Effect of Performing a Boundary-Avoidance Tracking Task on the Perception of Coherence Between Visual and Inertial Cues

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During flight simulation, the inertial and visual stimuli provided to the pilot differ considerably. For successful design of motion cueing algorithms it is necessary to gather knowledge on how pilots perceive the difference between visual and inertial cues. Some of the work done on this topic has concentrated on the concept of coherence zone. A coherence zone represents a range of inertial motion amplitudes, which although not being a match with the visual motion, are still perceived by humans as one realistic, coherent movement. To extend the knowledge on coherence zones an experiment was performed that tested the yaw motion coherence zone limits at two frequencies during passive and active situations. Subjects were required to perform a boundary-avoidance task as a mean to decrease the attention given to the perception task. This decrease in attention was thought to cause a widening of the perceived coherence zones. The boundary-avoidance tracking task had two levels of difficulty. The measured coherence zones did not change significantly with the addition of the control task. These results imply that unlike motion perception thresholds, coherence zones are little influenced by decreased levels of attention. This being true, for a range of tasks, such as supervisory tasks or procedural training in a flight simulator, pilot acceptance of the inertial cues might be measured in a passive manner and directly applied to the active scenario.

I. Introduction

During flight simulation, the inertial and visual stimuli provided to the pilot differ considerably. The motion cueing algorithms (MCA) used transform the inertial motion amplitude and phase differently for different signal frequencies. In order to quantify the effect of these MCAs on the realism of the simulation, it is necessary to evaluate how much the differences between inertial and visual cues affect human perception and behavior.

Many studies have been performed on the integration of inertial and visual stimuli in various simulation scenarios.1–4 A specific set of studies has concentrated on the concept of coherence zone.5–7 A coherence zone represents a range of inertial motion levels, either amplitude or phase levels, which although not being a match with the visual motion, are still perceived by humans as one realistic, coherent movement. These coherence zones determine the boundaries within which the inertial motion can be adjusted or modified to fit the simulator motion limits without hindering the quality of the simulation.

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Thus far, coherence zones have been measured for different amplitudes and frequencies of angular motion. All experimental setups had subjects judge whether or not visual and inertial cues matched in terms of amplitude or phase. Although much more data can be collected, there is now a basic understanding of how coherence zones are influenced by stimuli amplitude and frequency. However, before this knowledge can be applied to pilot-in-the-loop simulations, more information is needed as to how coherence zones change when the pilot is not fully concentrated on the visual and inertial cues, but actually has a task to perform, as for example, a manual control task.

Introducing a manual control task in a perceptual experiment is not without its challenges. A pilot-in-the-loop situation implies that there is less control over the amplitude and frequency of the visual and inertial stimuli that subjects are exposed to, making it difficult to analyze and compare results. Probably for this reason, the few studies that have been done measuring the effect of performing a manual control task on perception thresholds have maintained the control task out of the loop. Although in the work of Roark and Junker technically the control task was in-the-loop, the inertial stimulus used to measure the threshold was not the inertial the stimulus caused by the control task, but is was superimposed to it. In these studies it has been shown that the perception thresholds increase considerably when the control task is added. It is not sure whether the same holds for coherence zones. Although the coherence zone boundaries may also depend on the same mechanisms that determine the sensory motion perception thresholds, other higher level processes are probably involved in the integration of inertial and visual stimuli. It is hypothesized that, resembling what happens for inertial motion thresholds, when measuring coherence zones while performing a control task, subjects will spend less attention on the perception task and become more lenient. They will allow for a wider coherence zones due to a decrease in the lower threshold and an increase in the upper threshold.

In order to measure the effect of decreased attention on the perception coherence zones, an experiment was designed where subjects’ yaw amplitude coherence zones were measured while performing a pitch boundary-avoidance tracking task. For comparison purposes, also the passive coherence zones (without the control task) were measured.

II. Method

II.A. Apparatus

The experiment was conducted in the Simona Research Simulator (SRS). The SRS has an hydraulic 6 degree-of-freedom motion base which allows for a maximum displacement of ± 41.6 deg in yaw. The visual system consists of three LCD projectors, with a resolution of 1280 × 1024 pixels per projector, and a collimating mirror that provides a field of view of 180 deg × 40 deg. The visual update and refresh rates are 60 Hz. For a more detailed description of the SRS motion and visual systems capabilities and the computer architecture and software used, please refer to references. The visual scene showed Schiphol airport including the control tower, some lower buildings, part of a runway and some grass fields. The viewpoint height was 5 meters. During the active tasks, a Head-Up-Display (HUD) was also displayed on the center screen. The HUD had a field of view of 15 deg × 15 deg.

II.B. Experimental design

The experiment was divided in two parts. The first part consisted of measuring coherence zones without any control task, so a perception task only. In the second part coherence zones were measured for the same conditions as in the first part, although this time subjects had to perform a control task simultaneously with the perception task. Both parts considered, the experiment had a two-way repeated measures design, with the two independent variables being the frequency of the motion signal and the task difficulty. Two frequencies and three task difficulty levels were tested, resulting in a total of 6 conditions. The frequencies tested were 2 and 5 rad/s and the difficulty levels were perception task only, perception task and active control task of low difficulty, and perception task and active control task of increased difficulty. For all conditions a lower and an upper threshold for inertial motion were determined and each measurement was made 3 times, which resulted in 36 experimental trials per subject.
II.C. Motion and visual signals

For both frequencies, the amplitude of the visual signal was always 6 deg/s. The signals had a duration of 7 periods for the 2 rad/s frequency signal and of 4 periods for the 5 rad/s signal, resulting in approximately the same duration for both conditions.

The first and last period were used to fade in and out. The acceleration signal during the fade-in and fade-out phase and during the middle periods is described in Equation (1), where $\omega$ is the stimulus frequency, $T = 2\pi/w$ and $w_{\text{smooth}} = w/2$.

\[
a(t) = \begin{cases} 
A \sin(\omega t) (0.5 - 0.5 \cos(w_{\text{smooth}} t)) + A_c \sin(w_c t) & , \quad 0 < t \leq T \text{ and } 3T < t \leq 4T \\
A \sin(\omega t) & , \quad T < t \leq 3T 
\end{cases}
\]  

(1)

If the acceleration signal without the compensation term is integrated, a velocity signal is obtained that does not start at zero. A constant could be added to the velocity signal to compensate for the velocity initial value but that would result in a position signal that diverges with time. To prevent this situation, the compensation term was added. The amplitude $A_c = A/12$ and frequency $w_c = w/2$ were chosen such that the velocity signal starts at zero and is continuous at $t = T$.

II.D. Control Task

The control task consisted of a boundary-avoidance pitch tracking task. The tracking error and boundaries were shown on a compensatory display superimposed to the outside visual scene. This HUD consisted of a horizontal grey bar and the aircraft symbol, as shown in Figure 1. The grey bar’s width corresponded to a pitch angle of 3 deg.

As the visual scene moved to represent yaw motion, the aircraft symbol and the surrounding frame remained fixed with respect to the pilot’s view point, such that the HUD was always directly in front of the pilot. The vertical motion of the grey bar showed the pilot the tracking error between the desired pitch angle and the controlled element pitch angle. Information on the pitch boundary-avoidance task was only available through the HUD, since the outside visual scene was dedicated to the perception task and only showed yaw motion.

There were two difficulty levels for the control task, which were achieved by using two different system dynamics. The controlled system dynamics for the easy task was a single integrator and for the difficult task was a second order system with a positive pole, that is, an unstable system. The transfer functions for both systems, from stick deflection ($\delta_s$) to pitch angle ($\theta$) are displayed in Equation (2) and Equation (3). Both elements were tuned such that they had the same gain ($K = 0.8594$) at a frequency of 1 rad/s.
\[ H(j\omega) = K \frac{1}{j\omega} \]  
\[ H(j\omega) = K \frac{-2.6926}{-2.5j\omega + j\omega} \]

The tracking signal, or forcing function, was chosen to be relatively simple, when compared to other manual tracking control studies. As these studies focused on pilot model identification, the tracking signal frequency content was of crucial importance. Since that is not the case in the present study, the higher frequency content was not necessary. Moreover, this simple forcing function allowed for a very simple task when using the single integrator element, and a considerable control challenge when using the second order unstable system. For the latter system, a more difficult or complex forcing function would result in a constant loss of control. Using these two tasks with very contrasting difficulty levels was thought to deliver larger, and hence easier to observe, differences in the coherence thresholds.

The forcing function used was based on a previous pitch tracking task study found in literature and simplified to a sum of 5 sines with amplitudes, frequencies and phases as described in Table 1.

Table 1. Characteristics of the sine signals used to compose the forcing function. \( k_i \) indicates the multiple of the fundamental frequency, \( \omega_i \) the corresponding frequency in rad/s, \( A_i \) the amplitude is radians and \( \phi_i \) the phase in radians.

<table>
<thead>
<tr>
<th>( k_i )</th>
<th>( \omega_i )</th>
<th>( A_i )</th>
<th>( \phi_i )</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>0.41</td>
<td>0.0173</td>
<td>2.99</td>
</tr>
<tr>
<td>13</td>
<td>0.76</td>
<td>0.0173</td>
<td>2.65</td>
</tr>
<tr>
<td>17</td>
<td>1.00</td>
<td>0.0173</td>
<td>-3.12</td>
</tr>
<tr>
<td>24</td>
<td>1.41</td>
<td>0.0173</td>
<td>-0.56</td>
</tr>
<tr>
<td>31</td>
<td>1.82</td>
<td>0.0173</td>
<td>3.81</td>
</tr>
</tbody>
</table>

Since the forcing function was simple and to avoid memorization of the tracking signal, the time signal was mirrored around the amplitude axis, around the time axis and around both, creating four different time signals with equivalent difficulty. These sequences were used sequentially in each run.

The boundary avoidance task was preferred over a pure tracking task because it was thought that for the latter, despite the two levels of difficulty, subjects would deliver the same amount of attention and effort to the control task. The only difference would then be on the performance attained. With a boundary avoidance task there can be periods of time when no pilot input is needed to keep acceptable performance, in this case, to stay within the grey area. These periods can be made more or less frequent by changing the controlled element. By using an unstable system, distractions and lack of attention were heavily punished, making this a much more attention demanding task than the single integrator.

II.E. Procedure

As already mentioned, the experiment was performed in two parts, a passive and an active part. To avoid subject fatigue, each subject performed each part in a different day.

The perception task procedure was similar to the experiments described in Reference 6. In each experimental condition the visual amplitude was kept constant while the motion amplitude was varied throughout the runs of one trial. At the beginning of the trial, subjects were informed whether that trial corresponded to a lower or an upper threshold measurement.

In each trial, the amplitude of the first run was randomly selected between 1.1 and 0.9 times the visual amplitude. At the end of each run subjects could change the motion of the next run. They did this by pushing a switch button multiple times up or down until they reached a certain number of increments or decrements. The chosen number was displayed on the outside visual. A positive number meant the next run would have a higher amplitude motion, and a negative number meant a lower amplitude motion. After giving their answer, subjects pressed a second button to signal that they were ready for the next run. The trial ended when subjects’ answers had two consecutive reversals of one increment or decrement, i.e., a sequence of 1, -1, 1, or -1, 1, -1. This indicated that subjects converged to a certain amplitude of motion that could
not be increased or decreased anymore. The size of one increment or decrement was 0.025 of the visual amplitude.

For the part of the experiment where subjects had to perform both the perception task as well as an active control task, this same procedure was used for the perception task. However, during each run subjects had not only to judge the amplitude of the inertial motion with respect to the visual amplitude, but they also had to perform the pitch tracking task.

At the beginning of the second part and before the actual measurements were made, subjects performed training sessions to reach a constant performance on the tracking task. These sessions consisted of a minimum of 20 runs for each tracking task difficulty, per subject. If at the end of 20 runs there was evidence that a participant was still improving or adjusting his control strategy, more runs would be performed. Training runs were done until the subject showed a steady performance for at least 10 runs. The root-mean-square (RMS) of the subjects’ control input and total error signals were monitored to guarantee a consistent tracking.

To assess whether or not the two active task difficulties were indeed perceived as less and more demanding by the subjects, an effort scale was used, from “No effort at all” to “Maximum effort”. After each of the runs subjects were asked to fill in the effort scale on paper, with a vertical mark placed on a 10 cm line.

After training for both control task difficulties, the measurement part started. The experimental trials were divided in 6 blocks of 4 conditions each. In each block always the same task difficulty was used. Each block corresponded to measurements of the upper and lower thresholds for the two signal frequencies. In each pair of blocks all experimental conditions were tested. The presentation order of each pair of blocks was balanced across all 8 subjects. Before each block, if the task difficulty changed from the previous block (so, a different controlled element was used), subjects performed one test trial to adapt to the new task.

In the beginning of each run subjects had 3 seconds to get acquainted with the control task. After these 3 seconds the inertial and visual motion would also start. The tracking task stopped at the same time the inertial and visual motion stopped, indicating the end of a run. At the end of one trial, subjects were asked to fill in the average effort scale for the tracking task across all runs in that trial.

II.F. Subjects and subjects’ instructions

There were 8 male participants with ages between 23 and 35 (mean of 27.5).

For the perception task, participants were instructed to tune the motion up or down, depending on the threshold measurement of that trial. For example, when measuring an upper threshold they should increment the motion until it was perceived as too strong. Then, they were told to decrease it and increase it as many times as needed until they found the strongest motion condition that was still perceived as coherent with the visual motion. Subjects were advised to start with increments of 10 or more and decrease the number of increments or decrements at every direction reversal. They were informed of the stopping criteria of the trials.

With respect to the active task, subjects were instructed during training that they should keep the horizontal green line displayed in the HUD within the moving grey area, with the least effort possible. It was explained to them that after the training they would be performing both the perception task as well as the control task. During the measurement part subjects were encouraged to maintain the same level of control input and performance as they did during training.

After each trial during the active part of the experiment subjects filled in the effort scale. They were instructed to judge only the effort and attention they had to spend on the control task to keep acceptable performance. Their effort score should reflect the averaged effort across all the runs in one trial. For the training phase the instructions were the same but subjects were asked to fill in the scale after each run.

III. Results

During one of the training sessions of one subject there was a problem with the data recording. Since no reliable information was collected, this subject’s data were removed from all the analysis concerning training sessions. However, the recorded threshold data during the passive and active part of the experiment were still used.
III.A. Effort scores

To assess whether or not both control task difficulties were indeed perceived as requiring different levels of effort and attention subjects were asked to fill in an effort scale. The marks made on paper were converted to a value with two decimal places, from 0, representing “No effort at all”, to 10, “Maximum effort”. For the training sessions, the mean score was calculated from the average scores over the last 10 runs, where subjects had showed similar performance. For the active part, the mean scores were the averaged values recorded in each of the three repetitions of one condition.

Figure 2 shows the mean scores for the easy and difficult control tasks during the training and active parts.

![Figure 2](image)

Figure 2. Mean effort scores for both tasks, during training and actual experiment. The error bars indicate the 95% confidence interval.

The task difficulty was clearly reflected in the effort scores, with higher scores for the more difficult task. To investigate whether this effect was significant an Analysis of Variance (ANOVA) was performed and the results are shown in Table 2.

Table 2. ANOVA results for effort scores, where ** is highly significant \((p < 0.01)\), * is significant \((0.01 \leq p < 0.05)\), and - is not significant \((p \geq 0.05)\).

<table>
<thead>
<tr>
<th>Independent variables</th>
<th>Dependent measures</th>
<th>Effort scores</th>
</tr>
</thead>
<tbody>
<tr>
<td>Factor</td>
<td>df</td>
<td>F</td>
</tr>
<tr>
<td>Type</td>
<td>1, 6</td>
<td>0.25</td>
</tr>
<tr>
<td>Difficulty</td>
<td>1, 6</td>
<td>28.01</td>
</tr>
<tr>
<td>Type (\times) Difficulty</td>
<td>1, 6</td>
<td>1.02</td>
</tr>
</tbody>
</table>

The task difficulty had indeed a significant effect on the effort scores and there was no difference in perceived effort between the training sessions and the active part of the experiment.

Additional statistical tests have shown that except for the task difficulty, there were no other statistically significant differences found in the effort scores between experimental conditions in the active part. The stimulus frequency and threshold measured (upper or lower) did not influence the mean effort scores.

III.B. Control input and performance measures

As a complementary measure to assess the effort and attention demand of the task difficulty levels, the average duty cycles were calculated. The duty cycle is defined as the percentage of time during which subjects are acting on the control stick and thus changing their control input. In this analysis, these percentages were calculated by using the rate of change of the stick deflection signal. A rate of change different than zero
meant subjects were acting on the stick. However, in practice the rate of change is never exactly zero, since subjects can not steady their hand so perfectly as to immobilize the stick completely. For the duty cycle calculations the rate of change was considered small enough as to indicate a “no input change” period when it was below 1 deg/s. This value was chosen after visual inspection of the stick deflection signal.

The calculated duty cycle values were then averaged across conditions and subjects to investigate any change of control activity between the training sessions and the active part of the experiment. For the training sessions only the values of the last 10 runs were used. No significant differences were found between the duty cycle values during the training sessions and during the active part of the experiment \((F(1,6) = 0.24, p > 0.05)\). The task difficulty, on the other hand, had a very clear effect on the duty cycle values both during training and active experiment \((F(1,6) = 26.91, p < 0.01)\), with the duty cycle values being much higher for the difficult task than for the easy task.

To investigate a possible interaction between the control activity and the stimuli provided for the perception task, the duty cycle values were also analyzed throughout the different conditions of the active part of the experiment, that is, for trials with both upper and lower threshold measurements and the two different stimulus frequencies. Figure Figure 3 shows the average values for all the active conditions and the training sessions.

![Figure 3. Mean duty cycle values for both difficulty levels, during the training and active parts of the experiment. \(f_2\) and \(f_5\) refer to stimulus frequencies of 2 and 5 rad/s, respectively. \(low\) and \(up\) indicate lower and upper threshold measurements. The error bars indicate the 95% confidence interval.](image)

The Root-Mean-Square (RMS) of the input and error signals were also calculated to get some insight on subjects control activity and performance throughout the experiment. The error signal was zero whenever the system’s pitch angle was within the boundaries defined by the grey area. When the pitch angle exceeded these boundaries, the error was the difference between the system’s pitch angle and the boundary of the grey bar. For the training sessions only the last 10 runs were considered. The averaged values for the RMS of the input and error signals for all conditions are shown in Figure 4.

The RMS of the input signal shows the same trends as the duty cycle, with significantly higher values for the difficult task than for the easy task \((F(1,6) = 48.13, p > 0.05)\). There were no significant differences between the mean RMS values during training and during the active part of the experiment \((F(1,6) = 0.54, p > 0.05)\). The RMS of the error signal shows slightly different results, with higher values for the active part of the experiment than for the training sessions \((F(1,6) = 18.42, p < 0.01)\). This degradation in performance was more pronounced in the task with a higher difficulty level, which can be confirmed by a significant effect of the interaction term Type (training or active) \(\times\) Difficulty \((F(1,6) = 14.49, p < 0.01)\). The difficulty level also affected the RMS of the error significantly \((F(1,6) = 9.07, p < 0.05)\).

Across the different conditions of the active part of the experiment also differences were observed between the control activity indicators (duty cycle and RMS of the control input signal) and performance indicators (RMS of the error signal signal). The ANOVA results for the duty cycle, and the RMS of the input and error signals across all conditions in the active part are shown in Table 3.

The task difficulty had a significant effect on all three metrics, showing a higher control activity and
RMS of the input, deg

Type of task, -
easy
difficult

training f2 low f2 up f5 low f5 up

0
1
2
3
4
5
6
7

(a) RMS of the input signal.

RMS of the error, deg

Type of task, -
easy
difficult

training f2 low f2 up f5 low f5 up

0
1
2
3
4
5
6
7

(b) RMS of the error signal.

Figure 4. Mean RMS values of the input and error signals for both difficulty levels, during the training and active parts of the experiment. $f_2$ and $f_5$ refer to stimulus frequencies of 2 and 5 rad/s, respectively. low and up indicate lower and upper threshold measurements. The error bars indicate the 95% confidence interval.

Table 3. ANOVA results for the duty cycle and the RMS of the input and error signals. Only the main factors and the interactions for which there were statistically significant effects are shown. ** is highly significant ($p < 0.01$), * is significant ($0.01 \leq p < 0.05$), and - is not significant ($p \geq 0.05$).

<table>
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<tr>
<th>Independent variables</th>
<th>Duty cycle</th>
<th>RMS input</th>
<th>RMS error</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>df</td>
<td>F sig.</td>
<td>df</td>
</tr>
<tr>
<td>Threshold</td>
<td>1, 7</td>
<td>24.49 **</td>
<td>1, 7</td>
</tr>
<tr>
<td>Frequency</td>
<td>1, 7</td>
<td>4.40 -</td>
<td>1, 7</td>
</tr>
<tr>
<td>Difficulty</td>
<td>1, 7</td>
<td>42.48 **</td>
<td>1, 7</td>
</tr>
<tr>
<td>Threshold × Difficulty</td>
<td>1, 7</td>
<td>11.35 *</td>
<td>1, 7</td>
</tr>
<tr>
<td>Frequency × Difficulty</td>
<td>1, 7</td>
<td>18.72 **</td>
<td>1, 7</td>
</tr>
</tbody>
</table>

worse performance for the difficult task. The threshold measurement had an effect on the duty cycle and the RMS of the input signal, with higher values for the upper threshold measurement, but did not affect the RMS of the error signal.

The interaction terms Threshold × Difficulty and Frequency × Difficulty also showed an effect on the duty cycle values. In Figure 3 it can be seen that for the more difficult task, the duty cycle values remain fairly constant, whereas for the easy task the values increase with increasing frequency and going from lower to upper threshold measurements. For the RMS of the error the opposite seems to happen, that is, the RMS values for the easy task remaining fairly constant across conditions and show some changes only in the more difficult task. The performance seems to be worse in the upper threshold measurement runs.

III.C. Thresholds and Coherence Zones

The inertial amplitudes selected by the subjects in each condition were converted to upper and lower thresholds by averaging the last two amplitudes of every trial. The mean thresholds values are shown shown in Figure 5 in velocity (Figure 5(a)) and acceleration units (Figure 5(b)).

In general terms the upper thresholds increase and the lower thresholds decrease as we go from the passive (perception only) task to the easy active task and then to the difficult active task. One exception is the upper threshold for the 2 rad/s stimulus and the difficult task, which is lower than the corresponding values for the other task difficulty levels. To investigate if these trends are significant, an ANOVA was performed
and the results are shown in Table 4.

Table 4. ANOVA results for the upper and lower threshold measurements, where ** is highly significant \((p < 0.01)\), * is significant \((0.01 \leq p < 0.05)\), and - is not significant \((p \geq 0.05)\).

<table>
<thead>
<tr>
<th>Independent variables</th>
<th>Lower threshold</th>
<th>Upper threshold</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>df F sig.</td>
<td>df F sig.</td>
</tr>
<tr>
<td>Factor</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frequency</td>
<td>1, 7 29.86 **</td>
<td>1, 7 32.80 **</td>
</tr>
<tr>
<td>Difficulty</td>
<td>2, 14 2.31 -</td>
<td>2, 14 0.25 -</td>
</tr>
<tr>
<td>Frequency × Difficulty</td>
<td>2, 14 0.89 -</td>
<td>2, 14 1.92 -</td>
</tr>
</tbody>
</table>

For both the upper and the lower threshold measurements only the frequency had a significant effect, with lower values for the higher frequency, similar to what has been seen in previous work.\(^6,^7\) The task difficulty did not have a significant effect on the measured thresholds.

Although there was no significant effect of the task difficulty, it is still interesting to analyse the threshold results in terms of a coherence zone. A Coherence Zone Width (CZW) and a Point of Mean Coherence (PMC) were calculated according to Equation (4) and Equation (5).

\[
CZW = th_{up} - th_{lo} \quad \text{(4)}
\]
\[
PMC = th_{lo} + \frac{CZW}{2} \quad \text{(5)}
\]

The PMC and CZW in velocity and acceleration units are displayed in Figure 6(a) and Figure 6(b), respectively.

The PMC remains fairly constant whereas the CZW slightly increases with increasing task difficulty. The exception to this trend is the condition with frequency 2 rad/s and the difficult task, as also seen in the threshold results. Since the effect of the task difficulty was not statistical significant in the threshold data, it is not expected that this is different for the coherence zone data. However, for the sake of completeness, also an ANOVA was performed on these values and the results are presented in Table 5.
IV. Discussion

Coherence zone thresholds were measured during a perception only task, an easy control task and a difficult control task. As a means to monitor the attention demanded by the control task, a subjective effort rating was used, as well as control activity and performance metrics.

It was important to analyze these metrics to investigate whether or not the two levels of difficulty of the control task were indeed different. The duty cycle values and the RMS of the control input were much higher for the difficult task than for the easy task. This result is consistent with what was expected, since for the difficult task, the unstable controlled element required larger deflections of the control stick to attain acceptable performance. The confirmation that the two control tasks were of different enough difficulty levels comes from the large difference found between the effort scores for both tasks.

One other important goal of recording effort scores and control activity metrics was to guarantee that the attention effort dedicated to the control task was constant across the training and the active parts of the experiment. The training sessions set the baseline for how much effort should be put into the control task to attain acceptable performance. If subjects maintained this level of attention, then it could be assumed that there would be reduced attention for the perception task.

The analysis of the subjective effort scores, duty cycle values and RMS of the input signal show that, in general, subjects were successful in maintaining a constant level of attention dedicated to the control task even when they were required to perform a perception task simultaneously. The effort scores and the RMS of the control input showed no difference in the perceived effort between the training and the active parts of the experiment. The duty cycle values, on the other hand, despite similar values between training and active runs in general, show small but significant changes throughout the conditions of the active part. Namely, the threshold measurement had a significant effect and there were interaction effects for the task difficulty.
and threshold measurement and task difficulty and frequency. Looking at the average duty cycle values, it seems that for the more difficult task the duty cycle values were fairly constant, but for the easy task they increase with frequency and going from lower to upper threshold. It could be that the simulator inertial motion affected the subjects interaction with the control stick, artificially raising the amount of time subjects were acting on the controls. However, if that would be the case, the same trends should be observed for the difficult task.

The different results found for the duty cycle values and the RMS of the control input are not contradictory. The duty cycle indicates the time is spent changing the input, but it does not characterize how that change is made. The RMS of the control input is one way of doing that characterization. Reference 16 relates duty cycle and aggressiveness to inceptor workload and indicates the RMS of the control input rate as an average measure of aggressiveness. They also refer that the total work applied on the stick (stick displacement times the force applied) is a better measure of aggressiveness. Perhaps analyzing the control effort in these terms would provide a clearer view of the differences across conditions. Nevertheless, the current used metrics seem sufficient to argue that the control activity was constant between training and active sessions.

The performance, on the other hand, was not constant. The RMS of the error signal was higher for the active part of the experiment than for the training part. In the active part, the upper threshold measurements also resulted in worse performance, that is, larger errors. Despite the perceived effort scores and the control activity metrics indicating that the control effort was maintained from training to active runs, the performance was degraded. This may imply that although subjects dedicated the same effort to the control task, their control inputs were less accurate, or perhaps delayed in time, in such a way as to result in larger excursions outside the tracking boundaries. One other hypothesis is that subjects were bad judges of their own effort and in fact, despite the effort scores indicating otherwise, they spent less attention on the control task when they were to simultaneously perform the perception task.

Against what was expected and is found in literature, the coherence thresholds did not increase with the addition of the control task. The general trend of wider coherence zones for more difficult tasks is present, but not significant. Furthermore, there was a decrease in the upper threshold during the difficult task at the lowest frequency, which contradicts the expected results. In this case it might be that the task became too difficult and any kind of inertial motion was considered just a distraction from the control task. This could lead some subjects to tune down the inertial motion. However, if that would be the case, the upper threshold measurement for the higher frequency should show the same tendency. The fact that it only happens at the lowest frequency seems to dismiss this hypothesis, though care should be taken while interpreting trends in the data when there is no statistical significance.

The indifference threshold increase so clearly found in other studies was not encountered in the coherence zone thresholds. Although intuitively one might expect the same trend, it seems that the perceptual mechanism involved in a coherence threshold cannot be directly related to the perception mechanism underlying sensory inertial thresholds in the presence of other cues, or during higher workload conditions. Inertial motion perception threshold are often referred to as a signal-to-noise ratio mechanism. When sensor output rises above neuronal noise, the inertial stimulus is detected. For thresholds in the presence of other cues or during a control task, the signal-to-noise ratio has to be higher than normal before it is detected. For coherence zone measurements, the inertial motion is supra-threshold and the signal-to-noise ratio is high enough to always be detected. The coherence zone threshold is the outcome of the comparison mechanism between inertial and visual stimuli, which may not be so quickly affected by the addition of a control task.

One other explanation for the obtained results is that this comparison is not something subjects perform simultaneously with the control task, but in distinct periods of time. The inertial and visual stimulus comparison can be made during a short period of time within a run, leaving the rest of the time to perform the control task. Although control activity metrics and effort scores were recorded, these values refer to mean values, averaged across runs. It might be that what is being assessed is then not the effect of attention demanded by the control task, but available time to decide whether or not two cues match. For the perception task subjects had the entire run to decide. For the easy task they could dedicate a fair amount of time for the comparison while still maintaining the controlled element between boundaries. For the difficult task, since the controlled element was unstable, any loss of attention was heavily punished, so subjects had less time for the comparison. Nevertheless, it may be that even for the most difficult condition subjects had enough time to make a decision and in the other conditions they had time to spare. If that is the case, then no difference should be expected in the measured coherence zones.
This being true, for flight simulation application, the pilot’s acceptance of simulated inertial cues might be measured passively and directly applied to active situations, such as procedural or supervisory tasks. For manual control task with inertial motion feedback, if the control task is in a different degree-of-freedom of the one being assessed, the same might hold, although for definite conclusions more information is needed on how coherence zones change in the presence of inertial cues unrelated to the perception task. If the manual control task is in-the-loop, the passively measured coherence zones will probably not suffice to decide on the inertial motion feedback characteristics. In this case, pilots need the inertial cues for performance and inertial motion influences not only perception but also behavior.\cite{18,19}

The frequency had a significant effect on the measured thresholds. As also seen in previous studies,\cite{6,7} for higher frequencies subjects prefer less motion. The PMC decreases from above the one-to-one line at 2 rad/s to being close to a physical match with the visual stimulus at 5 rad/s. The CZW also decreases with the decrease in the PMC. The effect of frequency on the PMC has been qualitatively explained\cite{6,7} with the fact that at higher frequencies the dynamics of the Semi-Circular Canals (SCC) have a higher gain in velocity which is not accounted for in the internal comparison of visual and inertial cues. This effect is present in all the threshold measurements indicating that not only for the perception task only, but also for the active tasks, this relationship remains valid.

V. Conclusions

Perception coherence zones for yaw motion were measured during passive and active situations. During the active part of the experiment, subjects were required to perform an out-of-the-loop pitch boundary-avoidance task. Two different levels of difficulty for the control task were designed. Before starting the active part of the experiment subjects were trained for the boundary-avoidance task. This created a baseline for evaluation of the effort and attention dedicated to the control task, and indirectly, a measure for the attention dedicated to the perception task.

The task difficulty was assessed with a subjective effort scale and by recording the RMS of the input and error signals and the duty cycle. Based on all these metrics it may be concluded that the two tasks were indeed of different enough difficulty and that from the training to the active parts of the experiment, subjects maintained a mean constant level of attention dedicated to the control task.

Despite the addition of the control task, the measured coherence zones did not show any significant change from the passive to the active situations. It was hypothesized that the decision whether or not the inertial and visual stimuli were a match could be done in a short period of time, leaving the rest of each run to perform the control task. This time separation of the perception and active task could not be assessed based on the control input signal or the effort scores. This being the case, in flight simulation applications, the acceptable range of motion for a certain visual stimulus may be determined in a passive manner and directly used in situations where the pilot has a task to perform, such as procedural training and supervisory tasks. Also for manual control tasks the same might apply, if the control task is in a different degree-of-freedom of the one being assessed. An exception should be made for in-the-loop manual control tasks where the pilot relies on the provided inertial motion to attain performance goals or in which inertial motion influences the control behavior.

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References


