preliminary results are also offered.

Theoretical Underpinnings of Temporal Awareness

Psychology of time and timing processes have a relatively long history of sustained research. This substantial body of research can be classified by the regions in the temporal spectrum, into milliseconds to about 10 s range, seconds to minutes range, and the circadian range of 23 to 25 hours (Collyer & Church, 1998). Other distinctions between studies can be made based on whether they concern time estimation or production of temporal intervals. Time estimation studies can further be divided into those investigating retrospective timing and those examining prospective timing. Finally, a number of relatively recent studies have recognized the role of timing in control of complex systems and ergonomics research (Carmichael, 1997; De Keyser, 1995; Decortis et al., 1991; Hollnagel, 2002; Sougné et al., 1993). However, much of the existing timing literature is only remotely relevant to the problem at hand. The temporal region associated with air traffic controllers' tasks ranges from seconds to several minutes, making research on rhythmic behavior (in the milliseconds range) inapplicable. Similarly, controllers primarily rely on two-dimensional cues of the spatial relationships of the aircraft under their responsibility, available from their plan view displays, as well as other, more abstract and often numerical information. Hence, time-to-contact research (Gibson, 1966; Lee, 1974) is outside of the scope of this problem as well.

Literature relevant to the present topic can be found in the literature on theories and models of timing based on cognitive processes, particularly those of attention and memory (Zakay, Block, & Tsal, 1999), and the literature on prospective memory. It has been demonstrated that cognitive processing indeed affects judgment of durations, consistent with assumptions that visual stimuli are analyzed by visual information processor and a timer, and that attention must be shared with these processors (Thomas & Weaver, 1975). In a contextual model of temporal cognition (Block, 1989) the cognitive context in the timing period contains environmental variations, cognitive strategies, and emotional states. The crux of this as well as an alternative segmentation model (Poynter, 1989) is that duration judgment depends on what else is being processed during the estimation interval, processing of nontemporal information lengthening retrospective duration estimates. Many models of prospective timing, too, assume that temporal information is processed explicitly (e.g., Zakay, 1989) and that this processing requires attentional resources (Michon & Jackson, 1984).

The attentional gate model (Zakay & Block, 1995; Zakay et al., 1999) posits a pacemaker, pulsing at a rate influenced by both environmental and stimulus-specific factors, and an attentional gate that is opened allowing the pulse stream enter a cognitive counter. Attention to time opens the gate further, allowing more pulses pass to the counter and shortening the duration to be estimated. Conditions for allocation of attention to time can also be described (Zakay, 1992). Explicit attention to time increases when temporal relevance is high and when temporal uncertainty is low. Combinations of these determinants produce different levels of temporal awareness and affect the duration estimation performance (Zakay, 1992; Zakay et al., 1999). The model is able to explain many empirically observed phenomena and it provides a description of the nature of attending to time related to other cognitive phenomena. Perhaps the most intriguing aspect of temporal cognition emerges in dual-task conditions. Concurrent non-temporal tasks have been shown to have very specific and predictable effect on temporal secondary tasks, lengthening temporal production and shortening temporal reproductions (Brown, 1997) but the temporal tasks had little or no effect on the non-temporal tasks in the same experiment. This asymmetric interference has some very important implications, as will be discussed below.

De Keyser (1990) identified two kinds of temporal envelopes in a start-up process of an electric power plant: Temporal intervals associated with relatively stable and known states of the process, which allowed the operator attend the transitions and changes of state, and temporal patterns. Rhythmic operation of a simulated nuclear power plant has also been observed (Okada, 1992). Rhythmic operation implied an open-loop control mode using accurate and well-developed mental model and resulted in reduced control error and operator workload, enhancing overall performance. Grosjean and Terrier (1999) defined temporal awareness as a 'representation of the situation including the recent past and the near future," (p. 1443) echoing definitions of mental models and situation awareness (SA; e.g., Endsley, 1995). In an experiment on simulated production lines Grosjean and Terrier (1999) discovered that subjects who had developed good temporal awareness made fewer errors, prioritized their work more effectively, and managed their rest periods better than those with poorer temporal awareness.

Many operator errors can also be classified as temporal (De Keyser, 1995; Decortis et al., 1991). Such errors include mis-estimation of sequences of actions and event, mis-estimation of duration of events with precise boundaries, failures to estimate the right moment to take action, failures to anticipate events, and failure to synchronize collective actions. The commonly used class of errors, errors of omission, can also be divided into subcategories based on time. In addition to a true omission (i.e., a missing action), the action may be delayed or too early (Hollnagel, 1998).

The asymmetric interference effect of dual temporal and nontemporal tasks (Brown, 1997) and the close coupling of temporal cognition, memory, and attention (e.g., Zakay, 1992) seem to make a prospective duration estimation an ideal secondary task for workload measurement. Prospective duration estimation is a natural secondary task in many instances and sensitive to the demands of perceptual discrimination, perceptual-motor coordination, visual and spatial processing, mental rotation, visual search, memory search, and problem-solving, to mention just a few (Brown, 1997). Several researchers have advocated the use of time estimation or time production as an appropriate secondary task measure of workload (e.g., Hart, 1975). The relationship between workload and time estimation may also work in the other direction: Increasing nontemporal workload may affect performance in time-critical aspects of the task and result in timing errors.

Many of the aforementioned theories are closely related with the concept of executive control, first introduced by Baddeley and Hitch (1974) in their Model of Working Memory (Baddeley, 1990; Richardson, 1996). Baddeley's central executive is often compared to the supervisory attentional system (SAS) described by Norman and Shallice (1980), which is a limited capacity system used for a variety of purposes, including tasks involving planning or decision making, trouble-shooting in situations in which automatic processes may run into difficulty, novel situations, and technically difficult situations where strong habitual responses or temptations are involved. The above list is a nearly complete description of air traffic controllers' tasks. Furthermore, models of executive control and the basic mechanisms of executive function are often evaluated through tasks that employ executive resources and require a complex task set: that have been identified as 'executive' or as tasks that rely on processes that are considered governed by executive control, such task switching (e.g., Della Sala et al., 1995) and go/no-go tasks. The relevance of these tasks to ATC is again apparent.

Temporal Awareness in ATC

Temporal awareness in ATC may be hypothesized to be a 'product' of several parallel processes: an internal 'clock' or some timekeeping mechanism (cf. Zakay et al., 1999), and the attentional and perceptual processes that sample the external environment (cf., the perceptual cycle of Neisser, 1976). It may be further hypothesized that human sampling behavior depends on three distinct aspects of temporal awareness: (1) correct time to act on a task or update temporal awareness from cues available in the environment, (2) awareness of the time available for action or checking of cues, and (3) awareness of the time required to perform action or check cues. Temporal awareness might also contain 'quality' information; for example, 'losing the track of time' or suspicion that the internal model cannot be trusted would prompt a person to seek to check or update it by looking up some external cues (e.g., check relative positions of aircraft on a plan view display). Controllers may thus be assumed to maintain a mental 'to-do' list, in which tasks are in a specific order and associated with temporal windows of opportunity within which they must be completed.

An illustration will be helpful for grasping the rationale of the above hypotheses: Imagine a controller working traffic in his/her sector; scanning at the evolving situation on the plan view display (PVD), the controller constructs a mental 'laundry list' of events in the future he/she must do something about. This list might look something like this: '*...ok, hand this one over to center, watch this one pass the opposite traffic and then climb him to [altitude], turn that one on a heading behind the traffic, call center to tell them to reduce the speed of the inbound...*' and so on. This is an endless list, with new items continually added to it and completed items 'checked off' and forgotten. Now, it is clear from this example that the items in the 'to-do' list are in a specific order and that each has a certain temporal 'window of opportunity' (WO) to be completed. The question is then just how does the controller manage the list. It might be hypothesized that he/she does a fair job remembering the items, but does not rely on memory about their correct timing or even sequence, which may be too difficult to estimate with sufficient accuracy in the first place. For timing, then, the controller must frequently update his or her mental model by visually scanning the PVD for external cues for the right time and sequence to act, as well as to add and drop items in the list.

Effective time management in terms of appropriate prioritization, sequencing, and timing of tasks is therefore a critically important skill to meet the demands of the job and paramount to the successful completion of the requisite tasks (Loft, Sanderson, Neal, & Mooij, in press). Task prioritization serves also another, no less important, function in keeping the controller's task load and resultant workload at safe levels. Effective time management and task prioritization in turn plausibly depend on awareness of temporal task characteristics and constraints as well as controllers' own performance, which may be regarded as a special case of SA. Task prioritization, in turn, is driven by 'awareness of time available to perform tasks, anticipation of future difficulties, and the [controller's] knowledge of his or her capacity' (Loft, Sanderson, Neal, & Mooij, in press).

It may be further hypothesized that controllers may heavily depend on external cues and that such cues indeed dominate their attention allocation and timing and scheduling of tasks. Nevertheless, understanding the role and functionality of a temporal awareness is important, for in the absence of external cues or alarms the temporal awareness is all the controller has to make judgments and decisions on. Even if external cues are available, they carry too high information access cost for a given situation (e.g., waiting for several target position updates to accurately estimate its speed or trajectory) and the controller must make a 'snap' decision based on his/her mental model. Understanding the extent to which controllers rely in their temporal awareness *cum* external cues, as well as the fallibilities and biases of their temporal awareness *sans* external cues will help in modeling and predicting controller performance.

Performance implications

The question then is whether failures of temporal awareness follow any predictable patterns, whether they are triggered by particular events or conditions (e.g., task disruptions, workload, etc.), and how such failures (i.e., losing a picture) might be manifested. The Contextual Control Model (COCOM) developed by Hollnagel (1993, 1998) identifies several parameters that may yield useful and practical measures of operator performance. This model distinguishes four control modes, scrambled, opportunistic, tactical, and strategic. In the scrambled mode, human performance is haphazard and unpredictable, without planning, and can be best described as a state of momentary panic, representing a complete loss of SA. The opportunistic mode is only slightly better in terms of performance or SA; the operator merely responds to the most salient events (e.g., alarms) but is not able to plan actions or predict their consequences. The tactical control mode involves planning and the operator is in control of the situation or the system, implying a moderately good SA. Finally, in strategic control mode the operator is in complete control of the task, able to consider the global context, and exhibiting good SA. Human performance in the first two modes can be characterized as reactive and in the latter two modes as proactive. Reactive and proactive behavior may be distinguishable in the timing of actions, offering a potential means for performance measurement.

A Conceptual Model

Air traffic controllers' tasks can be depicted in a form of a timeline (Fig 1) reflecting the dynamic and forced-pace nature of their work. Placing a number of individual tasks that the controller must perform as bars on a moving timeline will show that accurate and appropriate task prioritization depends on estimation of three temporal task parameters: (1) the time when the task becomes 'available', or the time when a window of opportunity to perform it opens, (2) the latest time by which the task must be completed, or the closing of the window of opportunity, and (3) the time required to perform the task. Hence, in Figure 1, we can see that the proper task priority is A, C, B, D, F, E, and G; because task B takes longer to perform than the entire window of opportunity for task C, task C should be done first which still leaves enough time to do task B before its window closes.

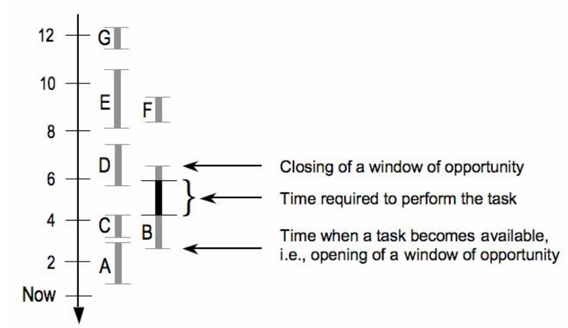

Figure 1. A time line representation of air traffic controllers' tasks. The numbers on the timeline depict minutes and the line itself if 'flowing' down with time; separate tasks to be performed are depicted my bars right of the line and labeled with capital letters. It can be seen that task E becomes available at about 8 minutes from now and must be performed before 10.5 minutes from now. Several parameters of temporal awareness may be derived from this figure.

Cognitive Demands of Temporal Awareness

It is clear that forming and maintaining accurate temporal awareness in ATC poses enormous cognitive demands on controllers. Viewing temporal awareness as a continuum, with reactive behavior in the low end and proactive behavior in the high end, it is reasonable to assume that controllers typically operate with less than perfect temporal awareness, or with awareness of only a subset of the temporal variables associated with the tasks. Exactly which temporal variables controllers may be aware of, and how accurately, as well as how temporal awareness may depend on momentary task load are important research questions.

Monitoring of tasks and temporal cues to them and estimation of time available to perform tasks, or the estimation of windows of opportunity (e.g., aircraft's distance to sector boundary or coordination point) will require attentional resources. These may be modeled by the SEEV model of Wickens et al. (2003; see also Schriver & Rantanen, this volume). Maintenance of a mental 'laundry-' or 'to-do' list, on the other hand, will place substantial load on working- and prospective memory (cf. Baddeley, 1990; Norman & Shallice, 1980; Richardson, 1996). Knowledge of time required to perform tasks draws from controllers' mental model of task requirements and own performance, which may be assumed to reside in the long-term memory and be subject to knowledge-based biases and errors (Reason, 1990). Finally, estimation of elapsed time during tasks and distractions will depend on some internal time-keeping mechanism (e.g., Zakay et al. 1999). Hence, temporal awareness in ATC offers a unique and very rich domain for research of a multitude of cognitive processes; conversely, existing research is readily applicable to modeling of controller performance.

Measurement of Temporal Awareness

From Figure 1, several measures of temporal awareness may be derived, such as the proper prioritization of tasks and the 'timeliness' of performance. In particular, it may be possible to measure the elapsed time from opening of a window of opportunity on individual tasks to an observable action on that task; good temporal awareness is manifested in timely performance on tasks, or consistently short 'time to first action' from the opening of the window. Degradation of temporal awareness in turn is manifested in increasing variability in attending of tasks and late performance (completion of tasks after closing of the window of opportunity). Figure 2 illustrates these metrics.

Indeed, it has been shown that the time to first action is a measure that is sensitive to workload (Rantanen & Levinthal, 2005), which plausibly disrupted the subjects' temporal awareness in two multi-task experiments. Similar results were obtained also from another study, examining controller performance in high-fidelity simulation; in a total of six different tasks the timeliness of performance deteriorated as task load in the simulated scenarios was increased (Rantanen et al., 2006). It was also shown that controllers exhibited awareness of the temporal characteristics of their tasks, manifested in strong trend to perform tasks that had been 'available' longer, i.e., whose window of opportunity had opened earlier, before tasks whose window of opportunity had been opened later, signifying a 'first come, first served' approach to task prioritization. This trend persisted as task load increased. Controllers also had awareness of the urgency of their tasks, as those with impending closing of window of opportunity were performed before tasks that had longer time available before closing of window of opportunity (Rantanen et al., 2006).

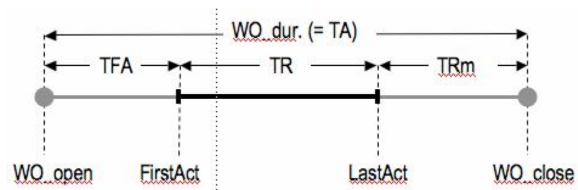

Figure 2. Derivation of measures of temporal awareness from know task demands and observable actions of the controller. Consistent and timely performance of tasks indicates good temporal awareness. Key: TA = Time Available, TFA = Time to First Action, TR = Time Required, and TRm = Time Remaining.

Conclusion

The results described above emerged from aggregation of large amounts of data. It is clear that innumerable factors are present in each prioritization decision made by controllers in the line of their work and that the first come, first served scheme as well as the apparent sense of urgency observed in the above results were only two possible factors among many. However, the fact that these patterns indeed did emerge from different experimental tasks and data collected from realistic and only minimally controlled situation attests to the strength of temporal factors and the controllers' awareness of them in task prioritization. It appears safe to conclude that no feasible model of controller temporal awareness could possibly consider all factors present in each prioritization decision or individual differences among the decision-makers to make accurate case-by-case predictions of task prioritization. However, consideration of the temporal task characteristics in prioritization algorithms could very well produce realistic aggregate level predictions of controller performance.

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