Reasoning about human error by modeling cognition and interaction

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Abstract. In this paper we focus on system resilience from the perspective of understanding human error. In particular, we consider systematic cognitive slips, including post-completion errors, which are persistent, though infrequent. We outline the findings from empirical studies that have identified various factors that provoke or mitigate against such errors. We then describe approaches we are pursuing to encapsulate these insights in ways that can be re-used within system design. More broadly, we argue that an understanding of the factors that influence the likelihood of such errors can support organizations in designing systems and processes to minimize the likelihood of such errors.

1 INTRODUCTION

Many system failures are attributed to "human error". However, there is now widespread recognition that, while "human error" may be the immediate and direct cause of failure, other factors such as organisational practices (Reason, 1990) or system design (e.g. Leveson and Palmer, 1997) are instrumental in facilitating or provoking error. While some errors appear to be stochastic, others have been shown to be systematic – i.e. there are patterns in the physical system design or user task structure that make particular error types more likely than pure chance. One aspect of resilience engineering – the one we focus on in this paper – is ensuring that new or adapted system designs do not provoke systematic human errors. Our approach to this is to investigate situations in which errors occur, under controlled laboratory conditions – an approach which complements work (e.g. Leveson and Palmer, 1997; Norman, 1983) based on accident reports and anecdotal accounts of error. The insights from such empirical studies are encapsulated in formal (interactive) system models that support verification to identify cognitively plausible errors.

The pervasiveness of many classes of error is strong. Our work has shown that even when an individual is actively engaged in avoiding erroneous performance they still, on occasion, fail (Back et al. 2006). Some classes of such persistent errors, such as "capture error" (Norman, 1983) and "post-completion error" (Byrne and Bovair, 1997) have been well described in the literature. Their surface manifestations, or phenotypes (Hollnagel, 1993), are reasonably well understood but their underlying cognitive causes, or genotypes, less so. We have developed ways of manipulating environmental conditions so that causal explanations of human error can be developed and represented within formal models. In this paper, we focus on post-completion errors, as a particular class of human error, present our approach to investigating these errors and summarize our findings from these studies. We briefly consider other kinds of systematic cognitive slips, as an extension to our approach. Then we outline ways to encapsulate these findings in a way that makes the insights reusable in new design contexts and discuss how this approach might be used in an organizational context.

2. POST-COMPLETION ERRORS: AN INTRODUCTION

Post-completion errors (PCEs) are a class of errors in which a terminating step is required – but omitted – after the main goal of an interaction is achieved. PCEs are persistent (they cannot be eliminated through training) but infrequent; they are a kind of cognitive slip (i.e. not due to incomplete or incorrect knowledge of the task). Examples of such errors include leaving the petrol (or gas) filler cap off after refueling; leaving the original on the photocopier but walking away with the copies; and leaving an ATM with the money but without the bank card. These errors all share some common features:

- Each involves an action sequence that opens with satisfying some precondition (that the filler cap be off, that the original be on the glass of the photocopier, that the card be inserted into the ATM).
- There is a subsequent action sequence that achieves the main goal of the interaction (that the car is refueled, that copies are obtained, that cash is possessed).
- There is a final 'clean-up' step to restore the state of the system (filler cap replaced, original retrieved, card retrieved).

A second class of PCEs omits the opening precondition, but finishes with a confirmatory step; examples include programming the VCR but forgetting to set it to record (Gray, 2000), and recording a voice-mail message but forgetting to save it (e.g. by pressing the # key). Byrne and Bovair (1997) and Chung and Byrne (2004) investigated the effects of working memory load and visual cueing on PCEs using a Star Trek-based game called the Phaser task in which the post-completion step was to turn off tracking of the phaser. They concluded that PCEs are susceptible to high working memory load, but that the errors can be mitigated by a timely visual cue.

3. METHOD

In our studies, we have used various games (developed in-house) that optionally include a post-completion step. Each game and associated instructions to participants involved the manipulation of factors such as visual cues, interruptions, working memory load and incentives to establish the effects of these factors on the frequency of PCEs and other cognitive slips.

The first series of experiments manipulated visual cueing: participants were required to solve a set of river-crossing problems (such as the well known 'Missionaries and Cannibals'), some of which included a post-completion step of returning the vessel (empty) to the first side of the river (Li et al., 2005). In one variant, participants had to recall the names of the people and objects to be sent across the river on each journey; in the other, they were able to select the names from a pull-down menu. The pull-down menu included the name of the vessel, which therefore served as a passive visual reminder to complete the final step of the puzzle. Two variants of the menu were tested: one where the items were listed in alphabetical order and one where the position of the vessel in the list was adjusted to be particularly obvious to users. A between-subjects experiment was conducted to establish whether the visual cue helped to reduce PCE rate and whether the position of the vessel name in the list made any difference.

In another series of controlled experiments, we investigated the effects of interruptions on PCEs (Li et al, 2006). Many real world PCE situations involve moving away physically from a device once a task is completed. Our interruption effect experiments simulated this environmental context. Primary and secondary tasks were implemented on separate computer terminals. The primary task was to make doughnuts following a set of predefined steps to operate the machine correctly in order to produce the required number of doughnuts. The secondary interrupting task was a mental arithmetic task that required participants to pack different numbers of doughnuts by following some simple arithmetic rules. The PCE step was the "Cleaning" step at the end of the doughnut-making task. It required the participant to click on a button labeled "Process/Cleaning". The presence of a new doughnut order indicator after the completion of a trial was a false completion signal, which is a distinguishing feature of many PCE tasks (Reason, 2002). Two sets of experiments were conducted: one manipulated the position of interruption within the task structure; the other manipulated the duration of the interruption.

Forgetting to perform a previously formulated intention can be induced by the visual salience of a subsequent procedural step that captures attention. This is one reason why false completion signals can trigger PCEs during routine interaction. However, a visually salient procedural cue is clearly not always cognitively salient. Cognitive salience is an individual's self-awareness of what they have to do next. Further experiments endeavoured to unpack this notion. In an attempt to boost cognitive salience, two experiments were designed that explicitly motivated participants to avoid error (Back et al, 2006).

The importance that an individual assigns to a particular goal may influence how the goal is performed. If the goal is critical to achieving a task then an individual may be motivated to ensure that performance is error free. Two gaming environments were designed to examine the frequency of omission errors where participants were actively trying to avoid them (Back et al, 2006). A modified version of the classic space invaders game and a car driving game were developed. After training, participants playing space invaders knew that after rescuing an astronaut they were required to return to firing mode. If this step was forgotten then all points accumulated for that level would be lost. Remembering to perform this step was difficult since when the primary task of rescuing an astronaut was completed, attention was switched to the secondary task (shooting aliens), which was a concurrent background task. Participants playing the driving game knew that after completing a police report they were required to release the handbrake before driving away from the kerbside. Failure to release the handbrake would result in all points being lost. This step was easy to forget since it required a participant's attention to be switched between tasks making it difficult for them to attend to the appropriate procedural cue (i.e., the brake light on the car).

4. FINDINGS

Our river-crossing experiments, which manipulated visual cueing, showed that even a passive visual cue helps to reduce error rates, but that the position of the vessel name in the list did not result in a statistically significant difference in performance. This finding is contrary to the prediction of Chung and Byrne (2004), who hypothesised that only an active visual cue that appeared immediately before the PCE step would have an effect. Our studies show that even a passive cue can have an effect in reducing the rate of PCEs (Li et al, 2005).

Our interruption effect experiments revealed that interruption position influences PCE rates (Li et al, 2006). The first experiment showed a significant main effect of interruption position on PCE rate: significantly more PCEs were obtained when the interruption occurred just before the PC step than interruptions at any other points in the task. The second experiment replicated the interruption position effect but did not show a reliable difference in PCE rates between a 45-sec and a 15-sec interruption. This indicates that position is of much greater concern than duration of any interruption for the effective completion of safety-critical tasks.

Results from the space invaders experiment show that motivating participants did not significantly reduce the frequency of the error between levels (i.e., practice did not assist error avoidance). This finding provides further support to the idea that a 'priming process' is needed to facilitate remembering. Space invader participants usually avoided making an error, but sometimes the associated link, remembering to activate the gun after rescuing an astronaut, was not strong enough if a participant was expending extra effort to avoid alien fire while rescuing an astronaut. It was found that if it took longer than usual to complete an astronaut rescue then the likelihood of an error occurring significantly increased. Although this finding is consistent with Byrne & Bovair's (1997) working memory theory, it also suggests that the intrinsic difficulty of the 'task critical' step might provide a causal explanation for why these errors occur.

The car driving experiment investigated whether the use of different cue types coupled with a participant's goal of avoiding error influenced systematicity. Neither the textual nor symbolic cue allowed participants to avoid errors. Although the textual cue reduced the number of errors when compared to the symbolic cue, this difference was not significant. Interestingly, it was found that an individual's ability to remember information relevant to the task (in short term memory) could be used to predict the likelihood of error. In this experiment the 'task critical' step was submitting a police report. If the process of providing the report, i.e. remembering details about cars of a specific colour, was more difficult, then the strength of the cue, i.e., remembering to release handbrake after submitting report, was lower and an error was more likely.

5. BEYOND PCES: INVESTIGATING OTHER COGNITIVE SLIPS

Thus far, only PCEs have been discussed. These errors are ones in which an individual forgets to perform a previously formulated intention. Recently we have also investigated errors that occur when the wrong action sequence is performed after failing to attend to a visually salient cue (Back et al, in preparation). The aim was to discover whether action sequence errors are sensitive to the same factors that influence omission errors. The effects of both intrinsic and extraneous load were considered. Intrinsic load is imposed by overall task difficulty. Extraneous load is imposed by the quantity of information presented to an individual that is not relevant to the task being performed. A simulation of a 'Fire Engine Dispatch Centre' was developed. A between-subjects experimental design was used: participants performed either the high extraneous load version or the low extraneous load version. Intrinsic load was manipulated between trials in both versions. It was hoped that this experiment would help to increase our understanding of factors that influence the allocation of attention to cues that are used to prime previously formulated goals.

In this study, it was found that the effectiveness of procedural cues, which may be used to facilitate a 'priming process' enabling recollection of previously formulated intentions, can be influenced by intrinsic and extraneous factors (Back et al, in preparation). When performing actions that involved repetitive device-specific steps that did not vary from trial to trial (in this case: prioritisation of incoming calls to the fire engine dispatch centre, and selection of a backup fire engine unit), participants were unlikely to attend to visual cues provided by the system. Although a cognitive process was required when deciding which call to prioritise and which backup unit to select, the device-specific procedural requirements (clicking a box, confirming the selection, and pressing "Start") remained consistent. Actions that required a participant to attend to an indicator (in this case: to determine the type of navigational information needed by a fire engine), when selecting an appropriate action sequence, clearly require an individual to be more proactive when allocating their attention. It was found that omission errors that occurred during actions, which involved repetitive device-specific steps, were significantly more likely if the intrinsic difficulty of the overall task was high. Unsurprisingly, the amount of extraneous perceptual load did not influence error rates since a participant was not actively allocating their attention. Errors associated with actions that did require attention to be allocated to an indicator were only significantly more likely when both intrinsic and extraneous load were high.

6. ENCAPSULATING INSIGHTS

Norman (1981) suggested that slips can be attributed to a failure to perform necessary attentional monitoring, making an inappropriate attentional check, or forgetting. Our series of experiments suggests that by investigating the effects of interruption and considering the cognitive salience of cues we can model these underlying cognitive causes.

This deeper understanding of users' cognition and system design can be encapsulated in various ways. We have explored several ways of doing this, including expressing it in terms of abstract, formal specifications of user behaviour and also encapsulating it as 'design rules'. In the former case, the understanding is expressed in a user-centered way: as a description of the systematic ways people can be expected to act as a consequence of cognitive principles. In the latter, it is expressed in a system-focused form: guidance about the way systems should or should not be if systematic human error is to be avoided.

Our focus has been on exploring how formal descriptions can be used for these purposes. A formal specification of abstract user behaviour gives a precise description that can aid understanding if validated by empirical evidence. By constructing formal specifications of both user and system, it also becomes possible to conduct formal verifications that particular classes of human error will not manifest themselves with particular system designs (Rukšėnas et al, forthcoming). This explicit encapsulation supports inspection of the assumptions made about user behaviour, and also reasoning about changes in system design that might change the likelihood of particular errors occurring.

Similarly, design rules can be expressed formally, making more precise the circumstances in which they apply, so addressing apparent contradictions in informally written rules. This also opens up the possibility of automatically checking that such design rules have been adhered to by a particular system. Furthermore, with both a formal description of abstract user behaviour and of design rules, it becomes possible to verify the design rules against the user description: in essence showing that the design rule is sufficient to prevent a person from making specific kinds of error when behaving in the cognitively plausible way encapsulated in the formal user specification (Curzon and Blandford, 2004).

A final advantage of creating such formal models is that, due to the preciseness needed, the process can drive the empirical studies – raising new questions due to uncertainties in the way features of cognition should be modeled. This helps refine the understanding of cognition, resulting in an improved understanding of human error and how to design it out of systems.

7. DISCUSSION

Resilience to human error may be considered from many perspectives: organisational, social, breakdowns in team working, etc. In our work, we are focusing on the individual. At this level, minimising human error in interactive tasks involves minimising both knowledge-based mistakes (caused by users having incorrect or incomplete knowledge of the system and how to operate it) and slips. In the work reported here, we have focused on understanding slips and their underlying cognitive causes.

One of the striking features of all the omission errors we have studied (and we have studied them because they are systematic) is that they involve actions that do not move an individual towards a goal state, but remain critical to performing a task correctly. We refer to these types of actions as being device-specific. Gray (2000) found that device-specific actions are the hardest type of actions to perform correctly even when a routine has been practiced. Gray suggested that if such actions are required then the device should be designed in such a way that makes their accomplishment unavoidable.

One widespread way of making such actions unavoidable is by modifying the task sequence so that the device-specific action must be completed before the task goal is achieved. For example, most ATMs have been designed so that they require the user to remove their card before the cash is dispensed. However, there are many situations where changing the sequence of actions required is not possible (e.g. when a sequence of actions is to be performed many times before the completion step and the number of iterations is determined by the user, not the system). In some situations, a solution is to use physical means to remind the user to complete the action; for example, many supermarkets have key-operated tills where the key is physically attached to the staff member so that s/he cannot leave the till without securing it. However, again, this solution is not universally feasible.

In our experiments, we have established the importance of procedural cueing and visual or auditory cueing in encouraging correct task performance. This, in turn, suggests ways of making systems more resilient to errors of this type. Where possible, interruptions should be minimized, or their timing should be controlled. For example, in a study of ambulance dispatch (Furniss and Blandford, 2006) it was found that one of the important roles of the radio operator in the dispatch team was to act as a buffer for information to the controller: this buffering meant that the timings of interruptions were controlled to avoid times when the controller was at a critical point in any dispatch task. There are many situations in which is it impossible to eliminate interruptions, or to control their timing: in such situations, procedural cueing (in which one step in a task is cued by preceding steps) cannot be relied on. Therefore, external cues are needed. Chung and Byrne (2004) propose that such cues should be timed; our studies have shown that even passive cues can help mitigate against error.

A final, important, finding – which contradicted our intuitions – is that motivation does not appear to have an effect on error rate for people forgetting device-specific actions. Results from the space invaders and driving game show that even when a participant is motivated to avoid error, and the system provides symbolic or textual cues, some types of omission errors remain pervasive (Back et al, 2006).

This work has established the importance of cognitive salience in minimizing cognitive slips. Where cognitive salience is low (notably for device-specific actions that do not move the system state towards a task goal), design moves need to be made to minimize the likelihood (or consequences) of users forgetting actions. Where it is not possible to force actions (through task sequence or physical means), procedural or external cueing can be used to minimize the likelihood of error. This understanding is one important contribution to an approach to reasoning about resilience in interactive systems design.

ACKNOWLEDGEMENTS

This work is funded by a UCL studentship to Simon Y. W. Li and by EPSRC grants GR/S67494 and GR/S67500. We are grateful to all participants in our studies.

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