

# The Role of Visual Cues and Whole-Body Rotations in Helicopter Hovering Control

Daniel R. Berger <sup>\*</sup>      Cengiz Terzibas <sup>†</sup>      Karl Beykirch <sup>‡</sup>

Heinrich H. Bühlhoff <sup>§</sup>

*Max Planck Institute for Biological Cybernetics, Tübingen, 72076, Germany*

Helicopters in flight are unstable, and hovering at one spot requires the pilot to do a considerable amount of active control. To date, it is still under discussion which sensory cues helicopter pilots use for this stabilization task, and how these cues are combined. Here we investigated how cues from different sensory modalities (visual cues and body cues) are used when humans stabilize a simulated helicopter at a target location in a closed perception-action loop.

Participants were seated inside a closed cabin on a Stewart platform equipped with a projection screen. They had to stabilize a simulated helicopter on a target spot. To investigate the influence of individual visual cues on the stabilization, a minimalistic visual scene was used. Two spheres in the scene represented the location of the target and the position of the helicopter. Optical flow was provided by world-stationary random dots, and a horizon was produced by a black ground plane and white sky. We measured stabilization performance in ten different conditions: black background, horizon, optical flow, both horizon and optical flow, and horizontal stripes; all of these both with and without platform rotation cueing. Physical pitch and roll body rotations were presented by tilting the platform exactly as the simulated helicopter tilted.

Our results show that all manipulated cues – horizon, optical flow, and platform rotations – can help the participants to stabilize a simulated helicopter. In particular, adding physical rotation cues to visual stimulation in a simulator can significantly improve the ability of trained participants to stabilize the simulated helicopter at a target location.

## I. Introduction

A helicopter is inherently unstable, much like an inverse pendulum, and therefore flying a helicopter requires continuous control input. If the helicopter is not perfectly upright, it will accelerate in roughly the direction to which it is tilted. If, for example, it leans slightly to the left, it will start accelerating to the left. To hover at a fixed position requires the pilot to continuously compensate such drifts, which can also be caused by external forces, e.g., wind gust.

Conventional helicopters are mainly controlled using three input devices. The *cyclic stick* can be moved forward/backward and sideways, similar to a computer joystick, and controls pitch and roll rotations of the helicopter by changing each blade angle of the main rotor individually during a rotation cycle. Foot *pedals* control heading rotations by adjusting the blade angles of the tail rotor. The *collective* lever controls the angle of the main rotor’s blades collectively, and with this the lift force (and height above ground) of the helicopter.

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<sup>\*</sup>Research Scientist, Max Planck Institute for Biological Cybernetics, P.O. Box 2169, 72012 Tübingen, Germany; daniel.berger@tuebingen.mpg.de.

<sup>†</sup>Research Assistant, Max Planck Institute for Biological Cybernetics, P.O. Box 2169, 72012 Tübingen, Germany; cengiz.terzibas@tuebingen.mpg.de.

<sup>‡</sup>Research Scientist, Max Planck Institute for Biological Cybernetics, P.O. Box 2169, 72012 Tübingen, Germany; karl.beykirch@tuebingen.mpg.de.

<sup>§</sup>Professor, Max Planck Institute for Biological Cybernetics, P.O. Box 2169, 72012 Tübingen, Germany; heinrich.buelthoff@tuebingen.mpg.de. Member AIAA.

What makes helicopter flight control particularly difficult is the fact that the different degrees of freedom are coupled by the helicopter dynamics. For example, a change of the collective control changes the torque of the main rotor systems, and the resulting yaw rotation of the helicopter has to be compensated with the appropriate control input at the foot pedals.

During training, pilots learn to control the dynamics of the helicopter, and with enough training pilots are able to hover the helicopter above a point with centimeter precision. Pilots handle this complex control problem without much cognitive effort, perhaps comparable to the (much simpler) control involved in riding a bicycle.

To date it is still unclear which senses are important for hover control. It is not possible to stabilize a helicopter without vision, since a blindfolded pilot has no means of distinguishing standing still from moving with a constant velocity (if we ignore aircraft vibrations and flying noise under different flight conditions). Even when starting in a stabilized position, small instabilities will add up over time and the pilot will start drifting if he or she does not perceive and compensate those drifts in position and orientation. But vision is probably not the only sensory cue used for stabilization: pilots often report that the "seat of the pants" feeling, the sensation of accelerations from pressure on the skin and the vestibular system are particularly helpful cues for hover control.

There are several visual cues a pilot might use for stabilization. One important visual cue for the orientation of the helicopter in pitch and roll is provided by the *horizon*. When the helicopter tilts forward, backward, or to the side, the horizon will move upwards, downwards, or tilt in the pilot's view, respectively. Yaw (heading) rotations can also be noticed visually – and distinguished from lateral displacement – when objects which are far away (close to the horizon) move sideways. For nearby objects the perceived motion of a single object cannot be easily used to separate helicopter rotation from lateral drifts.

Another important visual cue is provided by the movement of visual features of the environment in the observer's field of view when the observer moves. The motion field pattern thus formed is called *optical flow*.<sup>1,2</sup> This movement field contains all information necessary to reconstruct the motion of the observer (up to a scaling factor), if visual features are not themselves moving and the shape of the terrain is known.

Apart from vision, pilots can also use force cues of self-motion. One important sensory modality to detect inertial forces on the head is the vestibular system in the inner ear, which can sense both rotations and accelerations of the head. There are also other sensors in the body which can sense body accelerations, for example pressure sensors in the skin.

The role of different sensory cues for vehicle action control has been extensively studied in driving; see, for example, Kemeny and Panerai (2003).<sup>3</sup> Motion cueing and force cueing for flight simulators have also been investigated in many studies.<sup>4,5</sup> Chung, Bürki-Cohen, and Go (2004)<sup>6</sup> argue that the effectiveness of motion cueing depends on task, vehicle dynamics and the properties of the algorithms and setup used for motion cueing. They suggest that future studies should carefully document the characteristics of the simulation and the cues that were used for motion cueing.

Experiments which specifically addressed sensorimotor control in helicopter stabilization, however, are comparatively rare. A study by Ricard and Parrish (1984)<sup>7</sup> investigated the role of inertial motion cueing and visual delays on helicopter stabilization with the simple methods available at the time. They found significantly better stabilization performance (measured in terms of mean-distance-to-target) when inertial motion cueing was available. For the visual delay, results were not so clear: most participants stabilized better with a shorter delay, but for some the opposite was the case (those participants stabilized better with a *longer* visual delay), and others did not show any difference. An earlier study (Ringland et al. (1971), cited in Ricard and Parrish (1984)<sup>7</sup>) found best control performance when only rotations, but not translations, were simulated inertially. Hall (1978)<sup>8</sup> also reported that inertial motion cueing can improve roll stabilization in a *Harrier GR Mk 3* flight simulation. In a study reported by Buckingham (1985),<sup>9</sup> adding physical motion and/or an additional horizon to different visual scenes also improved helicopter flight control.

Andre and Johnson (1992)<sup>10</sup> investigated the effect of stereo and complexity of the visual scene on helicopter hover tasks. The study used a large-FOV head-mounted display (HMD). Stereo viewing had almost no effect on the stabilization, except for a benefit for hovering close to the ground if other visual cues were sparse. Most significant effects of the visual scene complexity have probably been caused by particular properties of the visual scenes. The overall result suggests that pilots can base their control on different elements of a visual scene, and will choose to observe the best cue available, for example a roof top as a cue for vertical position. In this case the other cues of the visual scene will have little effect on performance.

How display collimation, field of view (FOV) and display resolution influence a helicopter hover task was investigated by Chung, Sweet, and Lewis (2003).<sup>11</sup> They found better stabilization performance in the forward/backward direction when a collimated display was used, and argued that the effect might be caused by better depth perception and less influence of head movements on horizon height in the view with a collimated display. A larger field of view also improved stabilization performance, in both forward/backward and lateral directions.

Hoh (1985)<sup>12</sup> compared helicopter hovering with different field-of-view and different coarse-scale and fine-scale image content in a real helicopter (*Hughes 500D*). Fine-scale visual content was removed by using lenses which could be 'fogged'. When the fine-scale image content was removed by fogging, pilots rated the visual motion cueing much worse, even though the horizon was still clearly visible to them. This indicates that small-scale visual information in the near field is also used by the pilots for hovering. A very small visual field also degraded hovering performance (pilots needed longer to complete the experiment and tended to give worse ratings).

Schroeder, Chung and Hess (1999)<sup>13</sup> report an experiment done in the NASA Ames VMS simulator, where very large translations can be simulated (up to 6.1 meters laterally and 9.14 meters vertically). They investigated the effect of inertial motion cueing and two different visual scenes on controlling a helicopter that performs a vertical step motion (change of altitude). They found a significant influence of the visual scene, and of the natural frequency of the wash-out filter used to convert the motion of the simulated helicopter to the physical motion of the simulator. The wash-out filter was implemented as a high-pass filter; the higher its cut-off frequency, the more the trajectory is changed and the more the ratings and task performance degraded. These results are consistent with another study which collected subjective ratings of motion cueing fidelity in a roll-lateral task also done in the NASA Ames VMS simulator.<sup>14</sup> The authors suggest that good motion cueing should keep both the roll and lateral motion phase distortions as low as possible (such phase distortions are typically introduced by wash-out filtering). More experiments performed in the same simulator are reported in Schroeder (1999).<sup>15</sup> This also includes a study on the influence of roll and lateral translation motion cues on a roll-lateral (side-step) task. It was found that accurate simulation of translations was more important than accurate simulation of rotations (in subjective ratings). That paper also reviews many more studies from the late sixties and early seventies which investigated pilot behavior in flight simulators. In many of these experiments, adding physical motion improved the pilots' performance.

In this experiment we investigated the role of different visual cues of self-motion in helicopter stabilization, namely a horizon and optical flow, and their interaction with body motion cueing. Stabilization performance was measured in five different visual conditions, both with and without platform rotation motion cueing. The task was to hover the simulated helicopter at one target location.

## II. Methods

All experiments were conducted in accordance with the requirements of the 1964 Declaration of Helsinki on "Ethical principles for medical research involving human subjects". Responses were recorded from nine participants (1 female, 8 male; age 21-37, mean age 29.5). None of them were experienced helicopter pilots. Before the experiment, participants were trained until they reached sufficient control performance. Our criterion was that they should be able to hover the simulated helicopter with a mean distance of less than 5 m to the target. Some potential participants did not reach this criterion even after extensive training; they did not participate in this study.

### II.A. Setup

Participants were seated inside a closed cabin on a Stewart platform (*CueSim MaxCue*), equipped with a projection screen (see Figure 1).<sup>16</sup> The visual field was 70° horizontally and 54° vertically, viewing distance to screen was 1.2m. During the experiment the motion platform cabin was closed with black curtains so that the participant could not look outside. Noise-cancellation headphones playing noise and seat shakers were used to cover the sounds and vibrations of the Stewart motion base.

A real-time simulation of the dynamics and aerodynamics of a small helicopter (similar to a *Robinson R-22*) was used.<sup>17</sup> The helicopter simulation used a mass-spring system with three objects – the two rotor blades and the helicopter body (see Figure 1). The blades were connected to the body by four springs each.

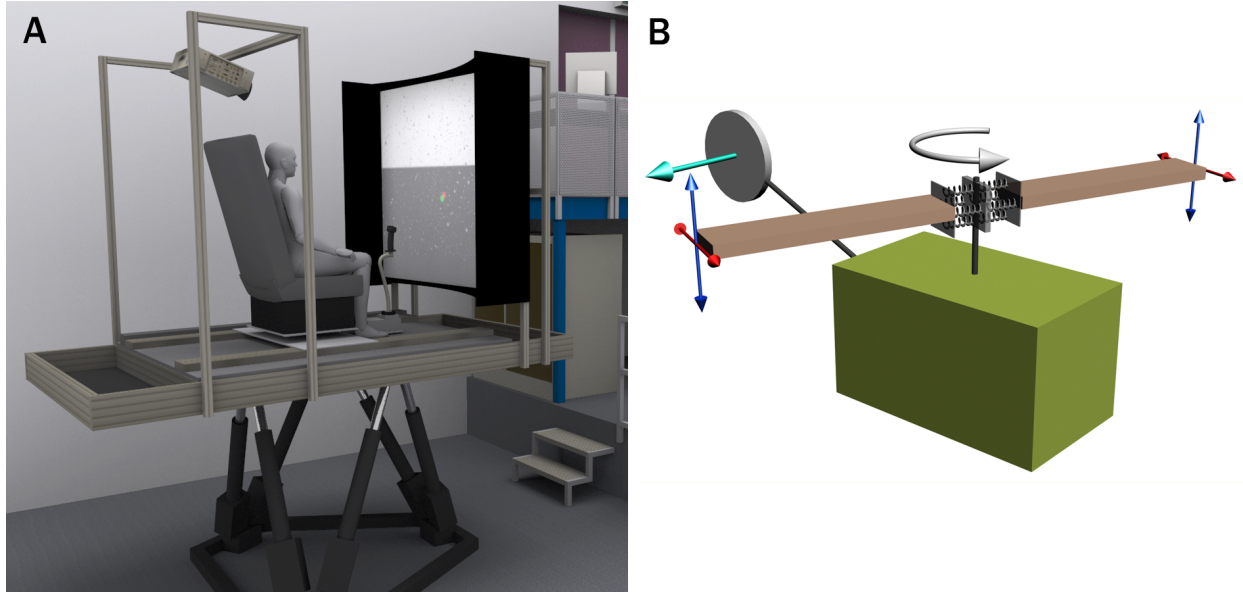


Figure 1. *A.* The setup used in the experiment – Flight simulator consisting of a Stewart motion platform with a projection system on top and a helicopter flight stick. The pilot compartment was completely enclosed by black curtains during the experiment, so that the participant could not see the laboratory. *B.* The kinematic system of the simulated helicopter. The main rotor blades are connected to the rotor axis by four springs each, which allows for flapping (blue arrows) and lagging (red arrows) of the rotor blades. The tail rotor provides a force (cyan arrow) which compensates the torque of the main rotor.

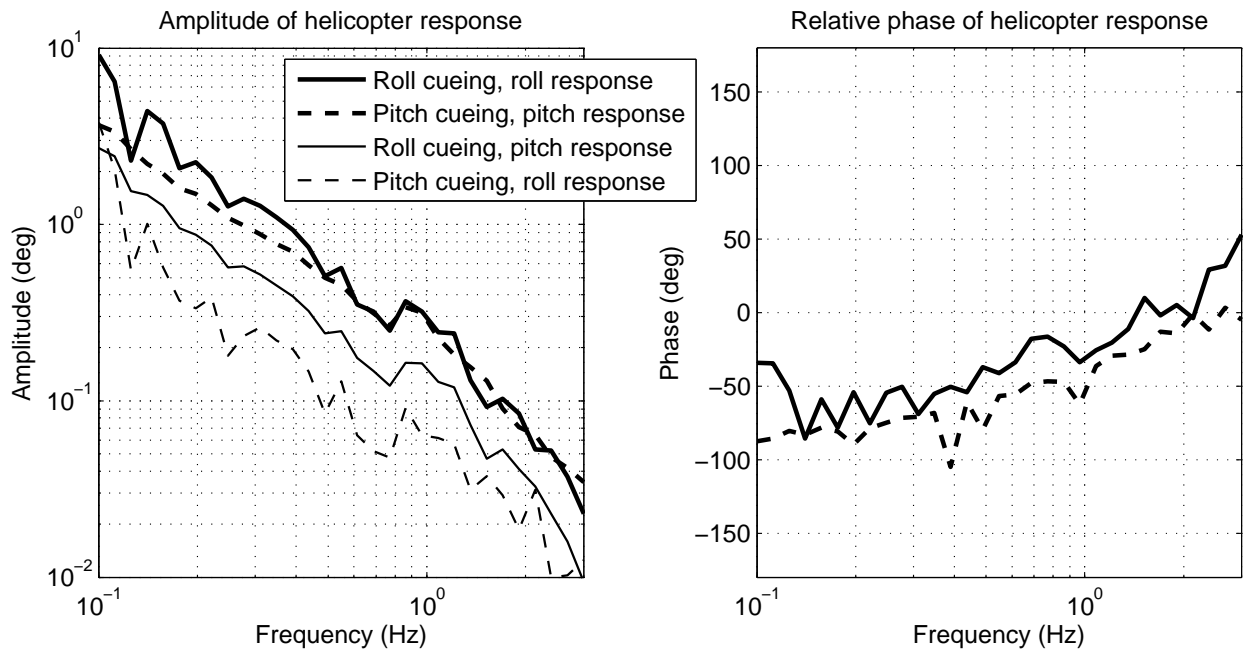


Figure 2. Dynamics of the helicopter simulation used, characterized by amplitudes and phase of the resulting helicopter movement in pitch and roll axes, when roll or pitch axes of the joystick are fed with sine forcing functions of different frequencies. Data was recorded in blocks of 25 s for each frequency; much longer presentations were not possible because the simulated helicopter would become unstable. The amplitude of the forcing functions was 1/20th of the maximal joystick range. Phase measurements of the cross-over responses were unreliable because of the system nonlinearities and are not shown.

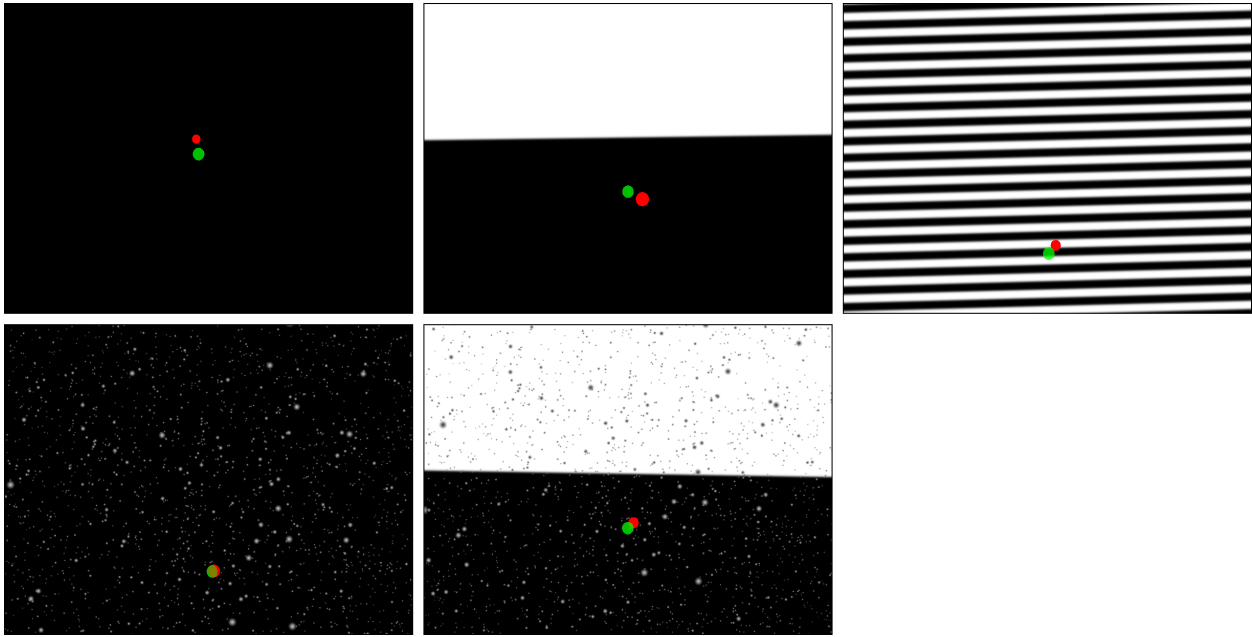


Figure 3. Visual stimuli used in the experiment. Left to right, top to bottom: Black background (B), horizon (H), horizontal stripes (STR), optical flow (OF), horizon and optical flow (H+OF).

Aerodynamics was calculated by using blade element theory, with linear approximations of the aerodynamic characteristics of the rotor blade. The simulation used an Euler-midpoint method to calculate numerical approximations for the system behavior. Parameters for weight, size, geometry, and rotor speed were set as in a *Robinson R-22* helicopter. Participants only controlled pitch and roll axes of the simulated helicopter, height above ground and heading direction were automatically stabilized.

The resulting dynamics of the simulated helicopter can not be easily described by a transfer function. However, by introducing sine forcing functions of different frequencies and measuring the response of the simulated helicopter, the dynamic properties of the system can be approximately described. This is shown in Figure 2. It can be seen that the simulated helicopter is in general more responsive to roll movements than to pitch movements, and that even though there is some crosstalk between pitch and roll axes, it is quite small compared to the effect of roll joystick movements on helicopter roll and pitch joystick movements on helicopter pitch.

Participants used a realistic helicopter cyclic stick to control pitch and roll rotations of the simulated helicopter, and with this forward-backward and sideways drifts. The cyclic stick was only moved by the participant and did not provide any additional force cues apart from passive recentering by springs.

The helicopter simulation ran on a distributed system involving four different computers, for joystick input, main simulation, motion platform control and realtime-rendering of the visual scene in OpenGL.<sup>16</sup> Joystick, simulation program, network, platform hardware and in particular the motion filtering for the platform introduced transport delays and phase shifts, adding up to an effective delay of platform motion varying between 225 ms and 575 ms, depending on frequency. Learning to stabilize the simulated helicopter thus also involved learning to cope with the system's delay.

## II.B. Experimental task and conditions

The task for the participants was to hover the helicopter at a target spot. While the participants stabilized, we continuously measured the distance of the position marker from the target in front-back and sideways directions, helicopter velocity, and pitch and roll angles of the simulated helicopter. The latter are correlated with the accelerations of the helicopter, as the simulated helicopter accelerates in the direction in which it is tilted. Good stabilization is characterized by small distances to the target, low velocities and small tilt angles. Participants only controlled roll and pitch angles of the helicopter, and with this forward/backward and sideways movements, whereas heading and vertical position of the helicopter were automatically held constant.

To indicate to the participant where the simulated helicopter currently is and where the target is, two spheres (0.6m diameter in the simulated environment) were shown in all conditions. The red one represented the target and was fixed in the environment; the green one represented the helicopter position and moved with the helicopter. The helicopter-representing sphere was placed 15m away from the observer. Helicopter and target sphere were automatically kept on a horizontal plane 2 meters below the observer. The spheres were rendered without additional shading or lighting, because that would have provided additional global visual orientation cues. The participant watched the scene from the helicopter pilot position. Vertical eye position of the participant was carefully controlled to be at horizon level by adjusting the seat height before the experiment started. This is important to prevent conflicts between visual vertical (defined by the horizon height) and body vertical (influenced by platform pitch).

We investigated the influence of the visual cues "horizon" (H) and "optical flow" (OF) on the stabilization performance, and their interaction with whole-body motion cues. Five different visual scenes were used, which are shown in Figure 3. The five different scenes presented together with the spheres were: black background (B), horizon (H), horizontal stripes (STR), optical flow (OF), and both horizon and optical flow (H+OF). The three-dimensional random dot pattern used in the optical flow (OF) conditions was static in world coordinates and provided optical flow cues, telling the participants about translations and rotations of the helicopter, but not about absolute position or orientation in space. In the horizon (H) conditions, participants got visual information on helicopter pitch and roll position and angular velocity, but no information about helicopter translations. The stripes (STR) pattern provided the same cues as the horizon, except stronger velocity cues for pitch and roll movements, and no cue for pitch position. The black background did not give any additional visual cues on self-motion, and served as a control condition to investigate how much information is provided by the relative position and motion of the two spheres alone.

These visual stimuli were designed so that they did not give conflicting, but ambiguous information for the uncued dimensions. The optical flow pattern does not provide information on absolute pitch and roll because it is isotropic, and the horizon does not provide translation information because ground and sky have uniform color. The stripes (STR) stimulus provides the same cues as the horizon, with the exception of absolute pitch angle, because of the repetition of the horizon at different heights in the horizontal stripes. This condition was added to test for the importance of the position versus the movement of the horizon. If the position of the horizon is important, the stabilization performance should degrade in the STR condition compared to the H condition, but only in the pitch direction.

All 5 visual conditions were presented with and without platform rotation cueing, leading to 10 different conditions. For body rotation cueing, the platform was tilted in pitch and roll directions exactly as the simulated helicopter tilted. Duration of each trial was 120 seconds. One experimental block contained one trial of each stimulation condition, with platform on and off conditions interleaved (20 minutes per block). Each participant ran 5 blocks with different pseudo-random trial orders, which amounts to a total of 10 minutes of stabilization per experimental condition.

Helicopter distance-to-target, velocity, and orientation trajectories were measured and analyzed for significant differences between different experimental conditions.

### III. Results

Example trajectories for the different conditions are shown in Figure 4. It can be seen that the participant fails to stabilize the helicopter in the 'black' (B) condition without platform motion cueing, that stabilization is generally better in left/right directions than in forward/backward directions, and that it improves if the platform is on.

Figure 5 shows the resulting stabilization performance measures for all participants and all conditions. This data was analyzed with separate four-way ANOVAs for distance, velocity and tilt; with direction (left / right vs. forward / backward), platform (rotation cueing on/off), horizon (on/off) and optical flow (on/off) as within-subject variables. The horizontal stripes condition (STR) was analyzed in a second set of (three-way) ANOVAs, again separately for the effects on distance, velocity and tilt; with direction, platform and horizon/stripes as within-subject variables. Due to the skewed nature of the original data distributions we used the (natural) logarithms of all measures for the ANOVAs, which made the distributions more Gaussian-like and variances more similar in the different conditions (see Figure 5). Both are requirements for the ANOVA to provide meaningful results.<sup>18</sup>

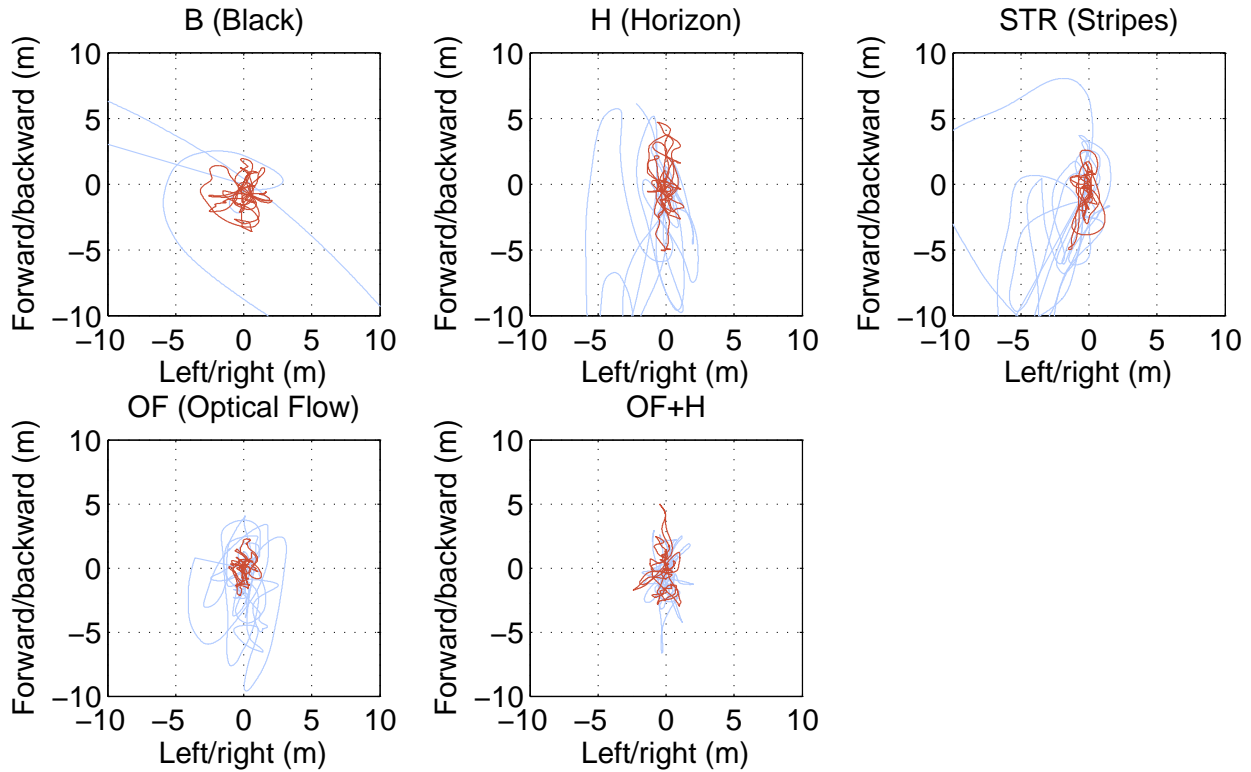


Figure 4. Example trajectories of one participant in all conditions. Light blue: platform off, dark red: platform on.

### III.A. Horizon, optical flow, and platform rotations

Table 1 shows the results of the four-way ANOVAs with direction, platform, horizon and optical flow as within-subject factors, calculated separately for mean distance, mean velocity and mean rotation angle. The data used for these ANOVAs is shown in Figure 5.

In this analysis, all factors had significant main effects on distance and velocity, and all but 'direction' also had significant main effects on rotation. Also many interactions were significant. In the data set the 'black' (B) condition without platform cueing caused response measures which were much larger than in all other conditions. This might be the reason why so many effects are significant.

Participants stabilized significantly better in the left/right direction than in the forward/backward direction, as can be seen from mean distances and mean velocities. However, they used similar amounts of rotations for both directions. Reasons for the difference might be better visibility of lateral deviations from the target than forward/backward deviations, caused by the low viewing angle on the two spheres, or differences of the dynamics of the simulated helicopter for forward/backward and sideways movements.

Platform rotation cueing, which provided inertial cues of orientation in space, improved stabilization performance significantly compared to visual-only stimulation (red vs. blue error bars in Figure 5). The improvement was particularly large in the 'black' (B) condition. In this condition, visual feedback for control came only from the relative motion, position and size of the two spheres. If in this condition the platform motion was off, participants quickly lost control over the helicopter, and flew erratically. Many trials were interrupted once control was lost.<sup>a</sup> If, in contrast, platform rotation motion cueing was provided in the B condition, stabilization performance was almost as good as in the other conditions with the platform turned on. This shows that even though seeing the two spheres alone is not sufficient to stabilize the helicopter at the target, participants manage to stabilize once they can sense their body orientation in space as cued by platform rotations. Stabilization improved more if optical flow was added to platform rotations than if a horizon was added. This is not surprising considering that platform rotations and horizon provide redundant information on orientation in space, whereas optical flow tells the participant about the

<sup>a</sup>Because of that, measures in the B condition without platform cueing are somewhat smaller than they would have been if the trial could have been completed, and are therefore not really representative of that condition.

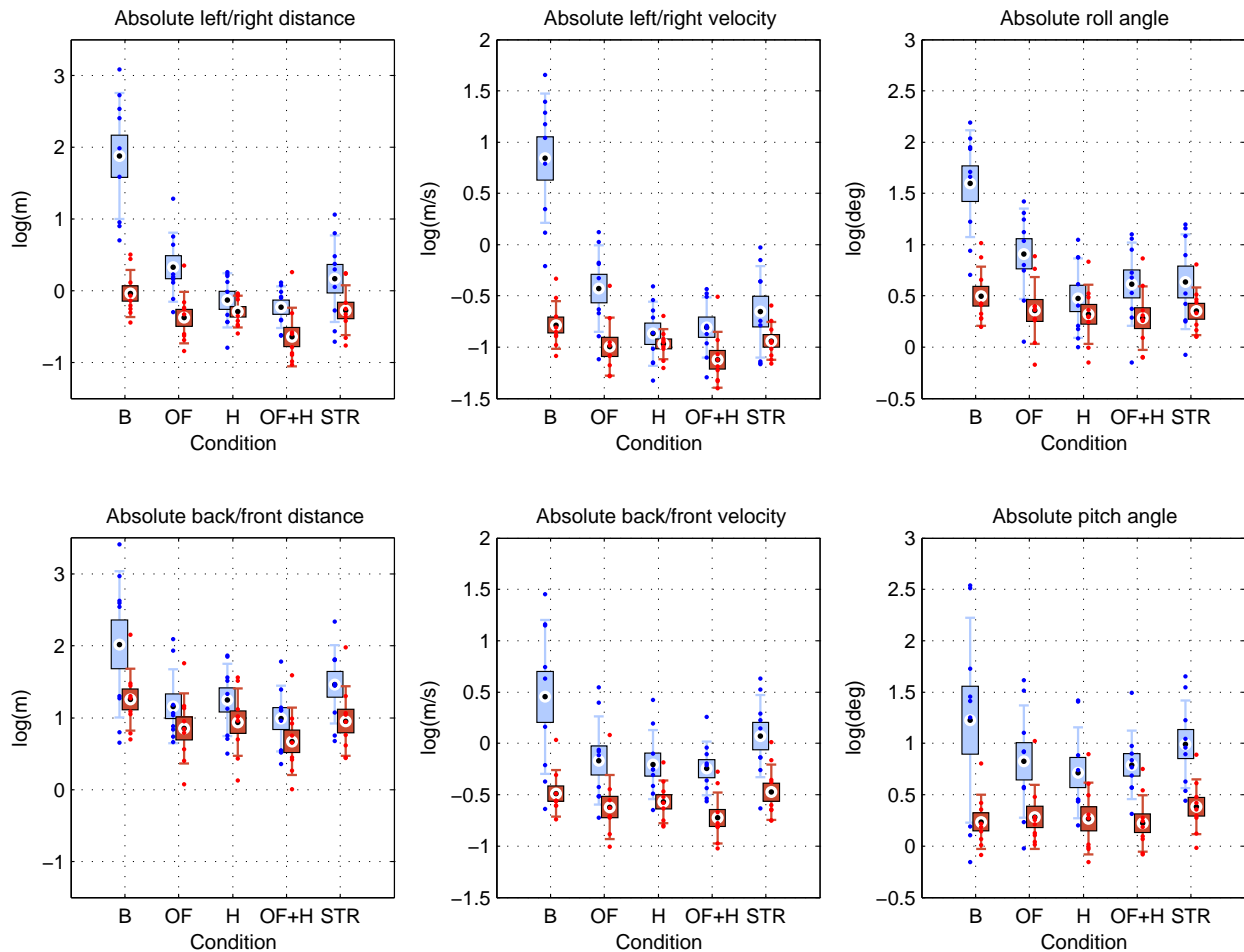


Figure 5. Results of all nine participants. B: black background, OF: optical flow, H: horizon, STR: horizontal stripes. Light blue: platform off, dark red: platform on (P). Dots show results of individual participants. Error bars and whiskers are standard error and standard deviations, respectively. Measures are shown on logarithmic scale of helicopter target distance in meters, helicopter velocity with respect to the target in meters/second, and helicopter tilt in degrees. The logarithm of the measured data points was also used for the ANOVA analysis to meet the requirements of unskewed distributions and similar variances for all conditions.

helicopter’s translation movements.

Also the horizon and optical flow improved stabilization performance significantly. In left/right directions, participants stabilized better with a horizon-only cue than with optical flow only, whereas both cues were approximately equally good for forward/backward stabilization. Possibly, human subjects are more sensitive to horizon orientation in roll, than to absolute vertical position of the horizon on a large display screen, and/or forward/backward optical flow is more useful for stabilization than sideways optical flow. With horizon-only cueing participants stabilize approximately equally well as with platform-only cueing (in terms of distance-to-target).

Presenting horizon and optical flow together (OF+H) slightly reduced distance-from-target, compared to the conditions in which either only horizon (H) or only optical flow (OF) were shown. This was also the case if platform rotations were on. For most participants, the best performance was reached if platform, horizon and optical flow cues all were available (P+OF+H).

### III.B. Horizon versus horizontal stripes

We introduced the ‘horizontal stripes’ (STR) condition as a means to distinguish between the influence of the absolute position of the horizon in the visual field and the influence of its movement on helicopter stabilization. In the STR condition, compared to the ‘horizon’ (H) condition, the information on pitch position is severely degraded, whereas information on roll position, pitch movement, and roll movement are conserved. We expected to see similar stabilization performance for roll in H and STR conditions, whereas

**Table 1.** Main ANOVA results for the effects of direction (D; front/back vs. left/right), body rotations (P; platform on/off), a visual horizon (H; on/off) and visual optical flow (OF; on/off) on the different measures of helicopter stabilization performance (distance, velocity, rotations) for all 9 participants. × denotes interactions. All  $F$  values are  $F(1,8)$ .

Measure	Distance	Velocity	Rotation
Mean	$F=21.82, p=0.002^{**}$	$F=38.87, p=0^{***}$	$F=32.11, p=0^{***}$
D	$F=352.16, p=0^{***}$	$F=64.18, p=0^{***}$	$F=1.17, p=0.310$
P	$F=30.03, p=0.001^{***}$	$F=29.79, p=0.001^{***}$	$F=24.70, p=0.001^{**}$
D × P	$F=17.21, p=0.003^{**}$	$F=2.20, p=0.177$	$F=2.08, p=0.188$
H	$F=73.44, p=0^{***}$	$F=40.35, p=0^{***}$	$F=18.64, p=0.003^{**}$
D × H	$F=32.53, p=0^{***}$	$F=35.61, p=0^{***}$	$F=8.21, p=0.021^*$
P × H	$F=13.38, p=0.006^{**}$	$F=16.62, p=0.004^{**}$	$F=10.40, p=0.012^*$
D × P × H	$F=65.72, p=0^{***}$	$F=134.19, p=0^{***}$	$F=4.71, p=0.062$
OF	$F=49.91, p=0^{***}$	$F=32.75, p=0^{***}$	$F=9.20, p=0.016^*$
D × OF	$F=6.74, p=0.032^*$	$F=11.13, p=0.010^*$	$F=4.12, p=0.077$
P × OF	$F=7.23, p=0.028^*$	$F=13.69, p=0.006^{**}$	$F=3.97, p=0.081$
D × P × OF	$F=5.60, p=0.046^*$	$F=7.20, p=0.028^*$	$F=0.03, p=0.876$
H × OF	$F=15.95, p=0.004^{**}$	$F=35.21, p=0^{***}$	$F=19.88, p=0.002^{**}$
D × H × OF	$F=15.30, p=0.004^{**}$	$F=17.83, p=0.003^{**}$	$F=3.99, p=0.081$
P × H × OF	$F=11.14, p=0.010^*$	$F=20.53, p=0.002^{**}$	$F=10.33, p=0.012^*$
D × P × H × OF	$F=37.11, p=0^{***}$	$F=16.25, p=0.004^{**}$	$F=0.531, p=0.487$

**Table 2.** ANOVA of the visual conditions 'horizon' and 'horizontal stripes' (H/STR) in combination with direction (D; front/back vs. left/right) and body rotations (P; platform on/off) on the different measures of helicopter stabilization performance (distance, velocity, rotations) for all 9 participants. × denotes interactions. All  $F$  values are  $F(1,8)$ .

Measure	Distance	Velocity	Rotation
Mean	$F=17.66, p=0.003^{**}$	$F=76.69, p=0^{***}$	$F=31.53, p=0.001^{***}$
D	$F=337.23, p=0^{***}$	$F=151.44, p=0^{***}$	$F=3.39, p=0.103$
P	$F=6.10, p=0.039^*$	$F=6.07, p=0.039^*$	$F=8.94, p=0.017^*$
D × P	$F=2.45, p=0.156$	$F=34.28, p=0^{***}$	$F=31.83, p=0^{***}$
H/STR	$F=4.73, p=0.061$	$F=20.06, p=0.002^{**}$	$F=21.21, p=0.002^{**}$
D × H/STR	$F=0.46, p=0.515$	$F=1.31, p=0.286$	$F=3.89, p=0.084$
P × H/STR	$F=8.71, p=0.018^*$	$F=6.22, p=0.037^*$	$F=6.38, p=0.035^*$
D × P × H/STR	$F=0.39, p=0.549$	$F=0.00, p=0.999$	$F=0.14, p=0.715$

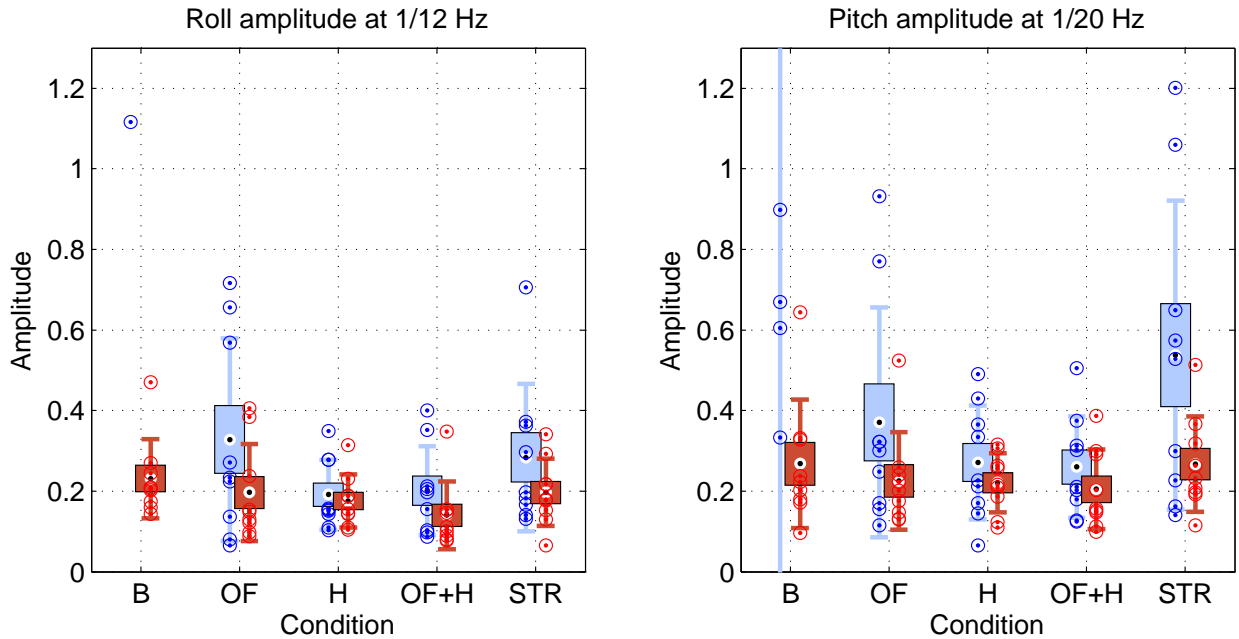


Figure 6. Amplitude at the resonant frequencies of 1/12 Hz for roll and 1/20 Hz for pitch of the simulated helicopter in different conditions. Dark red error bars show 'platform on' conditions, light blue show 'platform off' conditions. Error bars and whiskers are standard error and standard deviation, respectively. The data points in the 'black' (B) condition without platform cueing are far off, and, since the trajectories were mostly interrupted, not representative.

the stabilization performance in pitch should be worse in the STR condition, compared to the H condition, if the absolute position of the horizon is important for stabilization. If stabilization in pitch is equal in STR and H conditions, or better in the STR condition than in the H condition, it can be assumed that horizon movement is more important for pitch stabilization than horizon position.

The effects of platform cuing and horizon/stripes visual stimuli on control performance were analyzed using an ANOVA. The results are shown in Table 2.

Comparing H and STR conditions in Figure 5, it can be seen that control performance does indeed decrease in the STR condition compared to the H condition (main effect of H/STR in the ANOVA, which is significant for velocities and angles, and marginally significant for distance), but only if the platform is turned off (expressed in the ANOVA as a significant interaction of  $P \times H/STR$ ). This provides additional evidence that participants can use physical whole-body orientation cues to compensate for degraded visual orientation cues. If no physical orientation cues are available, participants appear to use the absolute position of the horizon for control. Interestingly, both pitch and roll stabilization performance were degraded in the STR condition (no significant interaction for  $D \times H/STR$  in the ANOVA). Possibly, bad performance in the pitch direction also has a negative influence on roll stabilization, either because of crosstalk between pitch and roll axes or because it is more difficult to align two spheres in left-right directions if they are separated in depth than if they are close.

However, comparing the STR condition to the OF condition without platform, in which neither absolute pitch nor roll position cues are provided (but pitch and roll movement cues are available), performance slightly improved in left-right distance, velocity, and roll, whereas it degraded in forward-backward distance, velocity and pitch. This also suggests that the absolute (roll) angle cue in the STR condition has a beneficial influence on roll stabilization, compared to roll motion or sideways motion of the starfield in the OF condition. For pitch stabilization, the optical flow provided by the starfield appears to help more than the horizon pitch movement in the STR condition.

### III.C. Compensation of the natural oscillations of the simulated helicopter

The helicopter model has a strong tendency to oscillate with a period of approximately 12 s in left-right directions (roll) and approximately 20 s in the forward-backward direction (pitch). These oscillations emerge from the dynamics of the simulated R22 helicopter. A pilot who can stabilize the helicopter well should be

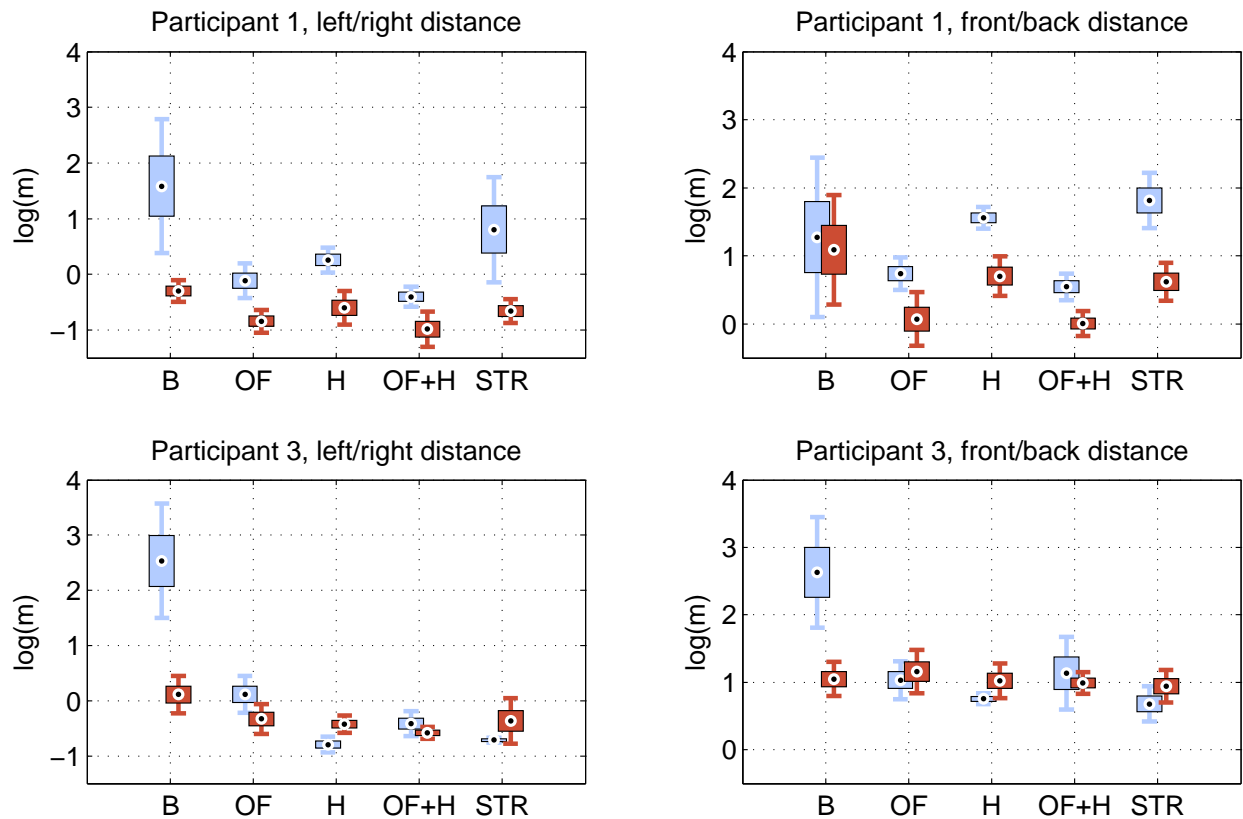


Figure 7. Control performance in terms of distance-to-target, of individual participants 1 and 3. Standard errors and standard deviations, shown by error bars and whiskers, characterize the control performance variability across the five repetitions of each condition.

able to compensate for these oscillations. The remaining amplitude of the helicopter movement in these frequencies during active control is therefore also a measure for the stabilization performance in the different experimental conditions.

Figure 6 shows the amplitudes for pitch and roll at their resonant frequencies in different conditions. It can be seen that participants completely fail to compensate in the 'B' condition without platform cueing, and that also the other measures qualitatively follow the performance measures shown in Figure 5. Comparing roll and pitch amplitudes in the 'horizontal stripes' (STR) condition without platform cueing, it can be seen that more participants have problems to attenuate the resonant frequencies in the pitch than in the roll direction, providing further evidence for the importance of the absolute orientation of the horizon in helicopter stabilization.

### III.D. Characteristics of the integration of visual and body cues of self-motion for control

The integration of information from several sensory modalities is currently a hot topic in the research of human perception. Many studies focus on the question whether and under which circumstances the integration of multiple senses is statistically optimal. According to the principle of maximum likelihood estimation (MLE), the influence of the sensory cues should then depend on their respective reliabilities. If the cues are integrated optimally, also the reliability of the combined estimate should be higher than the reliabilities of the individual cues.<sup>19</sup> Even though it makes ecological and evolutionary sense that perception should always try to evaluate an optimal estimate by weighting cues according to their reliabilities, also beliefs about the validity of the cues themselves could play a role in their weighting, especially for human observers. Ultimately, only sensory cues which belong together should be integrated. This becomes relevant if the observer receives conflicting signals from different sensory modalities, for example in a flight simulator, if inertial motion cues do not agree with visual cues of self-motion. In such a situation a robust perception system should discard one of the conflicting cues and base its estimates on the other. Depending on which cues participants then use for control, they might show completely different control behavior (use different

control strategies).

Experiments which investigate whether multimodal integration follows the MLE principle in a given situation usually first determine the reliabilities of the individual cues experimentally. These reliabilities can then be used to make quantitative predictions for the weights of the individual cues and the reliability of the combined percept if both cues are presented together, under the assumption that the cues are integrated according to MLE.<sup>20</sup> The predictions can then be compared to the actual weights and reliabilities during combined presentation, which are also measured experimentally.

In this experiment, due to the complexity of the dynamic system, it is not easy to specify or measure the actual reliabilities of the individual cues to make quantitative predictions which could be used to test for MLE integration. However, whether there is an increase of the reliability of the combined estimates with respect to the individual cues can be identified qualitatively from our measurements. Increased reliability of the estimates of the current state of the controlled dynamic system should lead to better control performance. Therefore, if several sensory cues are provided, control performance should be better than if only one is available. This is usually case in the group data as can be seen in Figure 5. Adding platform rotations never worsens performance, and in most cases improves it. Also, performance in the OF+H condition is better in most cases than performance in either the OF or the H conditions, both with and without platform cueing.

If, however, we look at the performance of individual participants, it becomes apparent that while for some, performance always increases when more cues are presented, others show some exceptions to this rule. Figure 7 shows data from two example participants. Whereas the control performance of Participant 1 is qualitatively consistent with MLE integration, Participant 3 gets worse if an optical flow field or platform motion is added to a horizon cue. This participant performs best in the H condition, where a horizon is the only available cue. Such effects were found in 6 of the 9 participants for some of the measurements. This behavior cannot be explained by MLE, which would assume that performance should get better, or at least not get worse, if additional cues are presented. Possibly these participants use different control strategies for hovering the simulated helicopter depending on which sensory cues are available.

## IV. Conclusion

In this experiment we investigated how human participants use optical flow, horizon, and whole-body rotations to stabilize a simulated helicopter in a motion simulator which uses a Stewart platform. We could show that each of these cues alone is sufficient for stabilization, and that the availability of multiple cues can improve the stabilization further. From the 'horizontal stripes' condition we learned that participants profit from the absolute position of the horizon for stabilization. We also found evidence that in some conditions, the provided cues are not fused optimally by the participant, or alternatively the participant might switch between different control strategies depending on the cues provided.

It would be nice if we could provide crossover frequencies and phase margins of the participants' control behavior in different conditions. For this, however, a detailed model of the helicopter pilot and the helicopter would be needed. Given the complexity of the helicopter simulation and feedback used in this experiment, this is not easily possible. In further experiments, we plan to use much simpler second-order dynamic systems, which should make a more detailed analysis of the control dynamics possible.

In this experiment, we only used physical whole-body rotations, but no translations, because the limited motion range of our Stewart platform does allow for veridical rotations, but translations would have to be strongly modified to fit within the physical motion range of our simulator. A new simulator setup now available in our institute, which is based on an industrial robot arm, the *Kuka Robocoaster*, has a much larger motion range than the Stewart platform used in this experiment.<sup>21,22</sup> We plan to use this setup for further experiments, so that we can provide veridical physical motion for such helicopter hover tasks, and compare them to hover performance in a real R22/R44 helicopter.

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