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Perception Coherence Zones in Flight Simulation

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The development and tuning of flight simulator motion filters relies on understanding human motion perception and its limitations. Of particular interest to flight simulation is the study of visual-inertial coherence zones. Coherence zones refer to combinations of visual and inertial cues that, although not being physically coherent, still provide the pilot with the perception of a congruent motion, indicating a realistic simulation. Coherence zones have been measured before during passive tasks, for predetermined stimuli. During a pilot-in-the-loop simulation, however, the type of inertial and visual cues being provided are considerably influenced by the pilot's control strategy. For this reason, it is important to understand how the amplitude and frequency content of the stimuli affect the perception of a coherent motion. Three experiments were performed to measure the effect of cue amplitude and frequency on yaw perception coherence zones. In accordance with previous research, the measured coherence zones were generally wider for higher amplitudes of the visual motion cue. At higher amplitudes of the visual cue, subjects preferred inertial motion amplitudes that were lower than the visual cue amplitude. The stimulus frequency was shown to have an effect on the coherence zones. For a higher frequency stimulus the preferred inertial motion amplitudes were significantly lower than for a lower frequency stimulus. These results are explained using a model of the semicircular canals dynamics.

I. Introduction

FLIGHT simulators have a limited motion space and it is impossible to reproduce aircraft motion one-to-one. Motion filters, which are used to transform aircraft motion into simulator motion, introduce phase and amplitude distortions. Whereas the motion cues are constrained to the simulator mechanical limits, the visual cues represent the modeled aircraft true motion. This situation causes the visual and the inertial cues provided to the pilot in the simulator to differ. It is important for the fidelity of the simulation that the pilot does not perceive this discrepancy between cues. While designing and tuning simulator motion filters, an attempt is made to minimize the difference between the pilot perceived motion cues and the aircraft actual motion that is shown in the visuals. For this reason, knowledge on human motion perception thresholds and perception and integration of visual and inertial cues is of crucial importance for flight simulation.

Throughout the past decades much research has been done on sensory motion thresholds [1–6] and motion thresholds in the presence of other visual and motion cues [7–11]. One step toward application of human perception knowledge in flight simulation are experiments with suprathreshold visual and inertial stimulation. Initially, many experiments on perception of combined visual and inertial cues were carried out on rotating chairs enclosed by a rotating drum [12–17]. These studies mainly focused on inducing and measuring self-motion perception during visual and inertial stimulation but failed to present a clear measure of to what extent the mismatch between visual and inertial cues was perceived by the subjects. Visual and inertial cues might differ in terms of amplitude, frequency, phase, timing, or direction. If the differences are detectable then the realism of the simulation might be impaired. Conversely, if no mismatch between the cues is perceived, then they are interpreted as consistent with each other and as belonging to one realistic scenario, that is, the cues are perceived as being coherent.

More recent studies, performed in flight simulators, have measured such mismatches in terms of phase and amplitude. For example, Grant and Lee [18] investigated the maximum phase difference between visual and motion that could go undetected by subjects in a simulator. Van der Steen [19] researched amplitude differences between visual and motion that still resulted in a realistic simulation. He called the coherent set of values between visual and inertial motion amplitude, the coherence zone. Although not explicitly stated by the authors, the study of Lee and Grant, in fact, also measured a coherence zone. Their measured threshold, the maximum motion phase lead for which visual and inertial cues were still considered to be coherent, defines a *phase coherence zone*.

The studies by Grant and Lee [18] and van der Steen [19], like most of the available work on perception, has been done during passive tasks, that is, there was no pilot in control. During a pilot-in-the-loop simulation it is difficult to have control over the precise visual and motion cues provided. More specifically, the frequency content and amplitude of the stimuli greatly depend on the pilot's control strategy [20,21]. The precise influence of the amplitude and frequency of the stimuli on the perception of coherent visual and vestibular motion is still unknown.

In this paper, although still with passive tasks, three steps are given in the direction of measuring perceived coherence between visual and inertial cues during a pilot-in-the-loop simulation. The effects of stimuli amplitude and frequency on perception coherence zones for yaw motion are investigated in three experiments in the Simona Research Simulator (SRS) of the Delft University of Technology.

The first experiment extends the coherence zones measured by van der Steen [19] to amplitudes closer to the ones used in vehicle simulation. The higher amplitudes are chosen based on data from helicopter yaw capture tasks [22–24]. The experimental procedure is

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similar to the one used by van der Steen [19]. That is, for a certain visual motion amplitude, the inertial motion amplitude is varied throughout a set of trials. Then, after each trial, subjects are asked about the coherence between the visual and the inertial cues. The subject's answer determines the inertial amplitude of the following trial according to a simple up–down staircase procedure [25].

The second experiment is designed to validate a new measuring method that gives the subjects a more active role. Using the same setup as in the first experiment, subjects are asked to tune the amplitude of the motion cue by increasing or decreasing its amplitude across trials. This self-tuning method aims to be faster and less tiring for subjects than the staircase method.

The third experiment investigates the effect of the stimulus frequency on the yaw coherence zones. Using the self-tuning method, measurements are made with three different motion profiles. The results obtained are explained based on the dynamics of the semicircular canals.

The paper is structured as follows. Section II defines the concept of coherence zone and summarizes the work of van der Steen [19] on this topic. Afterwards, each of Secs. III, IV, and V describes one of the three experiments, including the corresponding results. At the end, a general discussion of all the experimental results is presented in Sec. VI and the final conclusions are drawn in Sec. VII.

II. Coherence Zones

The term coherence zone was first introduced by van der Steen [19]. However, many others have studied the influence of combined visual and inertial cues in self-motion perception [7–10,12,16,26–29] and similar concepts that used different terminology can be found elsewhere [18,30–32]. Because the current work was based on the experimental methods of van der Steen [19], this section provides a description of his work on coherence zones. Also, the definition of coherence zone and related concepts as presented by van der Steen and as used in this paper are briefly discussed.

A coherence zone designates combinations of visual and inertial cues that are perceived by the pilot as being part of a coherent, realistic simulation. The limits of such a coherence zone are thus dependent on the definition of a realistic simulation. Van der Steen [19] defined a coherence zone as a combination of visual and inertial stimuli that, although being physically incongruent, still "provides the perception of an earth stationary visual scene." This is based on the fact that during locomotion in the real world the visual scene is always perceived as stationary with respect to an earth-fixed reference frame. Because the perceived self-velocity and the perceived velocity of the visual scene may be assumed to be inaccurate to a certain extent, there will be a range of values for which self-velocity and visual scene velocity will be perceived as matching although they are physically different. A large enough mismatch between these two would cause the perception of a non earth-stationary visual scene. In a virtual environment, the perception of a moving outside world signifies that the simulation is impaired.

Taking "the outside world is being perceived as stationary" as a measure for the realism of the simulation, van der Steen performed two studies on flight simulators. In the first study he varied the visual stimuli amplitude for given amplitudes of the inertial motion. The visual scene consisted of checkerboard patterns displayed shortly on monitors located in the subject's peripheral field of vision. Both the visual and the inertial stimuli were sinusoidal. For each inertial amplitude, he measured the maximum and minimum visual cue amplitudes that still resulted in the perception of an earth-stationary visual scene. When the visual cue amplitude was excessively large with respect to the inertial cue, subjects perceived the visual scene to move against their perceived self-motion direction. On the other hand, if the amplitude of the visual cue was too small, subjects perceived the visual scene to move in the same direction as their perceived self-motion, that is, as moving with them. These two scenarios represented two velocity amplitudes that defined the coherence zone (CZ): a *fast* threshold (V_{FAST}) and a *slow* threshold (V_{SLOW}):

$$\mathrm{CZ} = V_{\mathrm{FAST}} - V_{\mathrm{SLOW}} \tag{1}$$

Using a staircase method [25] van der Steen [19] measured these thresholds and for each pair of thresholds he calculated the point of mean coherence (PMC):

$$\mathrm{PMC} = 0.5(V_{\mathrm{FAST}} + V_{\mathrm{SLOW}}) \tag{2}$$

and the gain of the PMC (GMC):

$$\mathrm{GMC} = \frac{\mathrm{PMC}}{V_{\mathrm{SELF}}} \tag{3}$$

The GMC is a measure for the position of the coherence zone with respect to the inertial amplitude (V_{SELF}). A GMC less than one signifies that the measured PMC is less than the provided inertial velocity, indicating subjects are underestimating their inertial amplitude or overestimating their visually perceived velocity. If the GMC is larger than one, then the PMC is larger than the inertial velocity, indicating an overestimation of the inertial velocity or an underestimation of the visually perceived velocity.

Van der Steen [19] measured thresholds for surge, heave, roll, swing (combined sway and roll) and yaw using different combinations of inertial amplitudes and motion frequencies. For surge and heave one motion amplitude was tested: 0.5 m/s. For roll and swing, motion amplitudes varied from 3.7 to 12.4 deg/s and for yaw, they varied from 2.9 to 17.8 deg/s. The profiles frequencies were 1.2, 1.5, and 2 rad/s for all degrees of freedom and for roll and swing an extra condition with frequency of 1 rad/s was tested.

The calculated GMCs were in general below unity for surge and heave motion. Comparing his results with previous studies [28,33,34] van der Steen [19] concluded that for increasing inertial motion amplitude the GMCs slightly decreased. For roll and swing motions the GMCs were above one and decreased with increasing inertial motion amplitude. For the yaw motion the GMCs varied from 2 at the lowest inertial motion amplitude to slightly below one for inertial amplitudes of 9.7 deg/s and higher. This indicates that subjects overestimated their inertial velocity or underestimated their visually perceived velocity at the lower amplitudes. Van der Steen [19] concluded that these results were in agreement with previous studies by Wertheim and Bles [15] only for the larger amplitudes. A particularly interesting finding was that the yaw coherence zone did not increase with increasing amplitude as it was expected from previous studies [15].

For all motions tested the stimuli frequency had no significant effect on the measured thresholds and resulting PMC and GMC. However, as also remarked by van der Steen [19], the range of frequencies tested was rather small.

In a second study, van der Steen [19] varied the amplitude of the inertial motion for fixed amplitudes of the visual motion. The visual scene consisted of a hilly grass field with some houses and trees, displayed on a dome with a field of view of 142 deg horizontal and 110 deg vertical (partially occluded by the cockpit). The visual and inertial motion profiles consisted of acceleration steps. The amplitude of the inertial cue was varied, again using a staircase procedure. The highest and lowest inertial motion amplitudes that still resulted in the perception of a stationary outside world were called the upper and lower threshold, respectively. Van der Steen [19] measured these thresholds in roll and yaw for visual amplitudes of 0, 2, 4, 8, and 12 $\mathrm{deg/s^2}$.

The resulting coherence zones for both roll and yaw became wider for larger visual motion amplitudes. For yaw visual amplitudes higher than 4 $\mathrm{deg/s^2}$ the coherence zones were fairly symmetric, that is, the upper and lower thresholds were at similar distances from the one-to-one line. For roll this symmetry was not present: the upper thresholds were at a greater distance from the one-to-one line than the lower thresholds. For both roll and yaw motion the upper and lower thresholds could be linearly fitted. If the linear fit is extrapolated to higher visual motion amplitudes, however, the coherence zones became quite large. Figure 1 shows van der Steen's [19] upper and lower thresholds for yaw motion and the respective linear regression lines. As can be observed, for yaw visual motion with an amplitude of

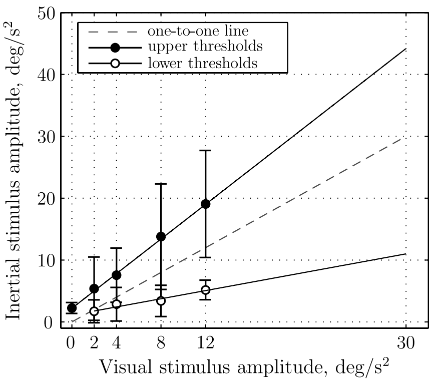


Fig. 1 Mean upper and lower yaw thresholds measured by van der Steen [19] with corresponding regression lines. The error bars indicate the standard deviation.

30 $\mathrm{deg/s^2}$ the coherence zone predicted by the linear regression would be between 10 and 45 $\mathrm{deg/s^2}$. This implies that for vehicle simulation around this amplitude the motion gain can be decreased to as much as 0.3.

Van der Steen [19] also collected verbal remarks from his subjects and divided their answers into three categories: *the motion was not realistic*, *something was out of the ordinary*, and *the motion was realistic*. He reported that answers of the first category were given when the visual scene was perceived as nonstationary and answers of the last category when the scene was perceived stationary. Reports that something was out of the ordinary occurred around the measured thresholds.

The verbal reports collected by van der Steen [19] seem to indicate that around the threshold value the amplitude mismatch was detected but the visual scene was still perceived stationary. If we consider that the realism of the simulation is hindered when an amplitude mismatch is perceived, then this should be the criterion used to delimit the perception coherence zone. For this reason, the definition of simulation realism adopted in the present work was different from the one van der Steen used. In this paper, the simulation is considered to be impaired when the inertial motion is perceived as *too strong* or *too weak* with respect to the presented visual scene.

III. Experiment 1

The goal of the first experiment was to extend the yaw coherence zones measured by van der Steen [19] to higher amplitudes. Based on data from helicopter tracking tasks [22–24] and taking into account the available motion space of the flight simulator used for the experiments, a maximum visual motion amplitude of 30 $\mathrm{deg/s^2}$ was chosen. For amplitudes of the visual scene motion ranging from 0 to 30 $\mathrm{deg/s^2}$ the coherence zone was measured in terms of an upper and a lower threshold. The upper threshold was defined to be the maximum inertial motion amplitude that was still considered by subjects to be coherent with the provided visual scene. The lower threshold was the smallest inertial motion still accepted by the subjects as coherent with the visual motion.

A. Method

The experimental method used was based on the one used by van der Steen [19], with a few adaptations. Also, a different simulator and a different visual database were used. The following sections describe the method, indicating where it differs from the original experiment.

1. Apparatus

The experiment was conducted in the Simona Research Simulator (SRS). The SRS has a hydraulic 6 DOF 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 180×40 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 [35–37]. For the visual scene, van der Steen used a grass field with hills and trees. In this experiment a different data base was used but an attempt was made to preserve the same number of visual objects. Figure 2 shows the outside visual scene, which consisted of a view of the Amsterdam Schiphol airport including the control tower, some lower buildings, part of a runway and some grass fields. The viewpoint height was the same as in the original experiment: 5 m.

2. Experimental Design

The experiment had a one-way repeated measures design. Coherence zones were measured for amplitudes of the visual scene motion of 0, 4, 12, 18, 22, 26, and 30 $\mathrm{deg/s^2}$. For all visual motion conditions a lower and an upper threshold for inertial motion were determined. Per subject the 14 threshold conditions were measured twice. This resulted in 28 experimental trials per subject.

3. Motion and Visual Signals

The stimulus profile used for visual and motion consisted of a sequence of smoothed steps in acceleration. Figure 3 shows an example of the position, velocity and acceleration time histories. The smoothing was done using a quarter of a period of a squared cosine function with a frequency of 10.5 rad/s. The longest acceleration plateau had a duration of 1.5 s.

4. Procedure

Subjects were seated in the left-hand chair of the simulator cabin. Motion was applied so that the subject's head was in the center of rotation. The subject wore a headset with active noise cancellation where engine noise was played. Three buttons located in the control

Fig. 2 Grayscale representation of the central part of the outside visual scene showing a view over Schiphol airport.

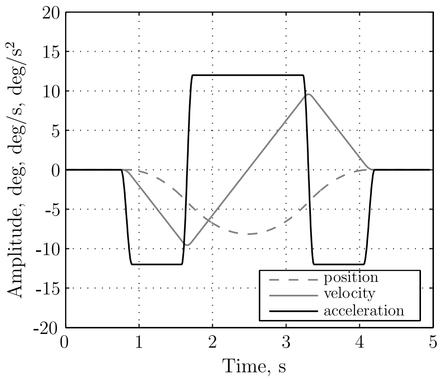


Fig. 3 Example of the steplike motion profile for an acceleration plateau of 12 $\mathrm{deg/s^2}$.

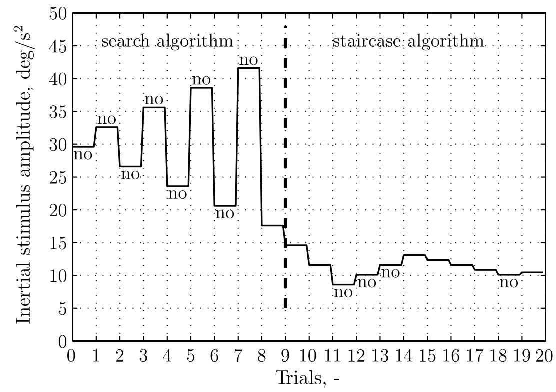


Fig. 4 Example of a sequence of trials illustrating the measurement algorithms used for a visual motion amplitude of 30 $\mathrm{deg/s^2}$. The negative answers are indicated above or below the corresponding amplitude level.

column in front of the participants were used to record their answers throughout the experimental runs.

The order of the experimental conditions was randomized for every subject. For each experimental trial, the visual motion amplitude was kept constant and the inertial motion amplitude was varied through a set of runs. After each run, subjects were asked to indicate whether or not the inertial motion amplitude was perceived as coherent with the visual scene motion. The subjects' answer determined the inertial amplitude of the following trial according to a simple up–down staircase procedure [25]. After each answer, the following run was calculated based on a step size and a step sign. A positive step sign meant that the following run would have a higher inertial motion amplitude than the previous one. A negative sign meant the next run would have a weaker motion. The initial step sign was negative for lower threshold measurements and positive for upper threshold measurements. The initial step size was chosen to be 0.2 times the visual amplitude. For the 0 $\mathrm{deg/s^2}$ amplitude case, the initial step size was a random number between 0.2 and 0.3 $\mathrm{deg/s^2}$. After a negative answer, which indicates the subject overshot his or her threshold, the step sign was reversed and the step size was halved. After four consecutive answers of the same type, always yes or always no, the step size was doubled. The staircase ended when the step size reached one eighth of the initial step size or at the end of 30 trials.

The procedure described by van der Steen [19], and summarized above, was slightly adapted based on test runs in the simulator. It was observed that some participants considered the inertial motion on the first trial too strong, although it was within 20% of the visual motion. For this reason, an initial search algorithm was added. The search algorithm started with an inertial motion between 0.9 and 1.1 times the visual scene and a step size of 10% of the visual motion amplitude. For the 0 $\mathrm{deg/s^2}$ amplitude case, the initial step size was a random number between 0.2 and 0.3 $\mathrm{deg/s^2}$ and the first trial amplitude equalled the initial step size. After each negative answer from the subjects, the step size was doubled and the step sign was inverted. After the first positive answer, indicating that the subjects were within their coherence zone, the staircase algorithm started. Figure 4 shows an example of a sequence of trials starting with the search algorithm and making the transition to the staircase algorithm after the first positive answer.

Before the actual experimental session started, subjects did two test trials to get acquainted with the procedure.

5. *Subjects and Subjects' Instructions*

In total, eight male subjects aged between 23 and 28 (mean of 25), participated in the experiment.

The participants were instructed to sit upright and refrain from making head movements throughout the experiment. They were, however, allowed to gaze over the visual scene at will.

They were told they were to perform a series of runs divided in blocks. In each block of runs the visual scene would move the same way but the amplitude of the simulator motion would vary. At the end of each trial, subjects were asked to answer the question *Did the amplitude of the visual movement correspond with the magnitude of the motion*? A positive answer would mean that they perceived the amplitude of the visual and of the motion to match, and a negative answer would mean that they considered the simulator inertial motion to be either too strong or too weak with respect to the visual motion.

Further, subjects were told that in each block of runs a sequence of amplitude levels would be tested that was chosen by an algorithm. No further information was given on the algorithm, nor were they informed that their answers had an effect on the next amplitude level.

B. Results

For the determination of the upper and lower thresholds, the amplitude levels tested during the search algorithm part were not taken into account. Only the data collected from the staircase algorithm were used. For each of the amplitude levels tested in one staircase, the corresponding answers were converted into a value. Negative answers were attributed a value of 0 and positive answers a value of 1. To each of these data sets a psychometric curve was fitted using a least squares method. The curves were defined in terms of a mean and a standard deviation as described in Eq. (4), for the lower thresholds, and Eq. (5), for the upper thresholds. P_{lo} and P_{up} represent the probability of a certain motion amplitude (A) to be perceived as coherent with the visual amplitude. The estimated value of μ, which is the amplitude level at 50% probability, was taken as the threshold of the coherence zone

$$P_{\mathrm{lo}}(A) = \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^{A} e^{\frac{-1}{2\sigma^2}(x-\mu)^2}\,\mathrm{d}x \tag{4}$$

$$P_{\mathrm{up}}(A) = 1 - \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^{A} e^{\frac{-1}{2\sigma^2}(x-\mu)^2}\,\mathrm{d}x \tag{5}$$

The estimated upper and lower thresholds were averaged for every repetition of every subject. The subjects' mean values are displayed in Fig. 5 together with data from van der Steen's [19] experiment. It should be noted that the standard deviations presented correspond to the deviation of the estimated thresholds from the overall mean, and not to the estimated standard deviations of the psychometric curves.

From Fig. 5 it can be seen that the measured coherence zone is narrower than the coherence zone measured by van der Steen [19]. This might be a result of the different questions posed to the subjects. The participants in van der Steen's experiment indicated when the outside world was perceived to move whereas in the present experiment subjects signaled an amplitude mismatch between visual and inertial motion. Perhaps the perception of an amplitude mismatch precedes the perception of a nonstationary outside world.

For a clearer visualization of the of the coherence zone width and symmetry, a coherence zone width (CZW) and a point of mean coherence (PMC) were calculated from the upper ($\mathrm{th_{up}}$) and lower

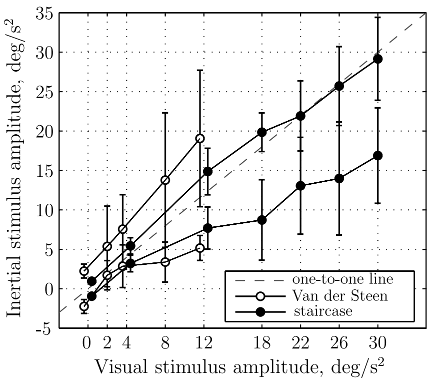


Fig. 5 Mean estimated upper and lower thresholds plotted together with data from van der Steen [19]. The error bars indicate the standard deviation.

(th_{lo}) threshold values using Eqs. (6) and (7). The PMC and CZW for all visual amplitudes are shown in Fig. 6

$$CZW = th_{up} - th_{lo} \tag{6}$$

$$PMC = th_{lo} + \frac{CZW}{2} \tag{7}$$

Up to the amplitude of 12 deg/s^2 the present results are comparable to the ones from van der Steen [19]. The coherence zone is fairly symmetric, as indicated by the PMCs very close to the corresponding visual amplitudes, and the coherence zone width increases with increasing visual amplitude stimulus.

For amplitudes higher than 12 deg/s^2 the coherence zone is no longer symmetric. The upper thresholds align with the one-to-one line causing the PMCs to deviate from the one-to-one-line. This indicates that for the higher amplitudes of the visual stimulus, subjects overestimated their inertial amplitude or underestimated their visually perceived velocity. It is also interesting to observe that for the visual amplitudes above 18 deg/s^2 the CZW hardly increases.

IV. Experiment 2

Although the experimental method used in the first experiment seemed suitable, it demanded a relatively large effort from the part of the subjects. All subjects reported the task to be difficult, as it required a constant high level of concentration for a long time. In an attempt to make the task easier and also accelerate the experimental data collection, a new method was designed, a self-tuning method that gave participants the control over the motion amplitude of each of the runs. It was expected that this would lead subjects to convert to a threshold value in less runs than with the staircase procedure. To validate this new method a small experiment was performed. Lower and upper thresholds were measured for two visual amplitudes with the staircase method used in Experiment 1 and with the new self-tuning method.

A. Method

1. *Apparatus*

As in the first experiment, all trials were conducted in the SRS, using the same visual scene.

2. *Experimental Design*

A two-way repeated measures design was chosen. Upper and lower thresholds were measured for amplitudes of the visual scene motion of 12 and 30 deg/s^2, with both the staircase and the self-tuning method. This resulted in four experimental conditions that participants repeated 6 times, 3 times for measurements of the lower threshold and 3 times for measurements of the upper threshold. In total, each subject performed 24 experimental trials.

3. *Motion and Visual Signals*

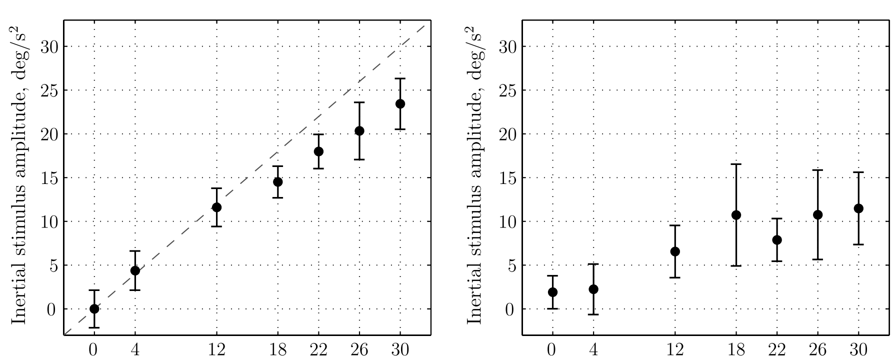
The visual and motion profiles used were the same as the ones used in Experiment 1.

4. *Procedure*

The experimental trials were divided in two blocks, one using the staircase method and the other using the self-tuning method. From a total of five subjects, two started with the staircase method and three with the self-tuning method. Within each block, the presentation order of the experimental conditions was randomized for every subject.

The staircase method was already described in Sec. III.A.4. For the self-tuning method, 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. To guarantee that this method had a similar measurement resolution to the staircase method, when subjects reached the conversion point, the difference between the last two amplitude



a) Point of mean coherence **b) Coherence zone width**

Fig. 6 Measured coherence zones. Error bars indicate the 95% confidence interval of the mean.

levels tested should be the same as in the staircase method. Recalling that the staircase method started with a step size of 20% of the visual amplitude and stopped when the step size was one eighth of the initial step size, the logical size of the increment or decrement in the self-tuning method is one eighth of 20% of the visual amplitude.

At the end of all trials, subjects were asked which method they preferred and why.

5. Subjects and Subjects' Instructions

All five subjects had participated in Experiment 1. They were aged between 25 and 28 years with a mean of 25.6.

Subjects were explained that the experiment consisted of two parts, each with a different experimental procedure. The instructions for the staircase part of the experiment were the same as the ones provided in Experiment 1. For the self-tuning part, participants were instructed to start their tuning procedure by finding a motion amplitude that matched the visual. From that point on, they should tune the motion up or down, dependent 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 8, 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.

Before each part of the experiment subjects performed 2–4 test trials.

B. Results

The upper and lower thresholds measured with the staircase method were calculated as described in Sec. III.B. For the self-tuning method, the threshold for each run was calculated by averaging the amplitude of the last two runs. For every subject, the threshold value for a certain experimental condition was averaged for all repetitions of that condition.

As in Experiment 1, the obtained upper and lower thresholds were used to calculate the PMC and the CZW. Figure 7 shows these values for both methods tested. For reference purpose, the PMC and CZW from Experiment 1 for the amplitudes of 12 and 30 $\mathrm{deg/s^2}$ are also presented.

The PMC and CZW values from Experiment 1 and those from Experiment 2 with the two different methods were quite similar. In Experiment 2, the mean PMC at the visual amplitude of 30 $\mathrm{deg/s^2}$ was around 24 $\mathrm{deg/s^2}$ whereas at the visual amplitude of 12 $\mathrm{deg/s^2}$ was quite close to the one-to-one point (12.5 $\mathrm{deg/s^2}$). Similar to the first experiment, the coherence zone appears to bend below the one-to-one line at higher visual amplitudes. As also seen in Experiment 1, as the visual amplitude grows from 12 to 30 $\mathrm{deg/s^2}$, the CZW also increases. The CZW measured with the self-tuning method was slightly lower than the CZW measured with the staircase method. To assess whether or not this result was significant, an ANOVA was performed.

Table 1 ANOVA results for the PMC and the CZW, where ** is highly significant ($p < 0.01$), * is significant ($0.01 \leq p < 0.05$), and —— is not significant ($p \geq 0.05$)

Independent variables	Dependent measures					
	PMC			CZW		
Factor	df	F	sig.	df	F	sig.
Amplitude	1, 4	676.81	**	1, 4	16.83	*
Method	1, 4	2.09	——	1, 4	6.43	——
Amplitude × Method	1, 4	0.95	——	1, 4	1.96	——

The effect of the visual motion amplitude and the measuring method on the PMC and the CZW are shown in Table 1. The amplitude had an expected effect both on the PMC and on the CZW. The method used had no significant influence on either metric and there were also no interaction effects.

The new method was neither faster nor slower than the staircase method in terms of the number of runs needed to converge. So, although from the experimenter point of view there was no advantage in using this method, when asked about it, all participants preferred the self-tuning method over the staircase method. Subjects answered that the new method was nicer and more motivating.

V. Experiment 3

A third experiment was conducted to assess the influence of the stimulus frequency on the coherence zones. Because Experiment 2 showed that the self-tuning method yields similar results as compared with the staircase method and was also preferred by the subjects, in this experiment the self-tuning method was used.

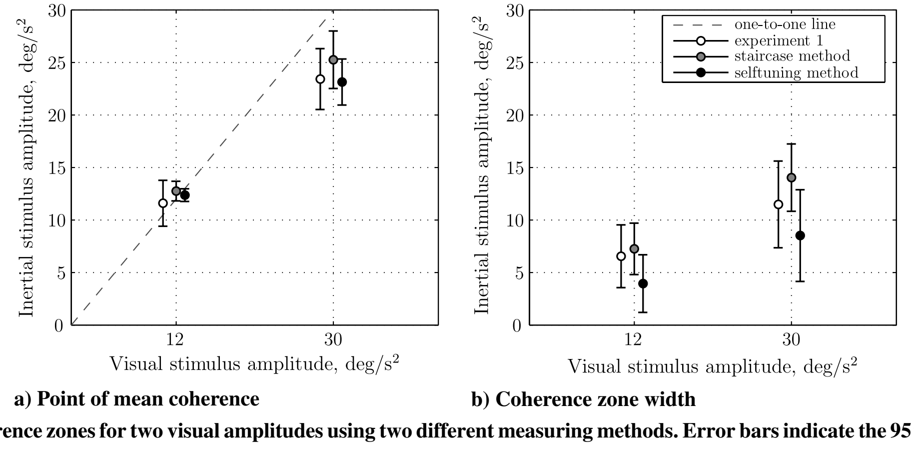
A. Method

1. Apparatus

All trials were conducted in the SRS and the same visual scene as in the previous two experiments was used.

2. Experimental Design

The experiment had a two-way repeated measures design. The experimental conditions were defined by two visual amplitudes, 12 and 30 $\mathrm{deg/s^2}$, and three stimuli profiles. Two of the profiles were sinusoids with frequencies of 2 and 10 rad/s. The third profile, included as a reference profile, was the steplike signal used in the previous two experiments. Both upper and lower thresholds were measured and each subject repeated each experimental condition 3 times. Every subject performed 36 experimental trials.



a) Point of mean coherence **b) Coherence zone width**

Fig. 7 Measured coherence zones for two visual amplitudes using two different measuring methods. Error bars indicate the 95% confidence interval of the mean.

3. Motion and Visual Signals

The steplike profile was described before in Sec. III. The other two profiles were sinusoids with frequency and maximum amplitude defined by the experimental condition. The sinusoidal signals had a duration of four periods. 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 Eq. (8), where $T = 2\pi/w$ and $w_s = w/2$

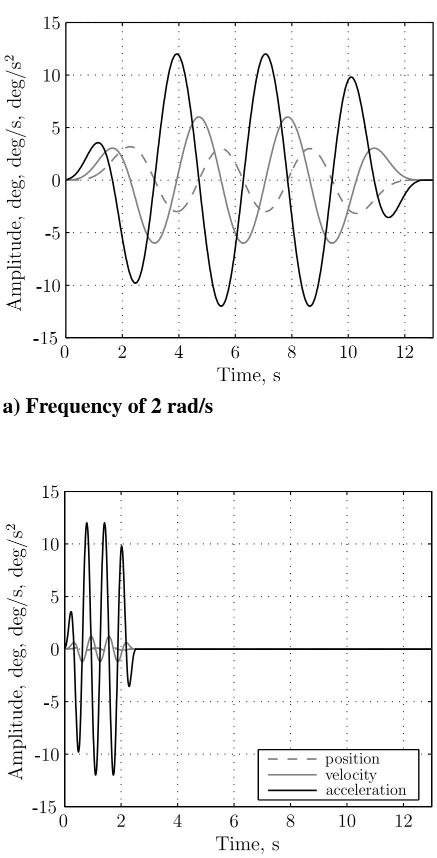
$$a(t) = \begin{cases} \frac{1}{2}A\sin(wt) & 0 < t \leq T \\ \quad -\frac{1}{2}A\sin(wt)\cos(w_s t), & \text{and} \\ \quad + \underbrace{A_c \sin(w_c t)}_{\text{compensation}} & 3T < t \leq 4T \\ \frac{1}{2}A\sin(wt), & T < t \leq 3T \end{cases} \tag{8}$$

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 $t = T$.

Figure 8 shows an example of the signals for the two frequencies tested and an amplitude of 12 deg/s^2.

4. Procedure

The procedure followed was the same as the one described in Experiment 2 regarding the self-tuning method part. The order of the experimental runs was randomized per subject.



a) Frequency of 2 rad/s

b) Frequency of 10 rad/s

Fig. 8 Example of two motion profiles of different frequencies with a maximum acceleration amplitude of 12 deg/s^2.

5. Subjects and Subjects' Instructions

There were eight participants, six males and two females, with ages between 23 and 34 (mean of 25.9).

The instructions given to the subjects were the same as for the self-tuning method part of Experiment 2. Subjects were told there would be different profiles of motion, some faster and some slower. Before the experiment, subjects performed 4–6 test runs.

B. Results

Again, as in Experiment 2, the obtained upper and lower thresholds were used to calculate the PMC and the CZW. They are presented in Fig. 9 for the three motion profiles tested.

As in the two previous experiments, the PMC for the higher visual amplitude was significantly lower than the one-to-one point. Comparing both sinusoidal signals, the PMC was clearly lower for the higher frequency signal than for the lower frequency signal. The same trend can be observed in the CZW. With respect to the steplike signal, because this profile contains both high and low frequencies it was not obvious where the results with this profile would be with respect to the other two profiles. The PMC was somewhat in between both sinusoidal signals and the CZW for the higher amplitude was also in between the two sinusoids. The CZW for the low amplitude was higher than for the two sinusoidal profiles.

An ANOVA was performed on the effect of the amplitude of the visual cue and the stimuli profile on the PMC and CZW. The results are displayed in Table 2.

Similar to the previous two experiments, the amplitude had a highly significant effect on both the PMC and the CZW. The effect of the profile on the PMC was also highly significant. Post-hoc pairwise comparisons, using Bonferroni correction for the level of significance, show that the PMC for the 2 rad/s signal was significantly higher ($p < 0.05$) than the other two profiles.

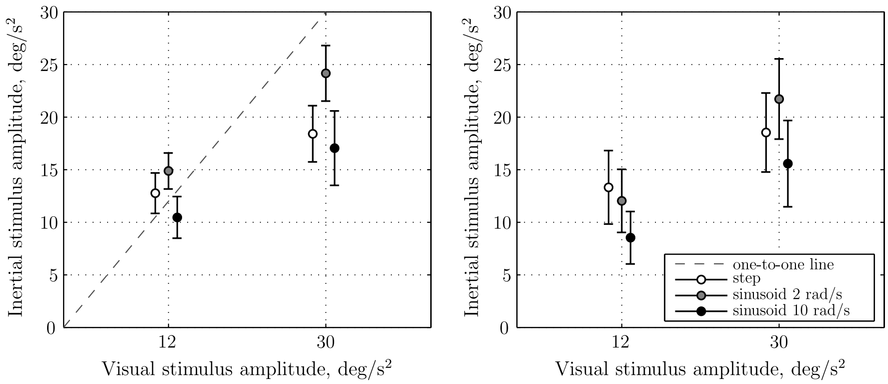
The main effect of the profile on the CZW was also significant. However, the pairwise comparisons did not show any significant differences between the profiles. The effect of the frequency on the CZW may be related to the effect of the frequency on the PMC. It was observed that for higher visual amplitudes, both the PMC and the CZW were higher. If for the 2 rad/s signal the PMC was higher, maybe a higher CZW resulted only from a higher PMC and not necessarily from the effect of the stimulus frequency.

VI. Discussion

Three experiments were performed to measure perception coherence zones in yaw for different amplitudes and frequencies and using two different measuring methods. From the measured data a point of mean coherence and a coherence zone width were calculated.

A. Experimental Method

The method used in the first experiment was quite similar to the one used in the original experiment of van der Steen [19], with a few changes, among them, the question posed to the subjects. In the present experiment the participants had to make a judgment about the relative magnitudes of the visual and the inertial cue, whereas in van der Steen's experiment they were asked to indicate a nonstationary outside world. The assumption that perceiving a mismatch in cues amplitude precedes the perception of a nonstationary outside world may explain why the measured coherence zones were narrower than the ones measured by van der Steen. The fact that the coherence zone measurements may vary according to the question posed does not harm the validity of the results or the method. The formulation of the question should follow from the definition of coherence zone. Using different definitions implies that different thresholds are being measured, which justifies the use of distinct questions. Despite all these considerations, no definite conclusions can be drawn as van der Steen also used a different visual system that might influence the visually perceived yaw velocity and consequently the width of the coherence zone.



a) Point of mean coherence **b) Coherence zone width**

Fig. 9 Measured coherence zones for two visual amplitudes and two stimuli frequencies. Error bars indicate the 95% confidence interval of the mean.

In the second experiment a self-tuning method to measure coherence zones was validated. The intention was to create a procedure that was faster and easier for the participants. By avoiding subjects to become tired, distracted or bored, the data collection could become more reliable. The new method was not faster nor slower than the staircase method in terms of number of trials per run. Nevertheless, all participants were positive about the self-tuning method, reporting that it was more motivating. Based on participants' preference and because the results obtained with both methods were equivalent, the self-tuning method was also used on the third experiment.

B. Effect of Amplitude

In all three experiments the PMCs decreased below the one-to-one line for amplitudes of the visual cue above 12 $\mathrm{deg/s^2}$. This indicates that at high visual amplitudes the participants preferred relatively lower inertial amplitudes. This result could arise from an artifact introduced by the simulator's motion system. However, after examining the data from the inertial measurement unit (IMU) mounted on the SRS, no differences were found in the simulator motion performance at higher and lower amplitudes. Another explanation could be that at higher amplitudes subjects were underestimating the visually perceived velocity. The GMCs presented by van der Steen [19], which were in general above one for angular motion, also indicate an underestimation of the visual velocity. However, for the particular case of yaw motion, van der Steen registered GMCs above one only for amplitudes below 9.7 deg/s, which is not in agreement to what was found here. Conversely, Melcher and Henn [14] have demonstrated that at high accelerations a visual scene is less optokinetic. Their results show that during visual stimulation only, the latency for the detection of self-motion increased for accelerations above 10 $\mathrm{deg/s^2}$. They also reported that for increasing visual stimuli velocities, the self-velocity was underestimated. An underestimation of the visually perceived velocity could lead to the down tuning of the inertial motion. For further investigation into this effect several visual related aspects should be taken into account, such as the characteristics of the visual system, the information content of the visual scene and the process of vection.

Table 2 ANOVA results for the PMC and the CZW, where ** is highly significant ($p < 0.01$), * is significant ($0.01 \le p < 0.05$), and —— is not significant ($p \ge 0.05$)

Independent variables	Dependent measures					
	PMC			CZW		
Factor	df	F	sig.	df	F	sig.
Amplitude	1, 7	132.87	**	1, 7	44.49	**
Profile	2, 14	7.25	**	2, 14	4.57	*
Amplitude × Profile	2, 14	2.78	——	2, 14	1.05	——

The visual cue amplitude also had a significant effect on the CZW. In general, the CZW increased with increasing visual cue amplitude. Based on van der Steen's [19] work, this was an expected result. In the first experiment, this trend was observed only for visual cue amplitudes up to 18 $\mathrm{deg/s^2}$. For higher amplitudes the CZW remained fairly constant. Apparently, for higher amplitudes of the visual stimulus, subjects become less accurate in their estimation of self-velocity but at the same time are relatively more sensitive to deviations from the visually perceived velocity. No explanation for this result was found.

C. Effect of Frequency

The third experiment investigated the effect of the stimuli profile on the coherence zones. The PMCs for the 10 rad/s signal were significantly lower than for the 2 rad/s signal. An explanation for the different PMCs with different profiles can be found in the dynamics of the semicircular canals (SCC). The SCC model used here is the one fitted by Hosman and Van der Vaart [3] through threshold measurements. The gain was set such that the model has a gain of 1 at the frequency of 1 rad/s. Equation (9) displays the SCC model for an angular acceleration input and an output that is proportional to angular velocity

$$H_{\mathrm{SCC}} = 5.972\,\frac{0.1097s + 1}{(5.924s + 1)} \tag{9}$$

If the SCC dynamics are represented in terms of velocity input, as depicted in Fig. 10, then the gain is higher for the higher frequencies.

The frequency dependent gain of the SCC may cause the visually and vestibularly perceived velocities to have a different amplitude. This difference is larger for higher gains of the SCC, which is to say, for higher frequencies of the stimuli. When the visual and vestibular signals are compared to make a judgment of coherence, the vestibular signal has an extra gain introduced by the SCC. This gain is higher for the 10 rad/s signal than for the 2 rad/s signal, which results in a greater difference between the visual and the vestibular path signals. This may explain why, at 10 rad/s, a lower amplitude of the vestibular motion was preferred by the participants, resulting in a lower PMC.

It is important to note that we are assuming that the comparison between the visual and the vestibular paths is done in terms of velocity. Although there is no clear evidence to support or reject this assumption, such a representation is compelling because visually we can perceive velocity [38] and the output of the SCC is also proportional to velocity [39]. The experimental design, however, considered the acceleration amplitude to be an independent factor. The choice to keep the acceleration amplitude, and not the velocity amplitude, constant across different frequencies was based on the fact that, although the SCC output is proportional to velocity, they are sensitive to accelerations [40]. The 2 and 10 rad/s signals had equivalent amplitudes in acceleration. In terms of velocity, the amplitudes have to be divided by the signals' frequencies. This

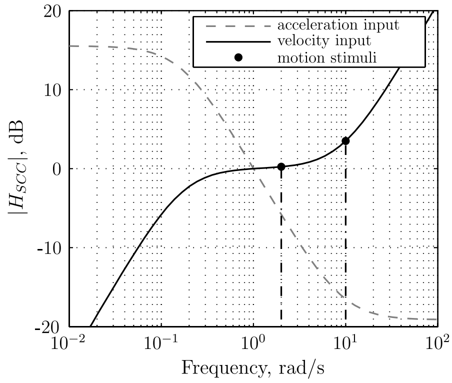


Fig. 10 Semicircular canals dynamics with indication of the motion stimuli frequencies.

resulted in different velocity amplitudes depending on the frequency of the profile, making it difficult to draw definite conclusions over the effect of velocity on the coherence zones. Perhaps in future work it would be useful to consider different frequency stimuli at fixed velocity amplitudes.

Qualitatively, the gain of the SCC at the two frequencies could explain the differences found in the PMCs. From a modeling point of view, this implies that the conflict detection mechanism does not take into account the SCC dynamics in its totality. The increased gain for higher frequencies could be accounted for, for example, by passing the visual signal through an internal model of the SCC canals, which was proposed by Zacharias and Young [27] and later also modeled by Telban and Cardullo [41]. In that case, the conflict detection between the signals from the visual and from the vestibular path would be independent of the stimulus frequency, with the exception maybe for a frequency dependency of vection.

Because there seems to be a frequency dependency on the visual-vestibular conflict detection, it can be suggested that the internal model of the SCC dynamics is not perfect. For frequencies between 0.2 and 9 rad/s the SCC function approximately like a velocity feedthrough, or, if an acceleration input is considered, like an integrator. It could be argued that for the lower and higher frequencies, which are maybe not that common in normal head movements, the internal model of the SCC is still just an integrator, or a velocity feedthrough. That is to say that for frequencies less common in natural head movements the SCC internal model is simply extended from the dynamics at more common frequency ranges. A simple way to test these assumptions would be to prefilter the inertial motion signal with the inverse dynamics of the SCC, so that the total system of prefilter and SCC dynamics would become the perfect velocity sensor at all frequencies; for an example, see Wentink et al. [42]. In such a case, the PMC should not be influenced by the stimulus frequency.

The effect of the stimuli frequency on coherence zones was also tested by van der Steen [19]. Although he found no significant results, it should be reminded that the range of frequencies tested, from 1 to 2 rad/s, was within the range in which the SCC function as a velocity feedthrough. Besides the work of van der Steen, no other study could be found that directly showed the effect of the stimuli frequency on the perception of coherent visual and inertial cues. However, it has been shown [14,17] that vection is a low-frequency process that complements the high-frequency characteristics of the vestibular system. As a consequence, at the higher frequency profile vection might not be occurring, making the judgment of coherent visual and inertial cues more difficult.

D. Application to Flight Simulation

The present results suggest that signals with high amplitudes or high frequencies can be more attenuated than low-amplitude, low-frequency profiles. Attenuating high frequencies leads to a low-pass filtering action, which is contrary to what is done in most motion cueing algorithms. Because low-frequency signals use more motion space than high-frequency ones, most algorithms high-pass filter inertial accelerations and use tilt-coordination and visual stimuli for low-frequency cueing. Thus, the presented trends are not in line with what is currently done in flight simulation.

Conversely, with respect to the amplitude of the inertial cue, the findings do favor the efficient use of motion space. More specifically, high-amplitude, high-frequency yaw motion can be tuned down to as much as 0.3, if considering the lower threshold of the coherence zone, or approximately 0.6, if considering the PMC. However, care should be taken when extrapolating the trends found here to other motion profiles. The steplike profile tested, for example, although containing frequencies above the 10 rad/s, resulted in PMCs and CZWs somewhat between the two sinusoidal signals. This indicates that when moving from motion profiles with one frequency to signals with a more complex frequency content, as it happens in flight simulation, then the perception of coherent visual and inertial cues might not follow the amplitude and frequency trends found with simple sinusoids. Even assuming that the effects of frequency and amplitude remain the same for more complex signals, then still the phase of the different frequency components has to be taken into account. By solely changing the phase values one can modify the time signal such that, for example, peak amplitudes vary considerably.

When transferring the current findings to motion cueing applications, not only the above mentioned effects should be considered but also the degree of freedom. The results from yaw could possibly be extended to pitch and roll, but for linear accelerations dedicated measurements should be made since other inertial sensors play a role. Moreover, the combined stimulation in more than one degree of freedom might also influence the perception of coherent visual and inertial cues.

VII. Conclusions

With three experiments, three steps were given in the direction of measuring coherence zones during an active task. First, amplitudes closer to the ones found in vehicle motion were tested. Second, a measuring method which gave participants a more active role in the measurement procedure was validated. Third, the effect of stimuli frequency on the coherence zones was investigated.

In all three experiments it was observed that the amplitude of the visual cue influenced both the PMC and the CZW. The PMC and CZW increased with increasing amplitude of the visual cue, although for amplitudes above 18 $\mathrm{deg/s^2}$ the PMC decreases below the one-to-one line and the CZW remains fairly constant.

The frequency of the stimuli also had a significant effect on the PMC and the CZW. For a low-frequency stimulus, the PMC and the CZW were higher than for the high-frequency stimulus. A model of the semicircular canals was used to qualitatively explain these trends.

These findings imply that in a flight simulation scenario high-amplitude yaw motions might be down tuned to approximately 0.6 of the visual cue and that high frequencies should be attenuated more than low frequencies. However, in a full motion scenario with cues that occur simultaneously in more than one degree of freedom, this value might change. Further research on this topic should extend the range of frequencies and amplitudes tested as well as add motion cues in other degrees of freedom. Moreover, to move toward a pilot-in-control situation, the effect of workload on the perception coherence zones should also be investigated.

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