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Post-error expression of speed and force while performing a simple, monotonous task with a haptic pen

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Control errors often occur in repetitive and monotonous tasks, such as manual assembly tasks. Much research has been done in the area of human error identification; however, most existing systems focus solely on the prediction of errors, not on increasing worker accuracy. The current study examines force responses before, during and after errors in a simulated assembly line task in order to determine an optimal feedback system for error reduction. Confirming previous findings, enhanced movement speed and reduced force occurred before erroneous trials and slowing occurred after erroneous trials. Given the results, we suggest a haptic feedback system which stimulates users to exert increased force levels after completing an erroneous task in order to increase degree of control and re-build worker confidence and thereby reduce overall error rate.

Keywords: haptic interface; human error; feedback

1. Introduction

As industrialisation spreads, so does the need for highly efficient production processes. Much research exists in the area of human error identification. However, most existing methods rely solely on error prediction and ignore the potential for increasing worker performance via haptic feedback. By developing systems for post-error feedback, workers could learn finer motor control and re-build confidence in their performance of the task. As workers adapt their skills, via such feedback, they would reduce their overall error rate. Thus, error prediction should not be considered as the goal in itself, but as a supporting element in a more comprehensive error reduction system.

The current article focuses on observing the behaviour of users after performing an error in a simulated assembly line in order to develop appropriate post-error feedback for error reduction. We chose a simulation of a manual production task for our experiment since repetitive and monotonous tasks remain highly error prone. In addition, in large and complex systems such as manual production lines, minor errors may lead to more serious consequences further down the line.

Previous work used the results of the same dataset to predict participant performance over the entire task and at any given instant within the task at over 90% accuracy based solely upon facial features automatically extracted from short video segments of the participants performing the task (Jabon *et al.* in press). Our work extends these findings to include analysis of the haptic responses of participants before, during and after an error. As observed in literature, higher speed (Wobbrock *et al.* 2008) and reduced force (Gehring and Knight 2000) occurred before erroneous trials. Furthermore, slower execution speeds occurred after errors (Laming 1968, Rabbitt and Rogers 1977). Based on the findings, we hypothesise that by monitoring control tasks appropriate feedback can be triggered when an error is made to increase subsequent accuracy and increase worker confidence.

1.1. *Previous work*

The speed by which a task is performed has been explored extensively in relation to accuracy (Plamondon and Alimi 1997), and it is well known that increased speed while performing a task leads to less accuracy (Fitts 1954). Thus, measuring the speed at which tasks are performed may support the prediction of errors (Wobbrock *et al.* 2008). In addition to measuring the speed before the onset of an error, the force employed while performing a task may also be a predictor for errors. In speeded response tasks, a reduction in response force has been observed during

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erroneous trials (Gehring and Knight 2000). This may be attributed to the fact that individuals attempt to correct errors while making them (Scheffers *et al.* 1996).

Given that feedback systems could support individual attempts to correct for errors, the movement dynamics after errors occur is also relevant. In speeded response tasks, individuals took longer to initiate a response after an error (Laming 1968, Rabbitt and Rogers 1977), since they might want to prevent another subsequent error (Laming 1979). This process is addressed to as post-error slowing, and some researchers suggest that it can only be observed when participants are aware of their errors (Nieuwenhuis *et al.* 2001). Post-error slowing may be attributed to adaptive control mechanisms that induce more careful behaviour to reduce the probability of committing a new error and are thereby likely to increase accuracy (Botvinick *et al.* 2001).

Feedback systems aimed at reducing manual errors while maintaining optimum speed of movement for a given task may utilise changes in speed of movement as mentioned above. Furthermore, observed changes in applied force levels during a control task may be utilised to inform the system (Wei and Körding 2009). However, there appears to be a lack of studies focusing on the degree of applied force during a movement task after an error, despite the fact that force feedback systems have gained importance in movement training systems (Feygin *et al.* 2002, Jacko *et al.* 2004). In experiments where participants had to respond to the Eriksen Flankers task by squeezing a dynamometer, errors, resulted in less force while squeezing. This behaviour related to the so-called error-related negativity is a component of the event-related potential and is suggested to be an attempt to break the erroneous response (Gehring *et al.* 1993). However, it is unclear whether applied force levels after errors occur in control tasks are also correlated with lower exerted force levels.

The current article describes an experiment that measured the development of speed and force before and after performing a control task. Differences between correct and erroneous trials were explored. As observed in literature, higher speed (Wobbrock *et al.* 2008) and reduced force (Gehring and Knight 2000) occurred before an erroneous trial. Furthermore, slower speeds occurred after an error (Laming 1968, Rabbitt and Rogers 1977). Based on the findings related to error-related negativity (Gehring *et al.* 1993), the hypothesis is that forces will decrease after an error and that this information can be used to develop relevant user-feedback systems for error reduction.

2. Method

2.1. *Participants*

Fifty-seven undergraduate and graduate students were recruited for either payment or class credit. Data from 10 of these participants were discarded due to technical problems during data collection. The final results are based on data from 18 female participants and 29 male participants.

2.2. *Task*

The experimental task consisted of a simple and monotonous routine of fitting screws into designated holes for half an hour. The session was administered at a computer station (Figure 1a) and the program led the participant through the experiment without any intervention from the experimenter. On the left-hand side of

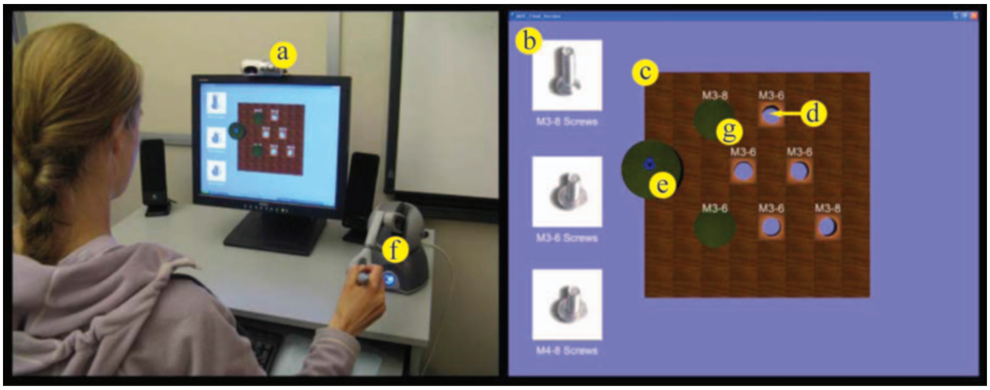

Figure 1. The left image shows the experimental setup with the PHANTOM Omni® haptic device (f) and the right image presents a screenshot of the experimental task screen (right). On the left-hand side of the screenshot are the three boxes (b), each containing a screw with a different part number. In the centre of the screen, is a large wooden board (c) with seven holes marked with a randomly selected set of the different part numbers (d). In the presented screenshot, the large green circle (e) represents a screw that is being moved and the smaller green circles (g) represent screws that have already been placed.

the monitor, participants were presented with three boxes (Figure 1b), each containing a screw with a different part number. In the centre of the screen, there was a large wooden board (Figure 1c) with seven holes also labelled with a randomly selected set of the different part numbers (Figure 1d).

Participants had to pick up a virtual screw (Figure 1e) from one of the boxes using a haptic pen (Figure 1f) and insert it into the hole with the correct part label (Figure 1g). Instructions explicitly indicated that participants did not need to worry about unfinished holes, as the screen would periodically refresh to show new wooden boards. Success or failure to screw in the parts was indicated by a beep; when a participant successfully 'screwed in' a screw by holding the screw inside the hole for 1 s, she heard a beep. The lack of a beep signalled that the participant had not screwed in the part completely. The program was designed to emit a beeping sound whenever a screw was completely fixed in the hole, regardless of the accuracy of the part matched with the hole in the wooden board. Thus, even when the participant screwed in a wrong part, she heard a beep. However, this happened only in 0.6% of the cases.

The wooden boards were programmed to refresh to a new board with a new set of seven empty holes after a pre-programmed amount of time, regardless of the participants' progress. Each presentation of a box was considered to be one 'phase' of the experiment. The first board was timed to refresh after 45 s but every time the participant successfully filled out two consecutive boards without any errors (indicating that the level of difficulty was too low), the given phase time was curtailed by 3 s. The curtailment was not inversed if participants made too many errors. At the end of the half-hour duration, a 'Thank you' screen was displayed, indicating the termination of the experiment.

2.3. *Apparatus*

A haptic device, the SensAble PHANTOM Omni® (Figure 1f), was used as an input device. The device is a pen with six degrees of freedom (x, y, z, pitch, yaw and roll), which is able to provide force feedback on the x, y and z planes with a maximum exertable force of 3.3N. The haptic device was placed on the right- or left-hand side of the monitor depending upon the handedness of the participant. Speakers were placed on both sides of the monitor to emit the confirmation beeping sounds for each fixed screw.

2.4. *Procedure*

Upon arrival at the lab, the participant was seated at a desk with a computer equipped with a webcam, a haptic device and speakers. After filling out a simple demographic information questionnaire, a general consent form and a photo/video consent form, the participant was introduced to the haptic device. Extra attention was given to explaining that although the flat screen monitor could only represent objects in two dimensions and no visual depth cues were present in the graphical representation, the haptic device allows for a third dimension which involves depth perception. During this explanation, the participant was encouraged to feel not only the height and the width but also the depth of the object displayed on the monitor. The haptic device moved freely but the maximum haptic force feedback was presented whenever the participant pushed against the virtual wooden board.

After exploring the haptic device, the task was explained in detail with built-in practice phases, which presented visual aid for the instruction of the unfamiliar device. The experimenter performed the first practice phase as an example and watched over the participant as she went through three more practice phases. The experimenter ensured that all participants were acquainted with using the haptic device before beginning the actual experiment. For the practice phase, each wooden board was displayed for 2 min each to give plenty of time for participants to familiarise themselves with the task. None of the participants requested additional practice sessions. After the practice phase, the actual experimental session began. The half-hour session was conducted without any communication between the experimenter and the participant although the experimenter was present in the room at all times, seated facing away from the participant. After the test, the participant was thanked and debriefed.

3. Results

From the raw data, first the times were calculated from the moment the screw was picked up until it was dropped or placed in a hole. Second, measures of force were calculated for the last second before the correct (with auditory feedback) or incorrect (without auditory feedback) placement of the screw. Finally, the time was calculated from the moment the screw was dropped or placed in a hole to the moment the next screw was picked up. The mean speed was calculated by dividing the distance over which the screw was moved, calculated by averaging the changes in x, y and z coordinates of pick-up location and drop-off location, by the time between drop-off and pick-up. The mean forces over the three periods were calculated by averaging the sum of the forces in x, y and z direction by the time between drop-off and pick-up. Mean amount of boards was 45.3 with SD 6.6 and mean

Table 1. Results RM ANOVA comparing speed and force before, during and after each trial.

	Before trial	During trial	After trial	df	*F*
Speed correct trial (m/s)	0.3 ± 0.1	n.a.	1.1 ± 0.3	1,46	318.2*
Speed erroneous trial (m/s)	0.6 ± 0.1	n.a.	0.5 ± 0.2	1,46	12.7*
Force correct trial (N)	3.5 ± 5.9	6.6 ± 12.3	1.8 ± 2.8	1,46	11.5*
Force erroneous trial (N)	2.0 ± 3.0	3.1 ± 5.7	0.8 ± 0.9	1,46	8.2*

Note: $^{*}\alpha \leq 0.01$.

board display time was 33.6 s with SD 7.7. The first six boards were considered as practice and are therefore excluded from further analyses.

An analysis of variance (ANOVA) with repeated measures (RM) design with speed and force for both correct and erroneous trial set as dependent and the moment (before, during and after) the trial set as independent variables yielded significant effects for all factors ($p < 0.01$). Participants increased their speed after a single successful trial $F(1,46) = 318.2$ and decreased after an erroneous trial $F(1,46) = 12.7$. Furthermore, forces were lower before successful trial $F(1,46) = 11.5$ and higher before an erroneous trial $F(1,46) = 8.2$ (see Table 1).

One-way ANOVAs with speed before and after a trial, and force before, during, and after a trial set as dependents and erroneous or correct trial set as factor, with significance set at 0.05, also showed significant effects ($p < 0.01$). Higher speed resulted in errors $F(1,92) = 152.0$ and errors caused post-error slowing $F(1,92) = 115.8$. Furthermore, forces were lower after erroneous trials $F(1,92) = 4.9$ ($p < 0.05$) (see Table 2).

Finally, one-way ANOVAs were conducted with speed before and after a trial, and force before, during and after a trial set as dependents and single and repeated errors set as independents. A maximum of nine errors in a row were observed, which occurred two times. Due to the infrequent observation of the higher amount of repeated errors, all repeated errors were grouped. No significant differences were found for average forces and average speed between repeated and single errors (see Table 3).

Table 2. Results for one-way ANOVAs comparing correct and incorrect trials for speed and force.

	Correct trial	Erroneous trial	df	*F*
Speed before trial (m/s)	0.3 ± 0.1	0.6 ± 0.1	1,92	152.0*
Speed after trial (m/s)	1.1 ± 0.3	0.5 ± 0.2	1,92	115.8*
Force before trial (N)	3.5 ± 2.0	2.0 ± 3.1	1,92	2.5
Force during trial (N)	6.6 ± 12.3	3.1 ± 5.7	1,92	3.2
Force after trial (N)	1.8 ± 2.8	0.8 ± 0.9	1,92	$4.9^{\dagger}$

Note: $^{\dagger}\alpha \leq 0.05$; $^{*}\alpha \leq 0.01$.

Table 3. Results for one-way ANOVAs comparing single and repeated errors for speed and force.

	Single error	Repeated error	df	*F*
Speed before trial (m/s)	0.6 ± 0.1	0.5 ± 0.2	1,61	2.2
Speed after trial (m/s)	0.5 ± 0.2	0.5 ± 0.3	1,61	0.8
Force before trial (N)	1.9 ± 2.9	3.8 ± 7.7	1,58	2.0
Force during trial (N)	0.8 ± 0.9	0.9 ± 1.2	1,61	0.0
Force after trial (N)	3.1 ± 5.6	4.6 ± 11.6	1,61	0.5

4. Discussion

This study investigated the development of force before, during and after an error during a simple, monotonous task. The principal finding is that the amount of force exerted on the haptic pen was lower after erroneous trials than it was after correct trials. No differences were found for repeated errors in comparison to single errors. However, the latter results should be considered with prudence given the low effect sizes. Additional behavioural findings of this study, relating to the same task, confirm findings observed in earlier studies. As found by Wobbrock *et al.* (2008), in the current experiment participants made more errors when they tried to complete the task at a higher speed. In addition, it took participants more time to initiate the next trial after an error, which is consistent with theories on post-error slowing (Rabbitt 1966, Laming 1968). Furthermore, the lower forces before and during an erroneous trial, which may be attributed to online corrections, are also consistent with what was found in literature (Gehring and Knight 2000).

As reflected in the study on reduced squeezing behaviour given a negative stimulus (Gehring *et al.* 1993), the results of the experiment showed a decrease in force after an error. This could indicate that in addition to post-error slowing, the reduced force after an error may also be the result of a more careful action (Botvinick *et al.* 2001). The reduced force level after an error is made may also be a continuation of the attempt to correct an error while making it (Scheffers *et al*. 1996).

In the introduction, two relevant aspects were addressed for measuring behaviour before and after the occurrence of an error. First, sensing these movements could provide insight on how to predict errors as suggested by Wobbrock *et al*. (2008). However, the main reason for investigating behaviour after the onset of an error is its relevance for the development of feedback systems that could support in reducing errors and gaining control. The human nervous system constantly uses error information to improve movement performance, for example people appear to be able to adapt the speed of their arm movements while compensating for changes in force application (Bock 1990). Wei and Körding (2009) suggest that feedback on errors during motor adaptation should be designed by combining visual and proprioceptive cues to facilitate the learning process. On the other hand, Jacko *et al*. (2004) suggest that haptic feedback is combined best with auditory cues to increase performance.

The results of the current study indicate that haptic feedback could guide manual movements after an error occurs, for example by braking the movement to stimulate the user to reduce speed while performing a task to gain more control and accuracy. Additionally, haptic force feedback could support the user after an error by increasing the speed of the movement after completing a task; this is likely to be less frustrating than providing feedback that counteracts a movement. However, future experiments are required to explore whether implementing such feedback mechanisms in real-time non-critical tasks or training systems could increase control and may thereby reduce errors.

5. Conclusions and future works

The current findings suggest that in line with post-error slowing, another expression of bodily actions, i.e. force expression is also inhibited by less-frequently occurring events such as errors. Expression of movement after an error could provide relevant information for the development of feedback systems that support in reducing errors and thereby increasing performance. Future work should explore how force feedback can be implemented in products to counteract errors. Furthermore, it should address whether these systems are beneficial and will provide a positive experience for the end-user.

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