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Complex Control Skills Acquisition Supported by Haptic Feedback

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Abstract *– This experiment explores the possibility to support the acquisition of complex physical control skills (e.g. balancing skills) by means of haptic feedback in the control interface. The actual physical control task is also perceived visually. This constitutes the common situation of remote controlling a complex, physical process while only visual feedback plus possibly a limited set of local measurements can be provided.*

Two classes of haptic feedback are distinguished. First, haptic feedback reflecting the remote sensor measurement in a guiding form (negative feedback) is considered as a form of communicating the local situation. In the second class the forces which are supposed to be felt are reflected in the haptic controls (positive feedback). The effects of changing interface forces as well as preferences in groups of different levels of experience or age are investigated.

The hypothesis: 'Human operators learn to remotely guide an acceleration controlled vehicle significantly faster and achieve higher accuracy, if vehicle-centric inertia data is provided via haptic feedback in the user interface.'

Keywords: **Haptic feedback, Human movement studies, Motor skill learning, Acceleration controlled vehicles, Remote control operation**

1. Introduction

The required skill set to manually guide fast, non-trivial, multidimensional systems includes a mental model of the plant which enables responsive, yet accurate control commands as well as the motor skills to deliver them in synchrony with the plant. Practical examples for such systems are: balancing a pole in the palm of your hand, avoiding an unexpected obstacle while riding your bike, or hovering a helicopter. Common to all those systems is that it is not sufficient to 'replay' learned motor patterns – even though a certain level of 'blind replay' also happens in those system on lower control levels.

Figure 1: Hovering a 1 m rotor span helicopter as an example of a complex and high-speed guidance task.

Fast sensor perception seems essential to address these high-speed problems accurately. Yet it is not clear how rich and diverse the sensor input needs to be to provide sufficient information for the human operator without 'flooding' his or her sensory system.

In this article the authors focus on the discussion of the meaning of the haptic (or force) feedback component in the learning phase of a complex system guidance problem. The question is approached by setting up a minimalist, yet sufficiently complex system, which can be simulated and displayed in a directly comprehensible way on a computer screen. It is possible to control and stabilize the system by means of the visual feedback alone. Yet it has to be shown whether additional haptic feedback of different kinds can or will improve the performance of the human operator.

A similar case of visuohaptic learning is discussed in [3] where blind reproduction of complex trajectories was investigated. It was found that the memorization of static trajectories could be improved by providing haptic feedback (in addition to visual feedback). This article raises very similar questions but in the context of interactive motor skills.

Results from this article are intended to be used to design a new interface for helicopter pilot training (Figure 1), in order to shorten the training times and to communicate optimal control paths as well as virtual control guides in an intuitive manner. While other works investigated the possibility to communicate the existence of obstacles in the flight path [2] this article focuses on haptic feedback with respect to the current dynamics situation of the craft itself. Furthermore the tactile information is only communicated via modified traditional controls, even though it is well understood that other sensor modalities play an essential role in the communication of flight dynamics as well. Nieuwenhuizen et. al. for instance investigates in [5] the impact of pilot seat roll rates and accelerations.

2. Experimental procedure

A group on n people who claim to have no prior experience in remote controlling complex systems and a group of m experienced remote control operators form the base for the following experiments. People of both groups are drawn for one of the three main test groups A, B and C. Index i denotes the inexperienced (A_i, B_i, C_i) and accordingly index e denotes the experienced sub-groups (A_e, B_e, C_e).

2-1. The experimental setup

A computer simulation of a ball on a horizontal plane produces an easily comprehensible, projected 3-d screen display. The plane is fixed at its centre point and is tiltable in both directions. The control stick which is connected to this simulation determines the rotation rates of the plane in x and y by the distance of the control stick from its centre point. Pilots will call them *pitch* and *roll* rates. The ball is controlled by simulated gravity and the current tilt angles of the plane. The perspective of the projection on the computer screen is fixed and does not pan or chase the ball. This is supposed to help the impression of sitting in front of a static mechanical system. At the edges of the plane the ball is stopped and can only be accelerated towards the inside of the plane from there.

The control stick affects the simulation always in the same way, but the forces which are communicated through the stick vary depending on the haptic feedback mode (detailed in the next section).

A sequence of random positions are indicated on the plane – each for a constant amount of time. The candidates are asked to move the ball as close as possible to these positions and keep the ball there.

2-2. The test modes

Table 1 enumerates the experimental phases for each group. The experiment is opened by a 'Balancing' or 'warm-up' phase, which does not provide goal positions on the board, but asks the candidate only to keep the ball stationary, e.g. to 'balance' the ball in whichever position. This first phase suggests that the candidates focus on balancing and slowing down the ball before they progress to the more demanding task of reaching a given goal. This also follows the common practice of learning how to hover a helicopter, before learning how to fly towards a goal position. The different forms of haptic feedback provided are:

a. *None (roll rate proportional)*: the control stick provides a constant centering force which – if the user does not provide any countering forces – slows down any current rotation rate of the plane to zero. This is not haptic feedback related to the dynamic state of the controlled system. This test mode relates closely to traditional helicopter training and flight modes via remote control (Figure 3).

b. *Guide (negative feedback)*: the control stick provides a force which is proportional to the current acceleration forces on the ball and its velocity but in opposite direction, i.e. the interface forces always suggest to slow down the ball (in case of no user intervention).

c. *Unstable (positive feedback)*: the control stick provides a force which is proportional to the current acceleration forces on the ball. This force (in case of no user-intervention) would accelerate the ball

	Group $A = A_i + A_e$	Group $B = B_i + B_e$	Group $C = C_i + C_e$
Balancing	None	Guide	Unstable
1st phase	None	Guide	Unstable
2nd phase	None	None	None
3rd phase	Guide	Unstable	Guide

Table 1: Haptic feedback for each phase and group

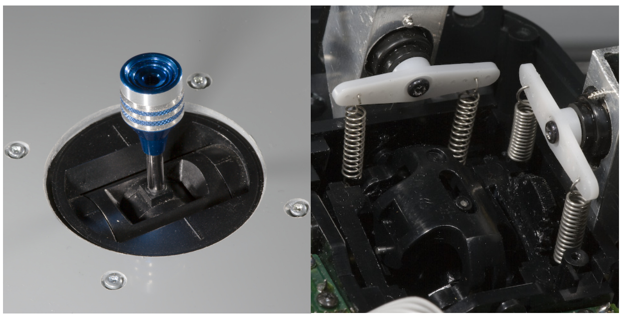

Figure 2: Control stick (left) equipped with haptic feedback servo motors (right)

Figure 3: Typical instructor-student scenario for helicopter hover training without haptic feedback. [Photography: Navinda Kottege]

even further, rather than slowing it down. The candidate can only balance to ball successfully, if countering forces are provided. Another way to describe this form of haptic feedback is that the interface delivers the force which the candidate is supposed to feel in order to slow down the ball. Rather then "guiding the candidate's hand" towards the right control direction (as in the second mode), here the surfaces of the candidates fingers which need to push against the control stick are stimulated.

All three forms of haptic feedback described above are generated by servo motors which are coupled via elastic springs to the control stick axes (Figure 2 left). The control stick as seen and used by the participants does not show any visual differences for any mode (Figure 2 right).

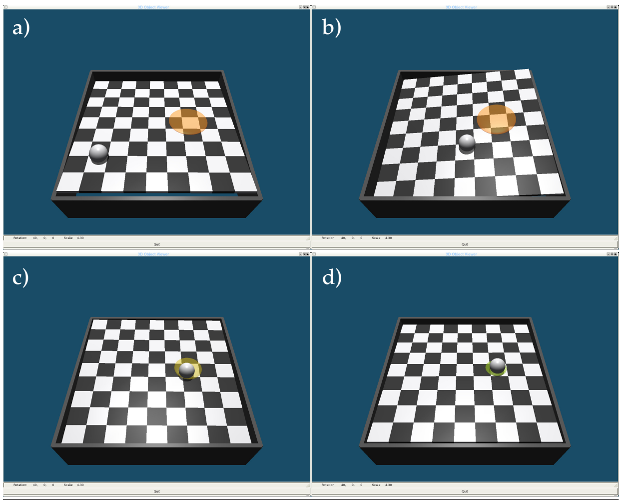

Figure 4: Simulated tiltable board with free rolling ball and goal position

The phases are long enough to allow for a 'saturation' of the performance, i.e. each phase contains a maximum of three different parts:

a. *Understanding the control strengths and magnitudes*: the performance during this part does not reflect anything about the impact of different haptic feedbacks and is deleted in the post evaluation process.
b. *Learning curve*: the part includes the initial performance and the changes in performance while the candidate becomes more 'used' to the control derivative provided. Motor skill learning curves are commonly considered to follow the power law [4] or expressed more mathematically: form a scale invariant polynomial relationship with time – i.e. *not* an exponential relation.
c. *Saturation performance*: the performance in each phase will reach a stable level eventually (provided that the phases are not so long that exhaustion or loss of concentration needs to be considered).

It is intended to keep the participants in a relaxed state at all times, as this experiment does not test performances in stress or competitive situations. Even though hardly avoidable, it is tried to keep the level of decomposed recognition and analytical decision making [1] to a minimum and rather enable holistic perception and intuitive decision making for the test candidates – which is also associated with a skill level often considered not accessible for novices.

2-3. The test protocol[1]

The experiment is completely automated and guided via instructions in the computer screen, which also serves as the visualisation for the ball and plane simulation. The test setup (Figure 5) consists of a centred control stick mounted slightly elevated over the table surface and with enough space to rest arms on either side. The computer monitor is titled backwards and lowered in a way that the simulated board appears approximately as resting on the same table as the control stick mount. The participants rank themselves in terms of experience and indicate their age group. The computer then randomly assigns the participant into one of the three groups (while keeping the group sizes as close as possible).

A set of on-screen instruction motivates the physical system to be controlled (ball on a tiltable board), the goal (manoeuvre the ball to a set of displayed positions on the board and keep it there), and the fact that the control stick directions refer to the x

1 The applied protocol has been approved by the ANU Human Research Ethics Committee (protocol number: 2008/252) and y tilt directions of the plane. The goal appears at a random position as a larger orange disk (Figure 4.a). Once the participant manoeuvred the ball closer to the goal, the colour of the goal shifts to green and the displayed disk shrinks to allow for more precise positioning (Figure 4.c & d). After a short while a new goal position appears at a different location.

The three different test phases are described as 'three rounds' of the same game. It is mentioned that the user-interface (the control stick) might 'feel' slightly different in the three rounds, but the nature of the changes are not described. The three test phases are separated in time by a short break so that the difference in haptic feedback are not directly perceived as switched mode changes.

The participants should start the interactive parts of the experiments with minimal expectations beyond the understanding that the plane on the screen will tilt towards the direction they move at with the control input (control stick). The evaluation criteria though is directly revealed and each test person is requested to guide the ball onto the goals with the highest precision they can provide. In order to keep the participants relaxed and in order to not avoid any mental phase shifts, there is no mentioning of a warming up time and an evaluation time – rather the provided performance is evaluated in post and the first trials where the test person only gains a perception for the 'scale' of the control inputs is ignored.

In the post-experiment questionnaire, the subjective impressions of the differences in the three rounds are recorded. First the performance impression in terms of 'easy' and 'hard' is requested in terms of a scale from 1-5 ('very easy' - 'very hard') for each phase of the experiment. Then also the participant's impression regarding the nature of the perceived interface is prompted. Possibly answers are: 'unnoticed', 'useless', 'de-coupled', 'lagging', 'helpful', 'obtrusive', 'irritating', 'direct' and 'intuitive' (multiple answers per phase are possible).

Figure 5: Test place from the candidate's perspective

2-4. Parameters

The chosen parameters are crucial for the validity of the experiment. Therefore they are summed up in this section for better overview.

a. *Maximal rotation rates*: 20°/second.

b. *Maximally added force*:
1.2-2.2 N depending on control stick position

c. *Relation between inertia, angle and applied force f:*

$$f \sim (g(k_1 v + k_2 \alpha) - u)^* s \qquad (1)$$

with gain $g = 0.39$ for positive feedback and $g = -0.62$ for negative feedback. The constants $k_1 = 5$, $k_2 = 0.4$ are identical for both modes. u represents the deflection of the control stick by the user with respect to the set centre position and s is the spring constant. v is the speed of the ball in m/s, and α is the current tilt angle of the board in degrees.

d. *Time per goal position*: 15 seconds.

e. *Number of goals per phase*: 12.

f. *Length of each phase*: 3 minutes.

2-5. Evaluation methods

The performance evaluations are chosen such that answers to the following questions can be found:

a. *"Which haptic feedback type allows for the best final performance?"* All three test modes are long enough to detect a temporary 'saturation' in performance with each candidate. This limit value is measured.

b. *"Which haptic feedback type allows for the fastest skill acquisition?"* Here only the early improvements are evaluated. It is measured how long it takes to achieve a minimum, 'acceptable' performance. This is evaluated in phase 1 of the experiment.

c. *"Reflect the acquired skills features of the underlying physical system? - i.e. has knowledge about the physical system itself been acquired, or relate the acquired skills only to the combination of the control interface and the physical system?"* For this question the sequence of modes in each group is considered. The performances of group A in phase 2 is compared to the performances of group B and C in

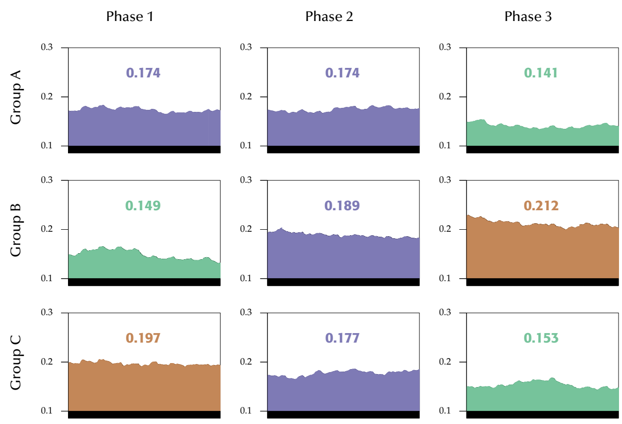

Figure 6: Results by group phases

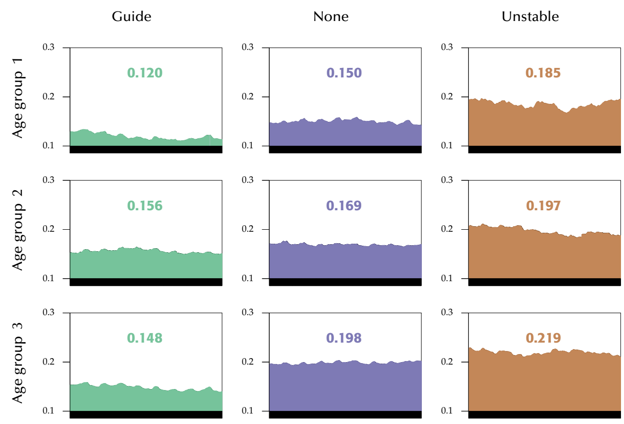

Figure 7: Results by age groups

phase 2, etc. (i.e. identical modes are compared between groups with different previous experiences according to Table 1).

d. *"Are the acquired skills transferable to other control modes? - i.e. could enough knowledge about the underlying system be learned in order to control the system by means of a different interface mode as well?"* Phase three of the experiment might offer insights in this regard, as the performances of well trained group can now either improve, deteriorate, and stay stable, after the interface mode has been changed significantly (specifically for groups *B* and *C*).

e. *"Do experienced and inexperienced participants prefer different haptic feedback types?"* Questions a. to d. are re-visited considering the indicated experience of the participants.

f. *"Is there a relation between age and learning speed, or preference for a specific haptic feedback type?"* Questions a. to d. are again re-visited, now considering the indicated age of the participants.

3. Results and discussion

The results presented here are based on the initial series of experiments which involved 33 candidates from all age groups and previous experiences. Due to the small sample set all results need to be interpreted as suggestions for further investigations rather than final results. All diagrams (Figures 6-8) depict the mean distance from the given goal position over the time of one test phase (3 minutes). The distance measurements are averaged over all candidates of the respective group. The number over each plot is the average distance of the ball from the goal over the whole phase. Green plots represent guided phases, blue plots are phases without haptic feedback, while brown plots represent positive feedback phases.

With respect to the questions *a-f* as formulated in section 2-5:

a. The first question can be answered clearly if only the observed performance is considered: Guiding support (or 'negative feedback'). Figures 6-8 demonstrates that irrespective of prior training, or other recorded candidate characteristics, negative feedback always seems to lead to the best overall performance.

b. It turned out that performances do not significantly improve over the short time of the test phases. A slight improvement over time might have happened in the case of negative feedback, but the test base is too small to be conclusive at this point.

c. Even though performances were significantly influenced by the feedback modalities in phase 1 of Figure 6, phase 2 of group *B* and *C* shows similar performances to the reference group *A*. Thus it seems unlikely that skills reflecting the underlying physical system would have been transferred to a larger degree by any of the haptic interface modes during the first three minute phase.

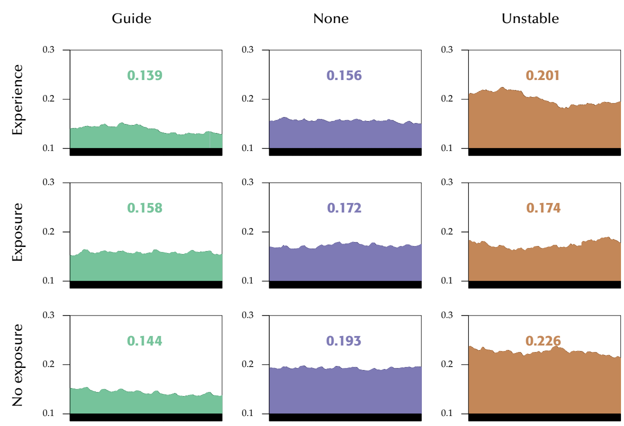

Figure 8: Results by experience

d. Transferable skill acquisition via haptic feedback modes could not be observed. All phase 3 measurements in Figure 6 depict comparable performances to other phases of the same kind, independent of the prior exposure to different haptic feedback controls.

e. Figure 8 indicates that the candidates overall estimated their own expertise correctly, as the middle column shows better performances for more experienced candidates in case of direct control without any haptic feedback. Interestingly though the influence of negative feedback (left column) seem to 'even out' previous experience in practical control, and the performances in this case seem to be comparable over all groups. Positive feedback seems to be least useful for the most experienced and the least experienced group. A potential phenomenon which requires further investigation.

f. Performances slightly degrade with age, but not uniformly (Figure 7). While consistently good performances allow for an excellent average in the youngest age group (age group 1: 14-19), the larger variances at ages of 30+ (age group 3) lead to a worse average. Irrespective of age, negative feedback leads on average to better performances, while positive feedback leads overall to worse performances.

4. Conclusions

A few questions could be answered, but even more new questions arose during the execution of this work. Negative feedback clearly leads to better performances. This is independent of prior experience, age or prior training via different haptic modes. What is also remarkable is that even though prior experience leads to a measurable difference in control performance without any haptic feedback, negative feedback leads to an almost identical degree of performance over all experience groups. The effects of positive feedback could not be captured by the measurements as presented here. On average it leads to significantly worse performances, but in individual cases the responses vary widely. This form of feedback deserves a further deeper investigation, but it cannot be recommended as a general performance improving measure.

It could be clearly shown that haptic feedback has a significant influence on instant ball balancing performances. On the other hand it could not be shown in the measurements up to here that haptic feedback has an effect on learning characteristics of the underlying physical system.

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