PRESENTATION REPORT

A Cognitive Framework for Modeling and Analysing Safety-Critical Human Multitasking

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1 Introduction

Nowadays people often interact with multiple devices at the same time. In such multitasking situation the human attention works as a scheduler among concurrent processes. The way attention is directed to different tasks is connected to the amount of cognitive resources required to the accomplishment of the goal. Thus if this amount for some task is too high this might prevent them from being completed. Moreover, if one of such tasks is safety critical, the wrong addressing of attention to such task could cause dangerous consequences.

Such kind of situations could lead to different potential problems. The concurrent use of memory may cause an overload and may lead the user to forget memory items that are crucial to complete a given task. Human multitasking could also cause the user to ignore the critical task for too long, while focusing attention on less critical tasks. Finally, a critical task could be ignored in a crucial moment because attention is directed to other tasks. Therefore, there is an evident need to study and analyze whether a human can safely perform multiple tasks at the same time.

We propose an executable formal framework which includes cognitive processes involved in the interaction [3]. The model is a modification and extension of the cognitive framework proposed by Cerone in [4] for the analysis of interactive systems. The main difference with this framework is that Cerone only considered the interaction with a single device, whereas we focus on analyzing human multitasking. Moreover our framework also captures the limitations of a humans working memory (WM) and includes timing features.

In [6] is proposed a similar approach, based on the *salience* of actions which the user may perform; such salience could be affected by several factors, such as the cognitive load imposed by the complexity of the task performed. However, their cognitive model does not explicitly model WM, and is guided mainly by assumptions about the salience of user cues.

Our framework enables us to analyze the interaction of a user with multiple devices by their interfaces through simulation, reachability analysis and model checking, in order to better understand the cause of the possible errors which may occur in multitasking, and in order to suggest possible design solutions to these errors. The framework is specified in Real-Time Maude.

We illustrate our formal framework by studying the use of a GPS navigator while driving [3] and the concurrent use of two infusion pumps by an clinical operator [2].

2 Cognitive Background

WM is a cognitive system with a limited capacity, responsible for the transient holding and manipulation of information. Several theories have been proposed to explain the functioning of WM. One of the most successful on explaining experimental data is the "Time-Based Resource-Sharing Model" [1]. The theory builds on the following hypothesis:

- Items stored in WM are subject to processing and maintenance activities; these activities use the same cognitive resource, the attention.
- When attention is drawn away from maintenance activities, the items decay over time.
- Each task is characterized by a measure of the temporal density of attentional demand: this measure is called cognitive load (CL). When activities on items in WM are performed at a constant pace, CL is equal to $\sum(a_i \cdot n_i)/T$, where n_i is the number of activities of type i, a_i their difficulty and T the total duration of the task. The higher is the CL of a task, the more it attracts attention.

Other experimental studies on human performance have shown that both attention and CL have a key role in multitasking scenario. In particular, in [5] it has been shown that human performance with a "main" task decreases when the CL of a "distractor" task increases, since there is a redirection of attentional resources from the main to the distractor task.

Our cognitive framework attempts to integrate the Time-Based Resource-Sharing Model with experimental results on human selective attention.

3 Formal Model

We model the cognitive framework in an object-oriented style. The state consists of a number of *Interface* objects, representing the interfaces of the devices with which a user interacts. A *Task* object inside each interface object, defining the task that the user wants to perform on that device. And an object *Working Memory* representing the users working memory.

Working Memory. Working memory is modeled as a map assigning to each interface the set of information needed for the interaction with that interface. An element in memory could be a basic information (that is a cognitive item acquired through a procedural step in the current task), a cognition (that is a mental plan resulting from the process of acquiring knowledge and understanding) or a goal (that is the objective of the interaction). The WM object has an attribute capacity denoting the maximal number of elements that can be stored in memory at any time.

Interfaces. We model an interface as a transition system. As regards the states we follow a user-centric approach: the state of the user interface describes what the user perceives. Some interface states may be subject to a timeout, capturing the fact that the state/perception may not last forever. After a given time the state will become expired.

An interface transition has the form p_1 `--` *act* `-->` p_2: the interface state changes from $p1$ to $p2$ when the user performs the action *act*.

Tasks. The task object is modeled inside the interface object as an attribute. We model a task as a sequence of subtasks, where each subtask is a sequence of basic tasks, actions that can be no longer decomposed. A basic task has the form:

$$inf_1 \mid p_1 \texttt{ ==> } act \mid inf_2 \texttt{ duration } \tau \texttt{ difficulty } d \texttt{ delay } \delta$$

which models that if the user's WM contains the information inf_1 and the user perceives the interface state p_1, then action *act* can be performed and inf_1 can be replaced with inf_2 in WM. The action has duration τ and difficulty d. Moreover, a basic task may not be enabled immediately: the time needed before the basic task can be executed is given by the delay δ. This delay could also be the time needed to switch from one task to another.

We define two kinds of basic tasks: one retrieved by a basic information and one retrieved by a cognition. The first represents the action the user need to operate on the device and the consequent change of state in the device; the latter represents a change of mind of the user with no involvement of the interface.

Rank function. We assign to each interface a *rank*, which measures the likelihood that the task associated with that interface will attract the users attention. The interface with the highest rank in the configuration will be executed by the user. The rank of each task is a function of the cognitive load of the "current" subtask, the criticality level of the task and the time that task has been waiting.

Since we consider structured tasks with delays we redefine the computation of the cognitive load as follows:

$$CL = \frac{\sum d_i \cdot \tau_i}{\sum \tau_i + \delta_i}$$

where d_i is the difficulty of basic task i, τ_i is the duration of the basic task i and δ_i is the delay of the basic task i. The cognitive load of a task therefore changes every time a new subtask begins, and remains the same throughout the execution of the subtask.

Rewrite Rules. We model a set of rewrite rules which apply to the interface with the highest rank and specify how attention is directed at the different tasks.

- *Interacting Rule*: models an interactive task with a device.
- *Cognitive Rule*: models a change of the mental state of the user or an acquisition of knowledge without no interaction with the device.
- *Closure Rule*: models the achievement of the goal.
- *Forgetting Rule*: models the deletion of items from WM when it is full and new information items have to be added.

4 Case Studies

We applied our formal framework to two case studies. In the first one we model the use of a GPS navigator system while driving, in the second one we model the

interaction with two medical devices, namely two infusion pumps, at the same time.
In the first case we use our framework to analyze whether:

- an enabled driving task can be ignored for more than six seconds.
- an enabled driving task can been ignored in a crucial moment, for instance during a bend in the road.
- the concurrent usage of WM could lead to memory overload and may cause the user to forget memory items that are crucial to complete the driving task.

We found such a bad state for all these cases.

In the latter case study we use our framework to check whether a given WM capacity is sufficient to achieve the goal. This helps to obtain a quantitative evaluation of the complexity of the task, in terms of memory load, and to identify memory overload which could lead to some omission errors. We found that when the WM capacity is set to 5 the operator can't never achieve the goal, since he forgets a useful information to complete the task successfully (i.e. to open the clamp).

5 Future Works

To validate the cognitive hypothesis embedded in our framework, an experimental study has been finalized in which users are asked to interact with a screen application presenting two tabs: one representing the main task, the other representing the distractor task. Users need to interact with both tabs concurrently. The experiment will be modeled in our framework to check the framework's predictive power and accuracy. The experimental results will also be used to tune some parameters of the model.

Finally, at the moment probabilistic features of the model are handled by a java probabilistic simulator. We aspect to develop a probabilistic framework based on PMaude.

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