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Haptic Support for Aircraft Approaches with a Perspective Flight-path Display

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Abstract—**Perspective flight-path displays are a viable alternative for the aircraft primary flight display, but increases the pilot head-down time. A haptic interface is developed to counter this effect and increase the task-sharing performance during approach. An experiment (n=12) was conducted to test the effects of the haptic design on primary task performance with a tunnel-in-the-sky display, in a low and high workload condition. To investigate the effects of the haptic interface on the head-down time, a secondary task was presented on the simulator outside visual, in the form of bucket-shaped figures, requiring participants to indicate the direction of the one divergent figure. Secondary task performance was measured by success rate, average time to answer correctly and – by means of eye-tracker measurements – head-up time and number of gaze switches. Pilots also provided a subjective measure of their mental effort after each run. Results show that haptic feedback significantly increases both primary and secondary task performance of the pilots, especially when the primary task is more challenging. Workload ratings are significantly lower, and head-up time increases with haptic feedback.**

I. INTRODUCTION

Since the advancement of computer technology in the cockpit, physical design constraints of instruments have been taken away, allowing designers to apply new control formats and ways of information presentation. Using new displays, cockpits have become more intuitive and easy to understand by pilots. An example is the Tunnel-in-the-Sky (TIS) display, a three-dimensional display that shows the aircraft trajectory to be flown in perspective fashion [1]–[3]. Providing pilots with a preview of the trajectory ahead supports them to quickly assess the situation, and makes flying a trajectory much more intuitive compared to current-day primary flight displays.

A potential drawback of the TIS is that, since all relevant flight information is available from just one visually-compelling central display, it attracts a disproportionate amount of pilot attention [4], [5]. Shifting a pilot's focus head-down harms task-sharing performance, which may become worse for smaller tunnel sizes which require pilots to more accurately track the tunnel [6]. Whereas in a two-person cockpit this is not a problem, as during approach the non-flying pilot will continuously look outside, it may be a problem in single-pilot cockpits. Here, the pilot will need to divide her attention between the flight instruments (head-down) and the world outside (head-up).

In this paper we investigate whether the use of haptics could help pilots to maintain a sufficient level of task-sharing performance when using a tunnel-in-the-sky display. Previous research often showed how haptic feedback can improve primary task performance [7], [8]. And advantages of using cross-modal communications – like *visual* and *auditive* – over intra-modal displays have been reported when performing a dual task [9], [10].

We hypothesize here that the same holds for a cross-modal system using vision and haptics. Where the TIS shows pilots the correct course of action through the visual modality, the haptic guidance system relays this information through the haptic modality. The continuous haptic guidance will not only work as a means of communicating the right course of action, it will also guide the pilot towards the right direction by means of *shared control* [11]. However, research also showed that too strong haptic feedback can cause over-reliance, decreased acceptance, and confusion to operators [7], [8], [12]–[14]. Thus the benefits of haptic feedback may depend on the haptic feedback design, which needs to be investigated.

In this paper we will show how the haptic feedback can be based on exactly the same cues as shown visually in the TIS display, and also how the haptic design can be tailored to the constraints imposed by the primary task. Results of an experiment will be discussed where several haptic designs are tested at two levels of taskload. Of special interest will be whether haptic feedback helps pilots to maintain sufficient time heads-up, also when tunnels are small and workload is high, and how this depends on the haptic feedback strength.

II. BACKGROUND

In this section we will explain how the haptic control law was designed, based on the main principles underlying trajectory-following with a tunnel-in-the-sky display. We will start with explaining the latter, then briefly introduce the haptic feedback laws, and the tuning of these such that they support the tracking task shown visually.

A. TIS display and Flight-path predictor symbol

Grunwald invented the combination of a three-dimensional tunnel-in-the-sky display and a flight-path predictor (FPP) symbol [1], see Fig. 1. Here, the tunnel shows the future reference trajectory of the aircraft, the green FPP symbol

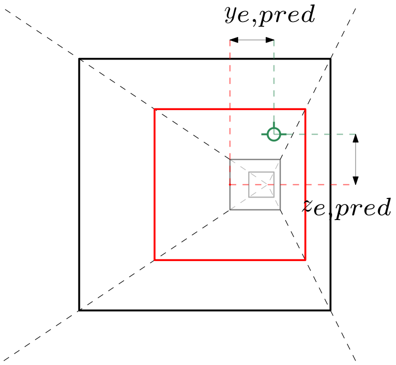


Fig. 1. Schematic Tunnel-in-the-Sky display with a superimposed predictor window (red) and flight-path predictor symbol (green), indicating the predicted lateral and vertical position errors $y_{e,pred}$ and $z_{e,pred}$

shows the predicted aircraft position T_{pred} seconds ahead, and the red square shows where the FPP symbol is relative to the trajectory ahead. Basically, with a well-tuned FPP symbol, the task of the pilot becomes one of keeping the FPP symbol in the center of the red reference frame, i.e., minimize the *predicted* lateral and vertical position errors which can be directly perceived from the display. When the prediction is accurate, then T_{pred} seconds later the aircraft will indeed be flying along the tunnel centerline. This concept very cleverly transforms the multiple-loop aircraft control task into a two-dimensional pursuit tracking task with preview, greatly simplifying the aircraft control task [3].

In order to properly tune the tunnel display and FPP combination, Grunwald proposed so-called predictor laws [15], later improved by Sachs [16]. The essence of the predictor laws is that, when properly tuned, the *equivalent dynamics* between the lateral (vertical) control stick deflection and the lateral (vertical) predicted position error, resp. $y_{e,pred}$ and $z_{e,pred}$ in Fig. 1, become a single integrator. From McRuer's crossover model [17] it is well-known that single integrator dynamics are (highly) preferred by human controllers, as these dynamics allow the operator to act like a proportional controller, that is, the required stick movement is *proportional* to the displayed error on the display.

For more details on predictor laws, the reader is referred to Refs. [15], [16]. Here it suffices to say that in our application we used a second order (circular) predictor for the lateral aircraft dynamics, and a first order (line) predictor for the vertical aircraft dynamics. Computer simulations with a paperpilot showed that the prediction time T_{pred} could be set to 3 seconds in both axes.

B. Haptic feedback

Figure 2 illustrates how we augmented the *visual* two-dimensional pursuit tracking task with preview with the *haptic* controller, yielding a shared control task. As explained in the previous subsection, the pilot can use the directly-perceived lateral and vertical predicted errors to close the loop visually by applying a force F_{human} on the stick. The haptic augmentation boils down to providing information about these predicted errors through computer-generated guidance forces on the control stick, $F_{guidance}$. By cleverly choosing the right haptic feedback control law and haptic gain, a shared haptic control system is obtained.

1) Haptic Design: The haptic feedback aids the pilot in two ways: by means of guidance and by means of communication. Guidance is provided by the haptic controller shown in the upper inner loop; it converts the predicted error in a required stick deflection, which when multiplied with the inverse stick dynamics results in a required force. This force is scaled by the haptic gain yielding the guidance force $F_{guidance}$. The stick position, after haptic and human forces are applied to it, provides useful information to the pilot, as it allows the pilot to perceive the predicted error not only by looking at the TIS display, but also by *feeling* the stick position.

The haptic support is designed to proportionally feed back the predicted lateral and vertical position errors shown on the TIS+FPP display. This means that the information presented through the haptic channel *exactly replicates the information presented visually*, supporting the operator in the highly-preferred proportional control mode. The only parameter which then needs to be tuned is the ‘haptic gain’ in Fig. 2.

2) Haptic Controller: The haptic guidance forces are scaled, proportional controllers of the predicted lateral and vertical position errors:

$$F_{y,guidance} = k_{s,roll} \cdot \left(K_{roll} \cdot \frac{y_{e,pred}}{HTS/2} \right) \cdot K_H \qquad (1)$$

$$F_{z,guidance} = k_{s,pitch} \cdot \left(K_{pitch} \cdot \frac{z_{e,pred}}{HTS/2} \right) \cdot K_H \qquad (2)$$

The desired lateral stick deflection is calculated as the ratio of the predicted lateral error $y_{e,pred}$ and the haptic tunnel size HTS, multiplied with a tuning gain K_{roll}. The required force is calculated by multiplying the desired deflection with the stick stiffness in roll $k_{s,roll}$; this force is then scaled by the haptic gain K_H, set to 0.6 to ensure shared control; the vertical guidance force is computed similarly. Using the fixed prediction time $T_{pred} = 3$ s, paperpilot computer simulations led to optimal values for K_{pitch} and K_{roll} of 0.075 and 0.25, respectively.

The HTS represents the limits of the haptic profile, as illustrated in Fig. 3: once the predicted error exceeds the border of the haptic tunnel, the haptic feedback no longer increases. The gradient $(\frac{\Delta F}{\Delta e_{pred}})$ of the haptic profile then determines *how fast* and *how much* the haptic force will increase, describing a proportional relationship between the visual error shown on the display and the haptic feedback through the side stick.

III. Experiment Design

To investigate the effects of haptic feedback on the task-sharing performance of pilots, a within-subjects experiment was performed. Twelve pilots ($n = 12$) with different flight

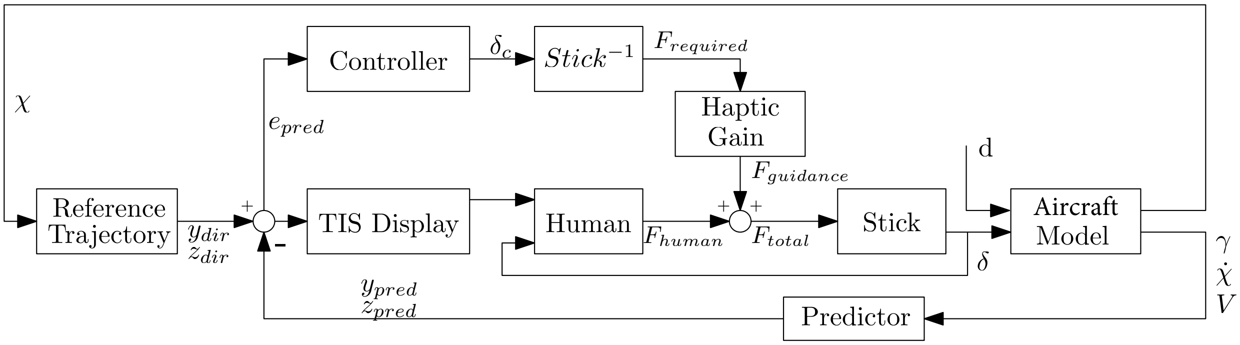


Fig. 2. The shared haptic control law based on the TIS display

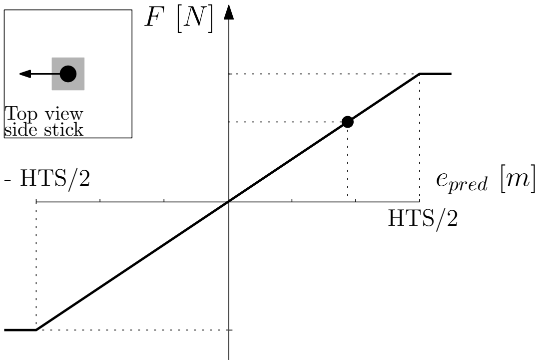


Fig. 3. Top view and haptic profile showing the relation between error, position and haptic feedback

experience flew curved approaches using a TIS display, with and without haptic support.

A. Independent Variables

Two independent variables were used. First, two visual tunnel sizes (VTS) were used, 20 m and 60 m, to manipulate the difficulty of the primary task of flying through the tunnel. Second, the haptic support was manipulated with three levels: a haptics-off condition (H0), and two haptics-on conditions. These were designed using the concept of the haptic tunnel size (HTS) introduced in Section II-B. Two HTS levels were used, 20 m (H20) and 60 m (H60), with which we manipulated how fast the haptic force would increase for a predicted position error. With H60 the haptic force reaches its maximum at a predicted error e_{pred} of 30 m; with H20, the maximum haptic force is reached at 10 m.

TABLE I
THE VISUAL AND HAPTIC TUNNEL SIZE OF EACH CONDITION

#	VTS	HTS	VTS vs. HTS
1	60	0	No haptics
2	60	60	Match
3	60	20	Mismatch: over-tuned
4	20	0	No haptics
5	20	60	Mismatch: under-tuned
6	20	20	Match

Table I lists the six experimental conditions. Clearly, these include conditions where the visual and haptic tunnel sizes have a mismatch. In case the haptic tunnel size is smaller than the visual tunnel size, the haptic forces could be perceived as ‘too strong’ for the task, an over-tuned system [14]. Vice versa, when the HTS is larger than the VTS, the haptic forces could be perceived by subjects as ‘too weak’ for the task at hand, an under-tuned system. This is illustrated graphically in Fig. 4.

B. Primary and Secondary task instructions

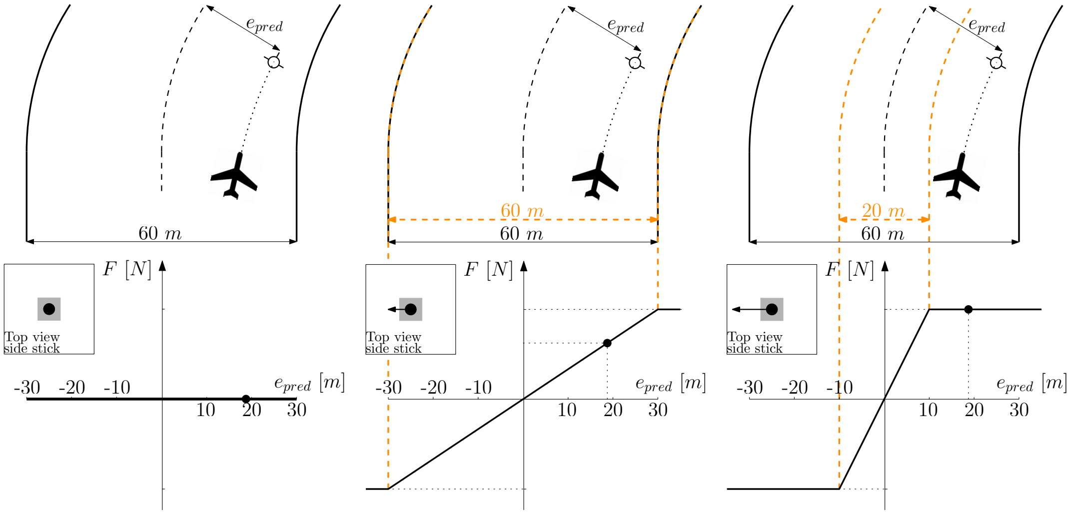
1) Primary Task: Subjects were instructed that their primary task (PT) was to fly along the tunnel centerline as closely as possible. The trajectories flown consisted of four straight descending and four curved level segments, separated by short straight and level parts to cancel-out transient effects, yielding eight ‘measurement sections’ for our dependent measures. In-between runs, the trajectories were mirrored to prevent our subjects to remember them by heart, and to cancel possible asymmetric effects in performance. All trajectories had the same height profile and led towards a runway.

2) Secondary Task: Subjects were instructed that, when the primary task allowed, they should perform a secondary task (ST) which was presented on the outside visual, Fig. 5. The ST required our subjects to look outside the cockpit window to check the ‘odd’ figure (of 25) shown, using a trim button (left/right/up/down) on the control stick, see [18] for details. The ‘U’-shaped polygons were all the same, except one. Every four seconds the ST resets the orientation of the symbols, and changes their color from magenta to red, and back, to distinguish between two successive tasks.

The ST was introduced for two reasons. First, literature suggests that the presence of haptic feedback will ‘free up’ the visual modality, so a pilot should be able to perform better in visual tasks when assisted by haptic feedback. Second, a visual task superimposed on the outside visuals represents an approach situation where a pilot needs to look outside regularly. The ST performance could then be a good measure of the task-sharing performance.

C. Dependent Measures

Three categories of dependent measures were defined.



(a) Haptic profile H0 (b) Haptic profile H60 (c) Haptic profile H20

Fig. 4. Combination of three haptic profiles (H0, H60 and H20) for a tunnel width of 60 m.

Fig. 5. Outside visual, with the superimposed secondary task showing the 'odd' figure (opening to the left).

1) Primary task performance: PT performance was measured using the root-mean square (RMS) values of the aircraft horizontal and vertical position errors relative to the tunnel centerline. In addition, RMS values of the aircraft attitude (pitch and roll angles) rotation rates were calculated to get insight in the used steering inputs.

2) Task-sharing performance: ST performance was measured using the *success rate* and *average time to answer* in the secondary task. Using an eye-tracker, the *head-up time* could be measured as well, to see how much time pilots would allocate to the secondary task.

3) Mental effort: After each run, subjects were asked to rate their mental effort required for executing both the primary and secondary task using the Rating Scale Mental Effort (RSME) scale [19]. Ratings were then normalized, yielding z-scores.

All data were analyzed statistically, with the significance level set at $p = 0.01$.

D. Apparatus

TU Delft's research flight simulator SIMONA was used, a 6-DOF motion-based simulator with an outside visual of 180° × 40°. Motion was turned off. Subjects were seated on the right-hand side and used an electrically control-loaded side stick; maximum stick deflections were ±18° for pitch and ±10° for roll. Similar second order (mass, spring, damper) dynamics were simulated in both channels:

$$H_s(s) = 1/(I_s s^2 + b_s \text{ß} s + k_s), \tag{3}$$

with $I_s = 0.03\ Ns^2/^\circ$ and $b_s = 0.22\ Ns/^\circ$. For roll, $k_{s,roll} = 1\ N/^\circ$, and for pitch $k_{s,pitch} = 1.11\ N/^\circ$. When haptics were applied, the maximum haptic force in pitch was 2.9 N, and in roll 8.6 N, see Eq. (1)-(2). These forces are well below the maximum human forces, such that pilots could overrule our haptics relatively easy.

The nonlinear aircraft model used was that of a small business jet, a Cessna Citation I. An auto throttle was engaged, which kept the aircraft at $148 \pm 4\ kts$ at all times. Moderate turbulence was simulated using a Dryden spectrum.

A faceLAB eye tracker was used to measure the pilots' head-up and head-down times [20]. Eye-tracker data were filtered using a median filter, removing all points more than 3σ away from the median value of six of its neighbors left and right. Pilot 'head-up' or 'head-down' position was determined by taking the median of the top and bottom 20% of the data. The value in the middle of these medians was the 'split' value, all data above this point were considered head-up, all data below were considered head-down.

E. Haptics-only run

In addition to the human-in-the-loop part of the experiment, the simulation was also run with the two haptic settings H20 and H60, without any human involvement, to see whether the aircraft would fly along the tunnel through haptics-only, as a baseline performance measure. Whereas in the H20 condition this was successful, no data could be obtained for the H60 condition as the aircraft did not follow the trajectory.

F. Hypotheses

Three hypotheses were stated. First, we expect pilot task-sharing performance to improve with haptic feedback (H.I). The presence of haptic feedback will leave the pilot with more mental capacity to perform the secondary task, yielding more 'head-up' time and better ST performance. Second, we expect that this increase in performance is more distinct for the more challenging primary task (H.II). For smaller tunnel sizes, and in curved sections, the beneficial effects of haptics are expected to be larger. Third, we expect that a mismatch in the haptic settings relative to the visual task will lead to a lower pilot acceptance (H.III). Either when the haptic feedback is too weak (under-tuned) or too strong (over-tuned), pilots are expected to get distracted, because what they feel (or not) does not correspond well to what they see (or not). This is expected to deteriorate their ST and perhaps even PT performance.

IV. RESULTS AND DISCUSSION

A. Primary task performance

Fig. 6 shows the RMS of the lateral (top) and vertical (bottom) position errors, for the straight tunnel sections (left) and curved tunnel sections (right), for all experimental conditions. Tracking performance increases significantly for smaller tunnels, and also when haptic feedback is present and stronger, as expected. Results for the haptics-only run are shown with the brown dot, and indicate that for the HTS of 20 m the aircraft was able to follow the trajectory by haptic inputs alone. The haptic-only case is 'on par' with the best shared control case in terms of horizontal tracking, whereas for vertical tracking the shared control (including the pilot input) is best. Note that this is also a matter of scaling of the haptic controller.

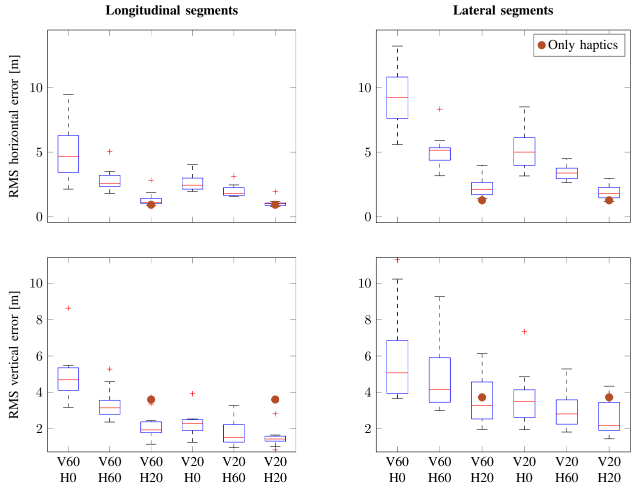


Fig. 6. PT performance, position tracking errors (In this figure and the following, data are shown for all subjects and all conditions).

The RMS attitude rates (not shown) indicate that with haptic feedback all rates decrease, especially the roll rates. The haptics-only run yields the lowest attitude rates of all.

B. Secondary task, task-sharing performance

Fig. 7 shows that, overall, ST performance increases with haptic feedback strength, supporting H.I. The percentage of correct answers increases, and the average time to answer decreases, for all conditions except for the easiest (sub)task, i.e., the longitudinal tunnel segments with a 60 m tunnel size.

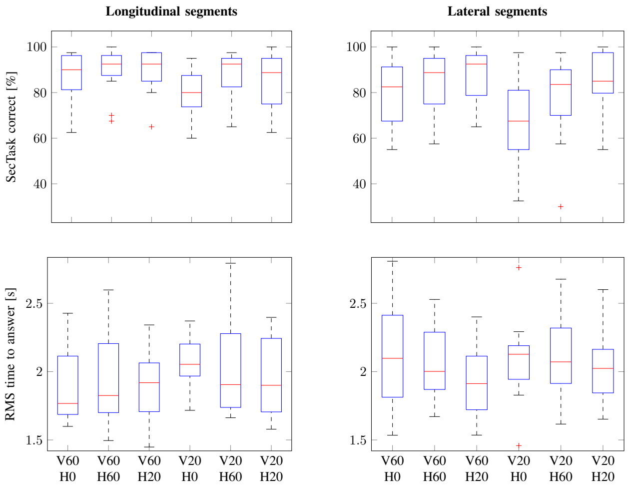


Fig. 7. ST: Percentage correct answers, time-to-answer.

Task-sharing performance is measured in the average head-up time and number of gaze switches, see Fig. 8. Data analysis shows that both measures significantly increase when haptic feedback becomes stronger, as hypothesized (H.II). Especially when the PT becomes more difficult – tracking the lateral tunnel segments with a small tunnel size – task-sharing performance improves. The conditions with a mismatch in visual and haptic information (V60 H20 and V20 H60) did not result in any observable differences in performance.

C. Mental effort

RSME z-scores are shown in Fig. 9; note that the ratings are averaged over the longitudinal and lateral tunnel segments. Workload (significantly) increases for the smaller tunnels, and also (significantly) decreases when the haptic feedback becomes stronger. No effects of the mismatch were found. A significant interaction between tunnel size and haptic strength indicates that the effects of haptics were larger when the task became more difficult.

V. DISCUSSION AND RECOMMENDATIONS

It is shown that the task of performing an aircraft approach with a tunnel-in-the-sky display can be supported with a haptic interface. The combination of the tunnel image with a well-tuned flight-path predictor symbol transforms the multiloop aircraft control task into a two-dimensional tracking task with preview. This task lends itself very well to be supported with

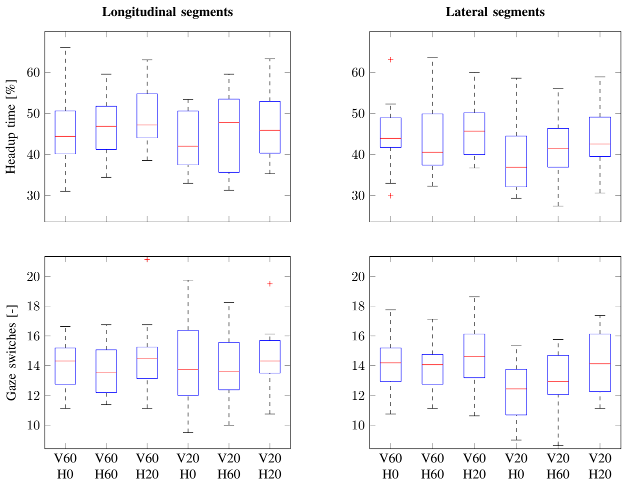


Fig. 8. Head-up time, number of gaze switches.

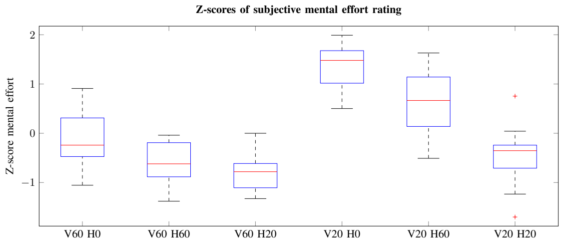


Fig. 9. Normalized RSME ratings.

haptic feedback, and the resulting feedback laws are relatively straightforward to be designed and tuned.

Results show that haptic feedback significantly increases performance in the 'head-down' primary task, accurately following the tunnel centerline. In addition, the presence of haptic feedback increases performance in the 'head-up' secondary task, and leads pilots to spend more time heads-up. These effects are observed already with a relatively low-strength haptic feedback, and are more distinct when the primary task becomes more difficult (small tunnels, curved segments).

Mental workload significantly decreases when the haptic feedback is stronger, and the effects of workload reduction are larger when the task becomes more difficult.

These findings support our first and second hypotheses, H.I and H.II. No evidence was found that would support our third hypothesis, H.III, that the mismatch in visual and haptics cues led to a decrease in pilot acceptance. However, we recommend to study the haptic forces, human-based and haptic guidance-based, in more detail. This paper only considered the performance-related dependent measures, and the potentially detrimental effects of the under-tuned and over-tuned haptic design on pilot acceptance were not analyzed in full detail.

Studying the haptic forces could allow us to investigate the total 'haptic contribution' in the control task, and also see whether the human forces at times are contradicting (or even 'fighting') the haptic support forces. Although this effect has been found in earlier studies, [8], [12], [14], we expect it to be much smaller here, since the visual task is relatively simple. In contrast to other haptic support applications, such as following a curved road where it is unknown how the driver uses the preview of the road ahead, in our application the tracking task is completely specified.

In addition, when the haptic controller can follow the trajectory all by itself, and pilots do not necessarily need to provide any control inputs, the risk of over-reliance exists, which needs to be further investigated.

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