Ego-motion perception from optic flow and stereopsis in tunnels with sinusoidally modulated diameter

Bachelorarbeit

der Mathematisch-Naturwissenschaftlichen Fakultät

der Eberhard Karls Universität Tübingen

Vorgelegt von

Ladina Franziska Pohl

Tübingen, April 2014

Erklärung:

Hiermit erkläre ich,

- dass ich diese Arbeit selbst verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt habe.

- dass die eingereichte Arbeit weder vollständig noch in wesentlichen Teilen Gegenstand eines anderen Prüfungsverfahrens gewesen ist.

Tübingen, den 23. April 2014

Danksagung:

Ganz herzlich bedanke ich mich bei Herrn Professor Dr. Hanspeter Mallot, der es mir ermöglicht hat diese tolle Arbeit am Lehrstuhl für kognitive Neurowissenschaften zu schreiben.

Ein riesiges Dankeschön geht an meinen Betreuer Dr. Gregor Hardieß. Gregor, danke für alles was du gemacht hast. Ohne dich wäre das Ganze nur halb so gut geworden und hätte auch nur halb so viel Spaß gemacht!

Ein Dankeschön geht auch an Marc Halfman und Dr. Hansjürgen Dahmen, welche immer ein offenes Ohr für mich hatten und mir immer mit Rat zur Seite standen. Außerdem danke ich der gesamten Arbeitsgruppe für das schöne Arbeitsklima und angenehme Miteinander.

Papa, vielen, vielen Dank für die Stunden an Arbeit und Geduld, die du in meine Arbeit gesteckt hast!

Contents

Abstract

Optic flow does not allow to distinguish ego-motion from object nearness and leads to erroneous ego-motion estimates in tunnels with varying diameters (Festl et. al. JoV 2012). Does addition of stereo cues support veridical ego-motion perception? Subjects used a game controller to keep a constant velocity (15 m/s) while flying through circular tunnels with sinusoidal diameter modulation. Tunnel length was five times the modulation period, varying from 157 to 314 m. Tunnels were presented as limited life-time, random dot stereograms on a mirror stereoscope. In two experiments, amplitude and frequency of the sinusoidal diameter modulation were varied. Velocity settings were recorded as a function of position in tunnel and response offset (meters), phase shift (degrees) and amplitude of velocity modulation (m/s) were analyzed.

Subjects were able to keep average velocity constant but showed a marked modulation of adjusted velocities depending on local tunnel diameter. Response offset varied with frequency (u-shaped curve) but not with amplitude of diameter modulation. Amplitude of velocity modulation increased with amplitude and decreased slightly with frequency of diameter modulation. Concluding, stereo information is not used to disambiguate ego-motion and depth in optic flow analysis.

1 Introduction

1.1 Motivation

Is it possible to disambiguate whether perceived changes in velocity arise from real velocity changes like deceleration or acceleration or from changes in object distance? The purpose of this bachelor thesis was to answer this question.

Changes of motion are known as optic flow. Optic flow describes the pattern of apparent motion of objects, surfaces and edges in visual scene caused by the relative motion between an observer and the scene (Wikipedia). The optic flow was described first by the American psychologist James J. Gibson in 1940. Optic flow can be imagined as a vector field where the direction of the vectors is defined by the opposite of the viewing direction of the observer (figure 1). At the same time, close objects are perceived as flying by faster than distant objects by the observer. This can also be compared to a train ride. The grass, stones, and bushes which are close to the train are passing very fast. Trees and houses that are more far away are moving slow. This phenomenon bases on the optic flow.

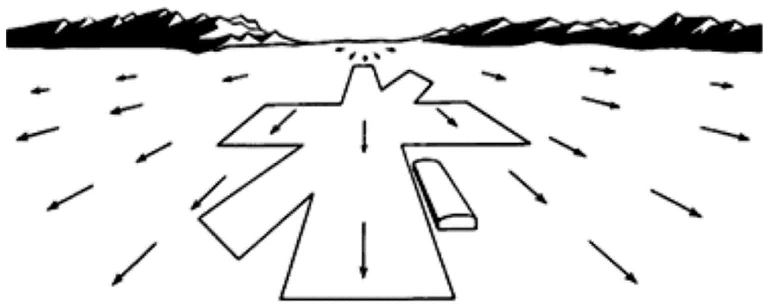


Figure 1: Pattern of the optic flow. Flow vectors in case of forward movement of the observer.

1.2 Technical Approach

A lot of investigations were done concerning the phenomenon of optic flow. Lange (2009) wanted to find out if it is possible to navigate a flying drone solely by using information from optic flow.

Therefore, the drone got optic flow information from camera pictures. Characteristic features of the field of view of the drone were selected with the aid of triple correspondence. Characteristic image points were tracked for three consecutive frames. Afterwards, the ego-motion of the drone was calculated. The outcome of this study revealed that the drone was not capable to navigate using information only coming from camera pictures that contain information of optic flow. Here, one issue was that acceleration was over-estimated. Nevertheless, Lange (2009) found factors with positive influence on the estimation of the ego-motion of the drone, e.g. a larger field of view. Taking these findings into account, it would be interesting to know whether and which factors have a positive influence on the estimation of ego-motion in humans.

1.3 Biological Strategies

In previous studies, a stereoscopic system was used for the evaluation of optic flow pattern in human subjects. A comparable system was also used in this study. A stereoscope typically consists of two screens that display the stimulus binocularly. The two screens can be separated by using a mirror to allow 3-dimensional vision. In the present experiments, a stereoscopic setup was used as basically described by Wheatstone (1852) (figure 2). This originally invented stereoscope was modified by the one-mirror-variant of Kollin and Hollander (2007) (see figure 3, Methods). Both screens display the same but disparate stimulus. The right eye looks straight to one screen, the other eye looks at the mirrored second screen, allowing 3-dimensional stimulus perception in normal sighted human subjects. Often, a random-dot-limited-lifetime stimulus is used, providing only depth (disparity) and flow field information to the subject. All other information of the stimulus are not perceptible when using a random-dot-limited-lifetime-stimulus (Hannig, 2012).

A random-dot-limited-lifetime-stimulus was also used in two other previous studies. In a monocular setup, Festl (2011) and Festl et. al. (2012) wanted to clarify whether changes in optic flow field can be perceived, or rather whether subjects can estimate their ego-motion using optic flow. Therefore, three different types of tunnels were used. A straight, a narrowing, and a widening tunnel one. In a two-alternated-forced-choice paradigm, subjects had to choose whether they perceived an accelerated or decelerated ego-motion. The results were analyzed using psychometrical functions showing different perceptions due to the type of tunnel. Subjects reported accelerated ego-motion in narrowing and decelerated ego-motion in widening tunnels. The reason for this effect was described in Festl et. al. (2012). Ego-velocity was assumed to be judged by a matched filter process. The perceived flow field is correlated with an expected flow field for the ego-motion type in question

(Festl et. al., 2012). However, in this work, it was indifferent whether the changes arose from changes in object nearness (narrowing or widening tunnels) or from changes in velocity (acceleration or deceleration). Based on the results of Festl et. al. (2012), Becker (2013) tried to answer a related question. His approach was to clarify the possibility to discriminate ego-acceleration from changes in optical flow and from information received by binocular disparity. Instead of monocular testing, he used binocular vision in a stereoscope (one-mirror) to enable 3d-vision in normal sighted humans. Again, a forced-choice experiment was carried out where subjects had to decide whether they perceived acceleration or deceleration in three different tunnel types: straight, narrowing, and widening. As found before, also in the binocular setup, subjects confused ego-acceleration and scene geometry and the results of Festl et. al., (2011) were confirmed. Becker (2013) concluded that although there was a depth cue (enabled by the stereovision), subjects were not able to distinguish between changes in scene geometry and changes in ego-acceleration. Taken these results into account, it is challenging to know whether one could obtain different results in modified experimental designs. Consequently, in the current experiments, a modified experimental design will be established to test the perception of ego-motion in optical flow.

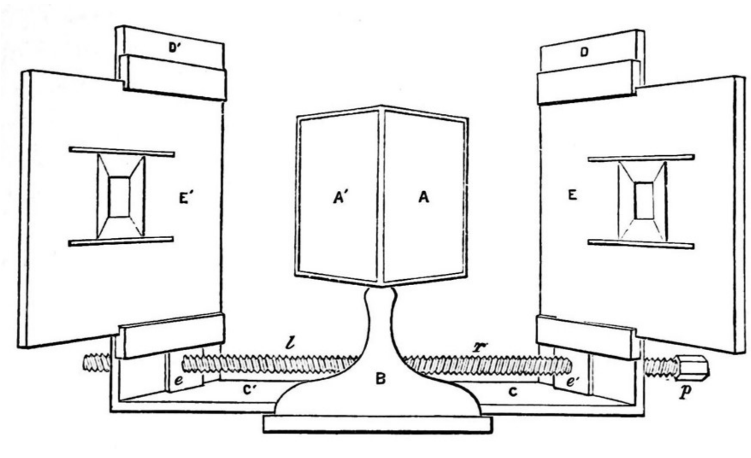


Figure 2: Two-mirror stereoscope (Kollin et. al. 2007).

1.4 Aim of the Study

The experimental design used in the actual study will change from forced-choice experiments to an adjustment experiment. Adjustment experiment means that the subjects had not only to decide between "YES" or "NO", rather, they had to adjust their own velocity in real time. This kind of experiment allows a continuous monitoring of the adaptation behavior of a subject when confronted with changing optical flow pattern. To implement an adjustment experiment, the stimulus had to be modified compared to the previous experiments. Hence, the stimulus was constructed as a continuous sine waved tunnel. Such tunnels include sequences of narrowing and widening tunnels as well as the transition between such episodes. Furthermore, additional changing parameters can be integrated. In the current experiments, the amplitude as well as the frequency of the sine waved tunnels was manipulated. Accordingly, the continuous stimulus allowed various measurements, as the own velocity profile, the covered distance, and time needed to react to and complete the tunnels. According to Becker (2013), random-dot-limited-lifetime stimuli were presented under stereovision. Here, stereo cues should provide depth information allowing a better perception of the shape of the tunnel (sine wave geometry).

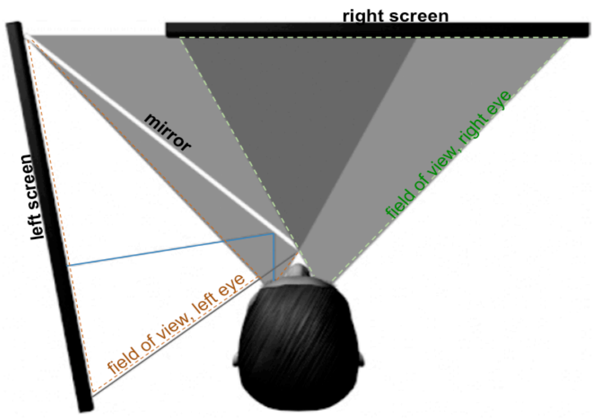
The following two hypothesis can be formulated considering the new experimental procedure and the knowledge of the previous results:

1. There is an influence of different sine waved tunnel frequencies on the offset and the phase shift of the response by the subjects and, there is no influence on the amplitude of velocity modulation (Experiment 1).
2. There is an influence of the different sine waved tunnel amplitudes on the subject's amplitude of velocity modulation, but no influence on the offset or phase shift (Experiment 2).

2 Methods

2.1 The Stereoscope

The stereoscope used in this experiments was developed by Hannig (2012) and was extended further by Becker (2013). The stereoscopic system was placed in an illumination controlled examination room to avoid scattering light. The room location was selected in an area to avoid noise related bias during the examination. Details of the stereoscopic system are illustrated in figures 3 and 4. It consisted of two calibrated 27” high-resolution computer screens (Samsung, S27A850D, frequency: 60Hz; resolution: 2560x1440 pixels). To enable stereoscopic vision, one screen displayed the right stereo image directly to the right eye. The left stereo image of the second screen was mirrored (figure 4a, mirror illustrated with a blue frame) into the left eye of the subject. Subjects were positioned 80 cm distant to the right screen (i.e., 40.2° horizontal and 24° visual angle) with their head placed on a chinrest ensuring stable head position. Room light was dimmed to mesopic condition. To further reduce disturbances due to scattering light during the procedure, the whole stereoscopic system and the subject’s eyes were light shielded. The experimental software was installed on an Intel Core i5 Computer (3 Gb RAM) with an enhanced GPU (NVIDIA: GeForce GTX 570). Subjects used a controller (Logitech Dual Action) as input device for velocity control (figure 4b)).



<u>Figure 3:</u> Schematic construction of the one-mirror stereoscopic system. The gaze of the right eye is directed (without mirroring) to the right screen. A mirror is used to project the left screen to the left eye. The green dotted triangle shows the field of view for the right eye, the orange triangle for the left eye. The blue line shows the view axis from the left eye to the screen.

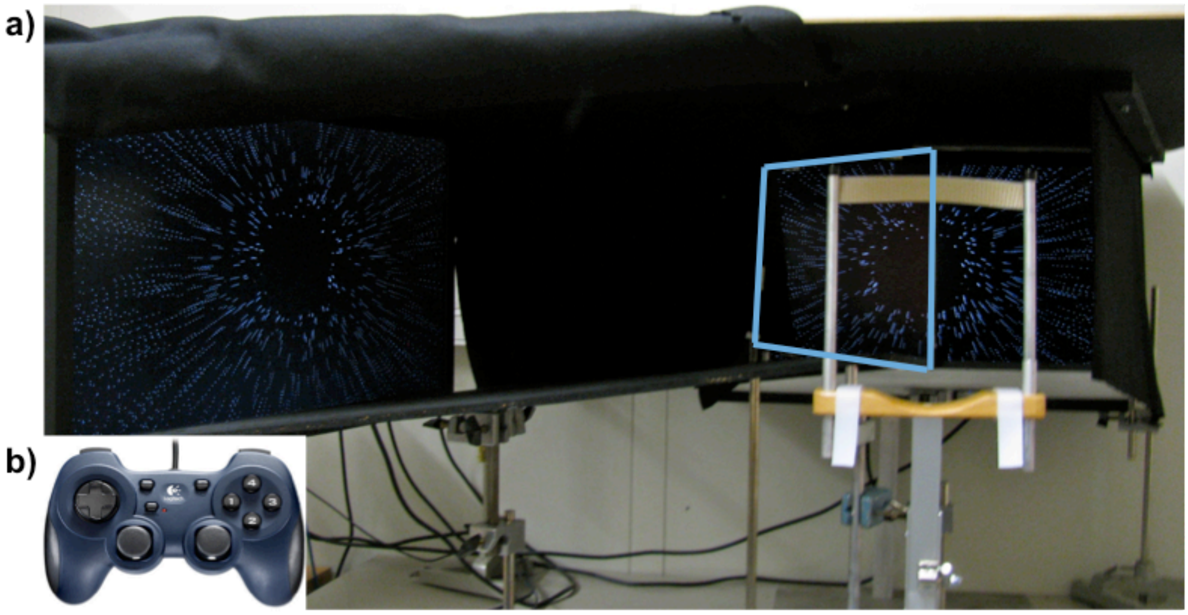


Figure 4: **a)** Picture of the stereoscopic system with the two 27" screens, chinrest (in front of the right screen), and the mirror (framed with a blue rectangle for the sake of illustration) in a light shielded chamber. **b)** Logitech Dual action controller as input device: right joystick was used to generate the velocity, one of the four buttons at the right could be used to enter into the next tunnel.

2.2 Software (MatLab and Creator)

The experiments based on the experimental software developed by Hannig (2012). This program was developed in OSG with C++. Hannig originally used it and Till Becker changed it so that it fitted for his experiment. Because the experiments, described in this thesis, based on Till Becker's, the program could be used in the existing way. The only differences concerned the stimuli. The stimuli used here were sine waved tunnels modulated in frequency (Experiment 1) and amplitude (Experiment 2).

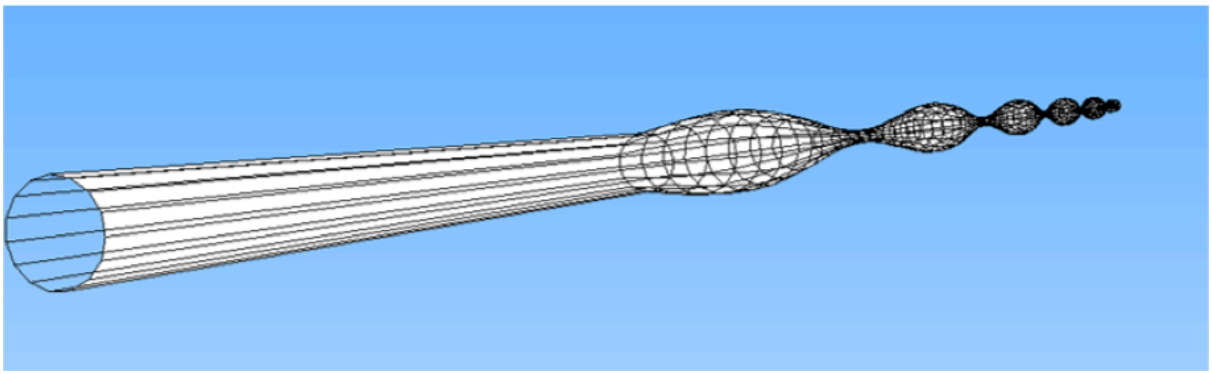


Figure 5: 3D-mesh model of the 950 m long sine waved tunnel (frequency b = 0.04) modeled with Creator. At the beginning (left part of the tunnel) the 100 m straight part followed by 5 sine waved can be seen. One of the sine waved period is 170 m in length.

In the following, a detailed description of the built up of the different stimuli (sine waved tunnels) used in this experiments is given. The MATLAB® software 2010a (The MathWorks Company) was used to modify the application programmed and described by Till Becker (2013). The tunnels were programmed and modeled based on a sine wave with defined frequency and amplitude according to:

$$f(x) = r_0 * \ a * \sin\left(\frac{2\pi}{wave\ length} * x\right), \text{ with } \ r_0 = rad_{min} + a, \ \ x \ in \ m$$

with a = amplitude in m, $\frac{2\pi}{wave\ length\ (m)}$ = b (frequency parameter), and $rad_{min} = 1.5$ in m. By modulating amplitude and frequency, tunnels were built as shown in figures 7 and 8. Calculated coordinates of each sine wave were used to construct tunnels in the 3D-modeling application Creator v2.5.1 (MultiGen-Paradigm®). An example of a 3D-model is shown in figure 5. Initially, the calculated coordinates of a sine wave were used to model the outer tunnel shape as line in the x-y plane. Then, the 3D-body was constructed by rotating the line around its length axis. These 3D-bodies (tunnels) were imported into the experimental program. The limited-lifetime-random-dot generator (Hannig, 2012 and Becker, 2013) rendered the tunnels where the number of dots was set to 1000. The dot size was always 5 px. The minimum lifetime was set to 40 ms and the maximum lifetime to 80 ms.

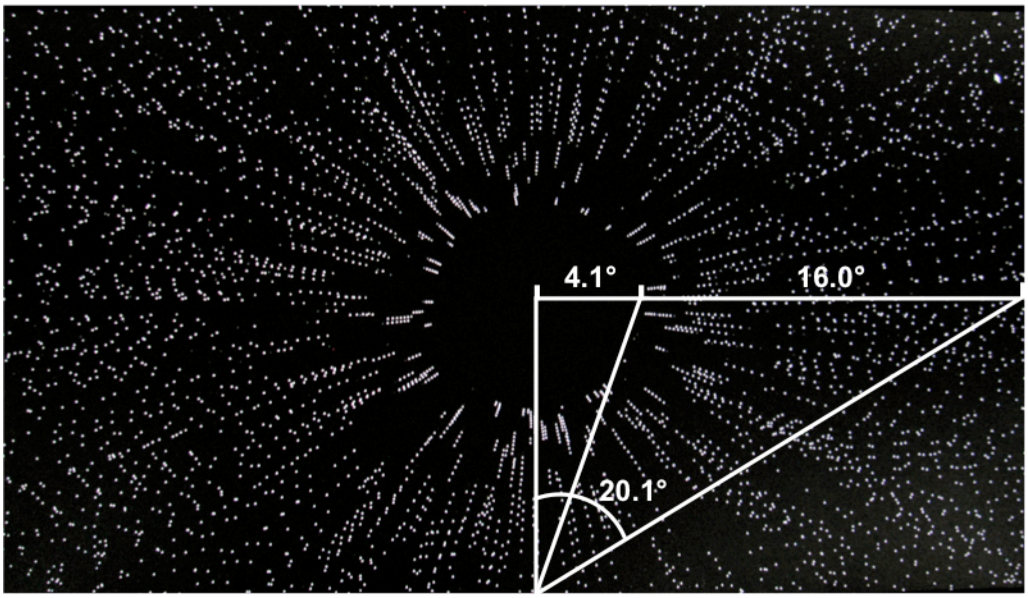


Figure 6: Monocular display of the stimulus when moving through the tunnel by overlay of 6 consecutive frames. In the center of the stimulus a black disc (rendered without dots) was always presented covering the end of a tunnel. Viewing angles are given in degrees (for detail about their calculation see section 2.2).

To have standard conditions for every subject and to avoid to see the end of a tunnel, a black disc was programmed to appear in the center of the tunnel in a simulated distance of ten meters. The disc's diameter was set to 3 m to avoid interference with any other part of the tunnel. All tunnels were generated in a way that the part of the tunnel with the smallest diameter was always 3 m and the field of view (fov) of the camera was 60° (see figures 5 and 6). The disc in front of the observer's eye covered a viewing angle of 8.2°. Consequently, the remaining viewing area was 20.1°. An example of a tunnel stimulus is shown in figure 6.

2.3 Experiments

This study consisted of two experiments where the sine waved tunnels were modified in amplitude and frequency. Experiment 1 approached the frequency modulation and Experiment 2 the amplitude modulation.

The overall task for the subjects was to keep their velocity constant while flying through a cloud of dots. To keep the velocity constant they got a controller and used the joystick for velocity modifications. All subjects were instructed on how to use the joystick combined with a practical training in a training tunnel. Every subject was handed over an information sheet in the beginning of the study (see Attachment 6.1, Experiment 1 and 6.2, Experiment 2). The total duration of the experiments per subject was approximately 30 minutes.

2.3.1 Experiment 1 - Frequency Modulation

Three different sine waved tunnels were used in Experiment 1 (see figure 7). The frequency of the sine waves varied in increasing steps of +0.01 starting from b = 0.02 to b = 0.04. The amplitude was set to a = 3 m for all tunnels. Each tunnel was modeled with a 100 m long straight part in the beginning, followed by five full sine waved periods (figures 5 and 7). The diameter of the straight part was set to nine meters. This straight part was introduced to adapt the subjects with the perceived velocity, which should be hold constantly during the whole passage through the tunnel. Because of the different frequencies, the tunnel with b = 0.02 had an entire length of 1671 m, the tunnel with b = 0.03 1147 m, and the tunnel with b = 0.04 was 885 m in total length (see figure 7).

For training purposes and to accommodate the subject to the experimental setup, a training tunnel was set to a diameter of 9 m over a total length of 500 m. With help of this tunnel, all subjects became familiar with the perceived basic-velocity without maneuvering with the joystick. Furthermore, they learned how to us the joystick and how the adjustment of the joystick changed their perceived velocity. During the experiment, test tunnels were altered with the training tunnel to ensure that subjects remembered the perceived basic-velocity and to avoid habituation to the test tunnel characteristics.

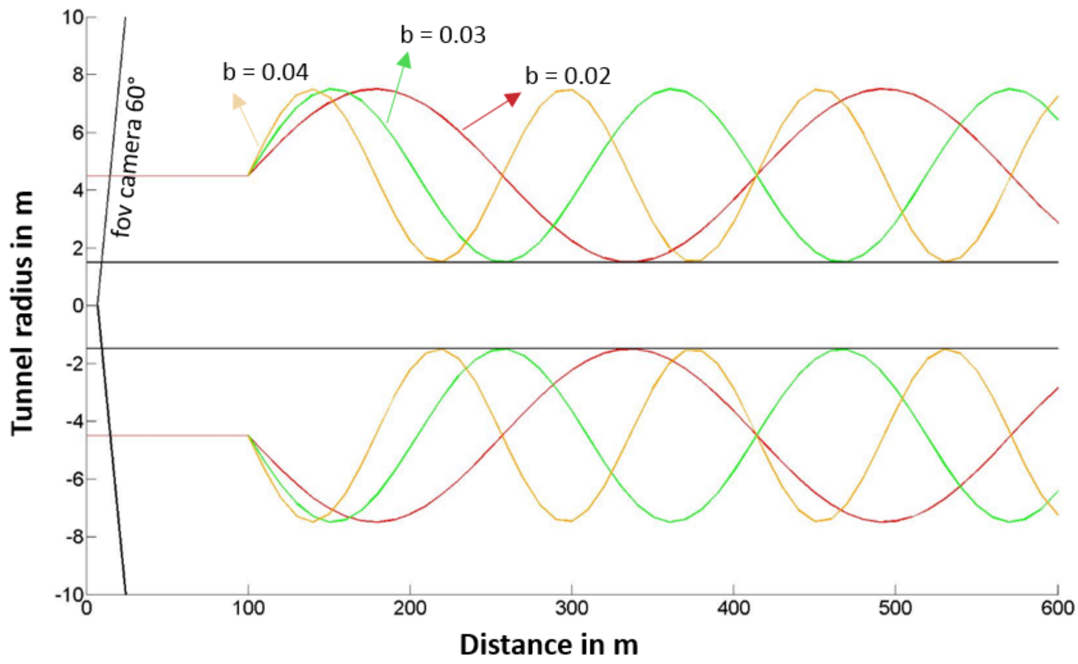


Figure 7: Tunnel modulation by frequency in Experiment 1 - the fov of the camera was set to 60°. The initial straight part (100 m without sine wave) was introduced for practicing and preparing to the tunnel. The diameter of this straight part of the tunnel was 9 m. The minimal diameter of the tunnels was always 3 m. Note, just the first 600 m of the tunnels are shown. Their entire length was dependent on the frequency parameter (see text).

Each subject had to perform three runs through each test tunnel. Altogether, 18 tunnels had to be passed by each subject in Experiment 1.

The (pseudo-randomized) sequence of these 18 tunnels was as followed:

T – 0.02 – T – 0.03 – T – 0.04 – T – 0.03 – T –

0.04 – T – 0.02 – T – 0.04 – T – 0.02 – T – 0.03

(T = 500 m training tunnel; frequencies: b = 0.02; b = 0.03; b = 0.04)

2.3.2 Experiment 2 - Amplitude Modulation

Three different sine waved tunnels were programmed in Experiment 2, where the preset amplitude of the sine waves varied in increasing steps of +0.5 starting from a = 1.0 m to a = 2.0 m. The frequency was fixed to b = 0.03 for all sine waves (see figure 8). Each tunnel was modeled with a 100 m long straight part in the beginning, followed by five full sine waved periods (figure 5). Due to amplitude modulation, the diameter of the straight part differed in its diameter. The perceived velocity in the straight part was constant enabling adaptation of the subject. This velocity was to be achieved by the subject during the flight through the tunnel. The tunnel length was always 1147 m.

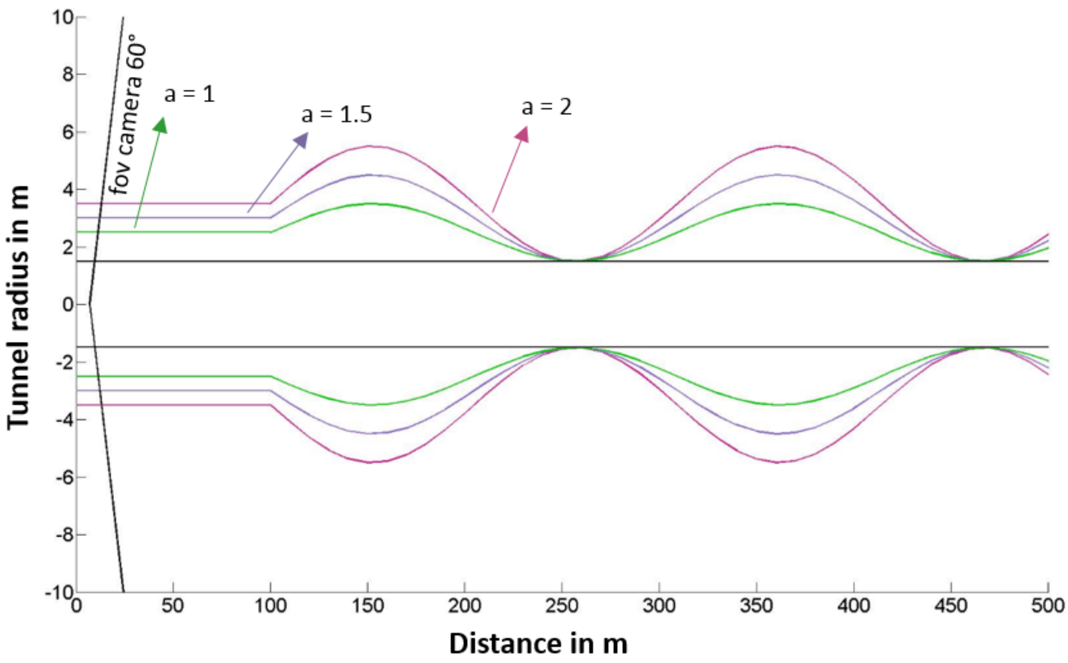


Figure 8: Tunnel modulation by amplitude in Experiment 2 - the fov of the camera was set to 60°. The initial straight part (first 100 m without sine wave) was introduced for practicing and preparing to the tunnel. The diameter of these straight parts of the tunnels differed with changing amplitude parameter. Minimal diameter of the tunnels was always 3 m. Note, just the first 500 m of the tunnels are shown. Their entire length was always 1150 m.

For training purposes and to accommodate the subject to the experimental setup, a training tunnel was set to a diameter of 9 m over a total length of 500 m. With help of this tunnel, all subjects became familiar with the perceived basic-velocity, without maneuvering with the joystick. Furthermore, they learned how to us the joystick and how the adjustment of the joystick changed their perceived velocity. During the experiment, test tunnels were altered with the training tunnel to ensure that subjects remembered the perceived basic-velocity and to avoid habituation to the test tunnel characteristics. Each subject had to go three times through each test tunnel.

As special characteristic in Experiment 2, an additional tunnel was introduced where the three amplitudes were altered within the tunnel (frequency was fixed to b = 0.03). The sequence of the amplitudes consisted of 6 periods, where each amplitude was repeated once in different order (see below).

The design of the additional tunnel looks like the following specification. The used preset amplitudes are labeled showing their amplitude parameters of 1.0, 1.5, and 2.0:

ADD = 2.0 – 1.5 – 1.0 – 1.5 – 1.0 – 2.0

As in Experiment 1, all test tunnels alternated with the 500 meter long practicing tunnel to avoid memorization by the subjects. Because of the additional tunnel in Experiment 2, the total number of tunnels to pass increased to 20.

The (pseudo-randomized) sequence of these 20 tunnels was as followed:

T – 1.0 – T – 1.5 – T – 2.0 – T – 1.5 – T –

2.0 – T – ***ADD*** – T – 1.0 – T – 2.0 – T – 1.0 – T – 1.5

(T = 500 m training tunnel; amplitudes: a = 1.0 m; a = 1.5 m; a = 2.0 m, ***ADD*** = additional tunnel)

2.4 Joystick and Velocity

A joystick (figure 4b)) was used to control the velocity when passing through the tunnels. The predefined basic-velocity was set to 15 m/s. Velocity was modulated linearly. Moving the joystick upwards simulated acceleration up to a maximum velocity of 27 m/s. When moving the joystick downwards, the velocity was decelerated to a minimum of 3 m/s. To enter into the next tunnel, the subjects had to click on a button on the joystick.

2.5 Subjects

Eleven subjects from the Tübingen University student's population were enrolled in the experiments. The 6 males and 5 females had an average age of 22.72 ± 2.18 years (ranging from 21 to 29 years). Visual acuity of subjects was not examined. However, all subjects reported normal vision. One subject used spectacles and one subject used contact lenses. Six subjects were randomly selected for Experiment 1 and, five subjects for Experiment 2.

2.6 Data Collection

According to the stimulus frame rate of 60 Hz, the actual velocity chosen by a subject when passing a tunnel was recorded every 16.667 ms. Changes in velocity were correlated with the time in the tunnel to obtain the actual distance in the tunnel. Online time and radius were calculated. Table 1 in Attachment 6.4 shows a printout of a standard data set. Offset and amplitude height were separately calculated from raw data collection (see 2.9 Statistic and Analysis).

2.7 Questionnaire

Subjects were asked to fill in a questionnaire to collect subjective information on how they perceived the experiment. Details of the questionnaire are shown in Attachment 6.3.

2.8 Statistics and Analysis

Data fitting & calculating offset, phase shift, and amplitude of velocity modulation

Offset and amplitude of velocity modulation were calculated from the raw data collection. Offset is defined as phase shift between the original sine wave of the tunnel and the motoric response (joystick maneuver) of the subject. Amplitude of velocity modulation is defined as the maximum of the motoric reaction (joystick maneuver) of the subjects. The regression line was solved in matrix notation (Mallot 2013). Hence, both values were calculated with MatLab by solving this formula:

$$v(x) = v_0 + a * \cos\left(\frac{2\pi * N}{KL} * \mathrm{x}\right) + \mathrm{b} * \sin\left(\frac{2\pi * N}{KL} * \mathrm{x}\right).$$

$v(x)$ stands for the measurements of the motoric reaction of the subject (joystick maneuver). x is the passed distance in m of the subject to the time of measure. $\frac{2\pi * N}{KL}$ is the frequency of the sine wave with N = number of sine waved periods (5) and KL = length of the 5 sine waved periods. KL differed with changing frequencies especially in Experiment 1. The three parameters $v_{0,}$ a and b had to be calculated with this formula. Subsequently, out of this formula it was formed an equation of matrices:

$$\begin{pmatrix} v_1 \\ \vdots \\ v_2 \end{pmatrix} = \begin{pmatrix} 1 & \cos x_1 & \sin x_1 \\ \vdots & \vdots & \vdots \\ 1 & \cos x_n & \sin x_n \end{pmatrix} * \begin{pmatrix} v_0 \\ a \\ b \end{pmatrix}$$

Whereas the matrix was not invertible it was formed the designmatrix, DM of the original matrix:

$$DM = \begin{pmatrix} 1 & \cdots & 1 \\ \cos x_1 & \cdots & \cos x_n \\ \sin x_1 & \cdots & \sin x_n \end{pmatrix}$$

With this designmatrix it was possible to construct the transposed matrix of the origin by multiplying it by the origin matrix. The result was a 3x3 Matrix ($M3$), which was invertible ($M3^{-1}$). Now the parameter were calculated:

$$\begin{pmatrix} v_0 \\ a \\ b \end{pmatrix} = M3^{-1} * DM * \begin{pmatrix} v_1 \\ \vdots \\ v_2 \end{pmatrix}$$

As a result, a continuous sine wave was obtained. With the resulting parameters, the fitted line was compared and superimposed to the raw data (see figure 9). The fitted sine wave followed the original tunnel sine wave but with an offset (Figure 9). The difference between the maximum amplitude of the fitted sine wave and the maximum amplitude of the tunnel sine wave was defined as offset in m and as phase shift in degrees ($\frac{offset}{wave\ length} * 360°$). The amplitude of velocity modulation was calculated from the value of the maximum amplitude of the fitted sine wave.

Changes in velocity

To investigate a potential influence of modulation frequency, modulation amplitude, or number of periods on the velocity, in both Experiments the average velocity for each (of the five periods) was calculated and figured as bar plot. This was also done for the additional tunnel.

Statistics

ANOVAs (repeated measurement) were calculated with SPSS 21 (IBM). Boxplots were built with Excel 2013. Descriptive statistics were used to analyze the questionnaire. The post-hoc significances are given for each plot with * < .05, ** < .01, *** < .001, n.s. = not significant.

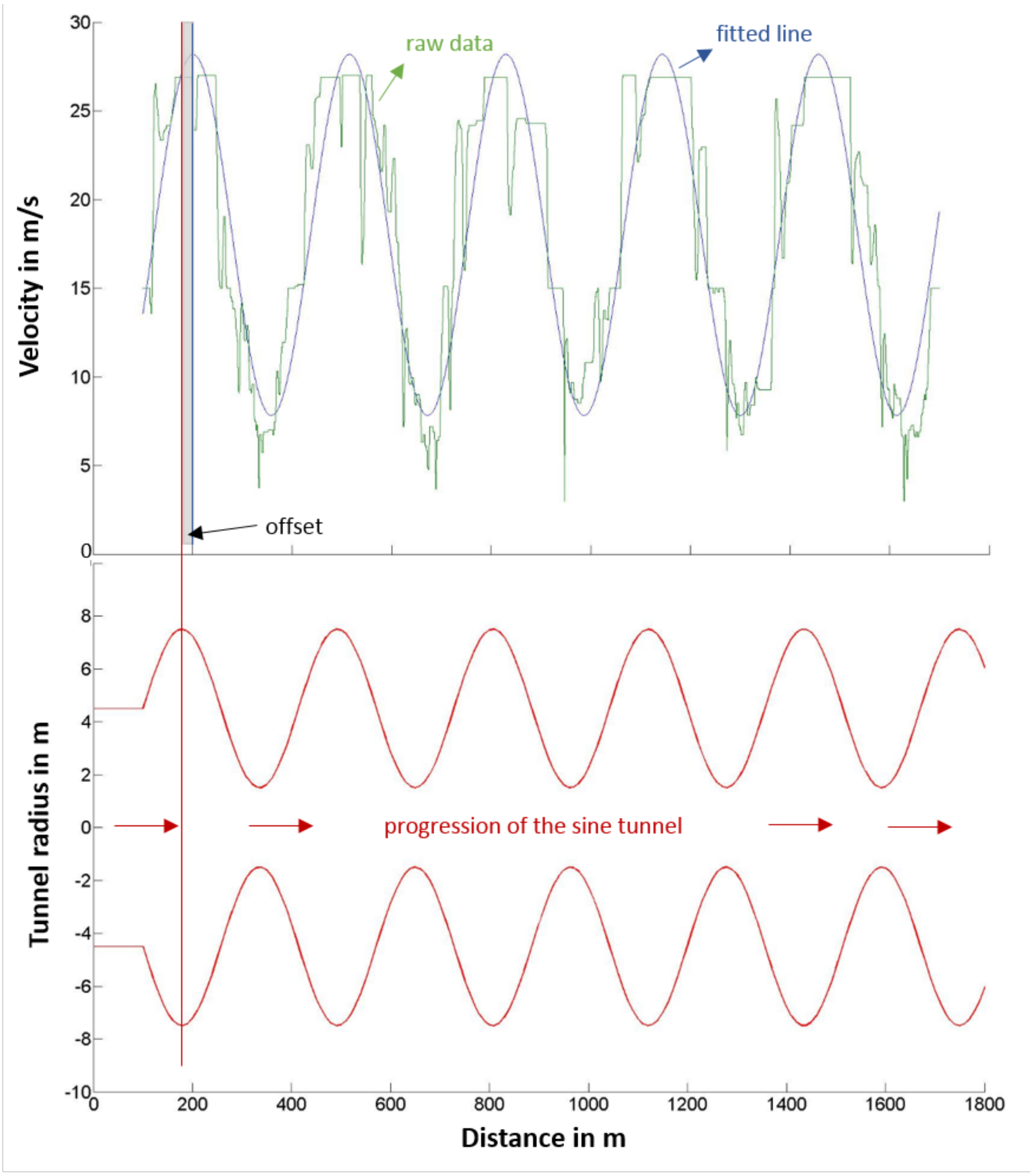


Figure 9: Plotting of the raw data (upper plot, green line), the fitted sine wave (upper plot, blue line) and the progression of the sine waved tunnel (lower plot, red line). The distance (in m) is plotted on the x-axis, the y-axis defines in the upper plot the velocity (in m/s) and in the lower plot the tunnel radius (in m). The offset is symbolized as grey area between the two maxima of the sine waves (vertical lines).

3 Results

In the following, the results of Experiment 1 and Experiment 2 are reported and described. Furthermore, the evaluation of questionnaires every subject had to complete after performing the experiments will be provided.

Explanation of Axes Labeling for the Figures in this Section

Terminology

Amplitude of velocity modulation in m/s:	the maximum of the motoric reaction (joystick maneuver) of the subjects, see also 2.9
Modulation frequency in m^{-1}:	preset frequencies of the three different tunnels in Experiment 1 with 0.00318 for b = 0.02, 0.00477 for b = 0.03 and 0.00637 for b = 0.04
Modulation amplitude in m:	preset amplitudes of the three different tunnels in Experiment 2 with 1 for a = 1.0, 1.5 for a = 1.5 and 2 for a = 2.0
Offset in m:	phase shift in meters (m) between the original sine wave of the tunnel and the motoric response (joystick maneuver) of the subjects, see also 2.9
Distance in m:	virtual distance in the tunnel expressed in meters
Phase shift in °:	phase shift between the sine wave of the tunnel and the fitted sine wave of the motoric response (joystick maneuver) of the subjects
Velocity in m/s:	average velocity of each period of all tunnels from one Experiment and the additional tunnel

Period: the 5 periods the test tunnels and the 6 periods the additional tunnel respectively, consisted of

3.1 Experiment 1

In Experiment 1, the adaptations of subjects regarding changes in the perception of optic flow induced by changing frequency were measured. The idea was to analyze the relation between (i) the offset and the modulation frequency and (ii) the amplitude of the velocity modulation and the modulation frequency of the three test tunnels.

3.1.1 Influence of Modulation Frequency on Offset and Phase Shift

Offset versus modulation frequency

In figure 10 the offsets in m (data over all subjects as boxplots and single data for each subject as colored lines) are shown for each modulation frequency. The highest offset (median = 24.92, min = 14.92, max = 32.90) was found for the lowest frequency. The fastest response was obtained for the medium modulation frequency with a median of 8.98 (min = 2.14, max = 18.62).

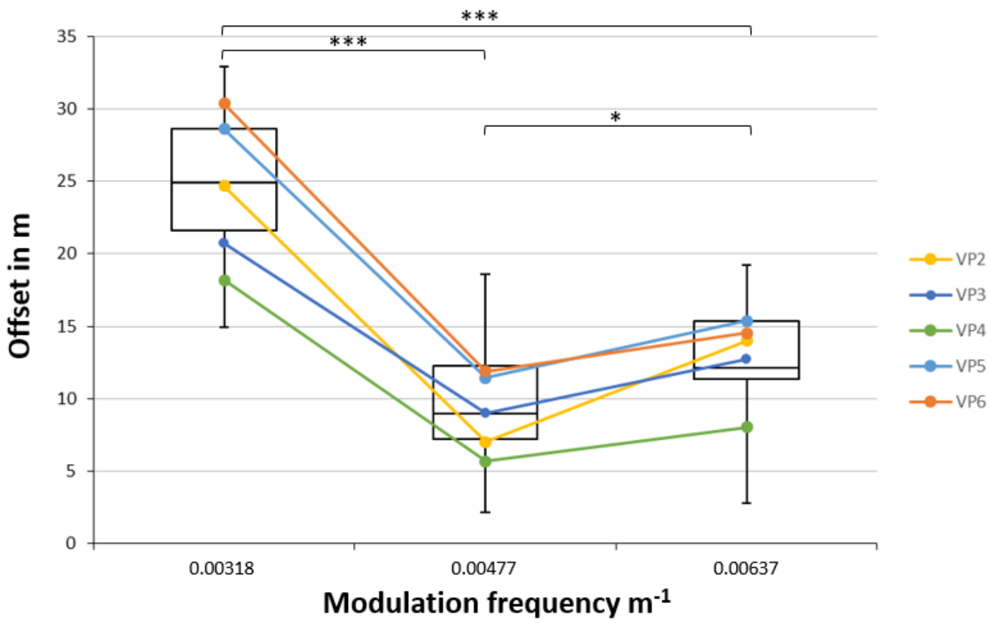


Figure 10: Boxplot of the offset for all three modulation frequencies 0.00318, 0.00477, and 0.00637. Individual data of every subject (VP2 to VP6) are shown in different colors. Colored dots show the mean values of the three runs through one tunnel for each subject. Asterisks indicate the statistical significance between the groups (n.s.: not significant, * $p < .05$, ** $p < .01$, and *** $p < .001$).

The influence of modulation frequency on offset was significantly tested by applying a repeated measurement one-way ANOVA ($F(2.28) = 86.98$, $p < 0.001$, $\eta_p^2 = 0.86$). Post-hoc analysis revealed significant differences between all three groups (see figure 10). The individual data (i.e., means of all three runs through the tunnels with the same frequency) showed comparable adaptations concerning the modulation frequency for each subject (small amount of overlap between the colored lines in figure 10).

Phase shift versus modulation frequency

Additional to the offset between the sine wave of the tunnel and the fitted sine wave of the motoric response of the subjects, the difference between the stimulus and the response was expressed as phase shift (in degrees). In figure 11, this phase shift is shown for each modulation frequency. Here, a minimum phase shift occurred clearly for the medium modulation frequency (median = 15.44, min = 3.67, max = 32.00). For the smallest and the largest modulation frequency the phase shift was equal with a median of 28.55 for the smallest (min = 17.10, max = 37.70) and a median of 27.80 for the largest modulation frequency (min = 6.41, max = 44.03). The influence of modulation frequency on phase shift was highly significant (repeated measurement one-way ANOVA: $F(2.28) = 28.74$, $p < 0.001$, $\eta_p^2 = 0.67$).

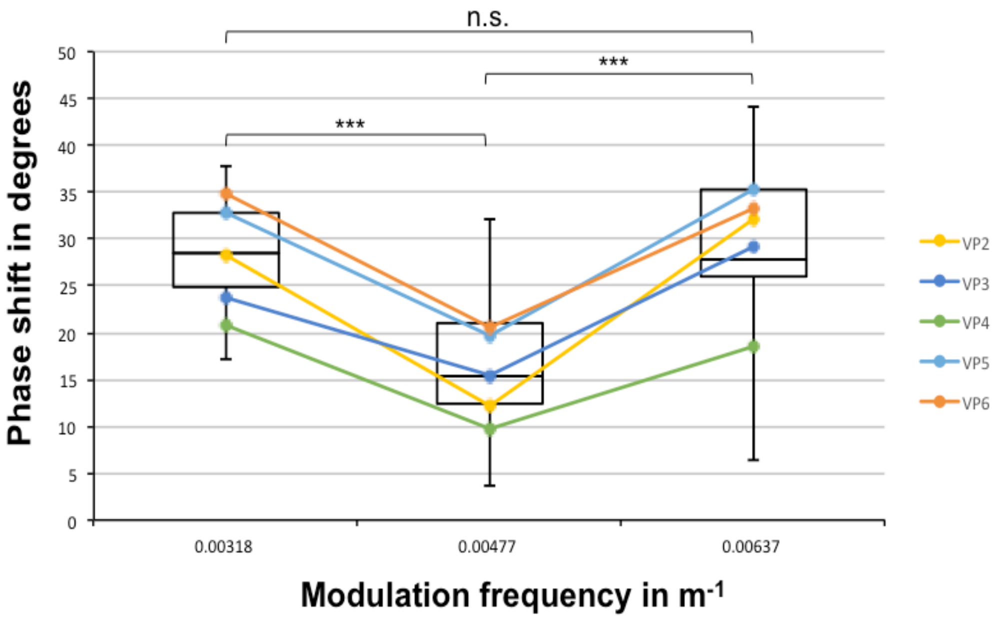


Figure 11: Boxplot of the phase shift for all three modulation frequencies 0.00318, 0.00477, and 0.00637. Individual data of every subject (VP2 to VP6) are shown in different colors. Colored dots show the mean values of the three runs through one tunnel for each subject. Asterisks indicate the statistical significance between the groups (n.s.: not significant, * p < .05, ** p < .01, and *** p < .001).

Post-hoc comparisons between the three groups revealed highly significant differences between the first and the second and between the second and the third group. The first and the third group were not significant ($p = 1.00$). The individual subject's data showed comparable adaptations concerning the modulation frequency (small amount of overlap between the colored lines in figure 11).

3.1.2 Amplitude of Velocity Modulation versus Modulation Frequency

Results about the influence of modulation frequency on the amplitude of the velocity modulation are shown in figure 12. It is noticeable that there was a constant decrease in amplitude of velocity modulation with increasing modulation frequency. The lowest modulation frequency showed the highest amplitude of velocity modulation with a median of 7.99 (min = 4.78, max = 10.54). The lowest amplitude of velocity modulation with a median of 7.28 (min = 3.22, max = 8.88) was found for the tunnel with the highest modulation frequency. The influence of modulation frequency on amplitude was significant (repeated measurement one-way ANOVA: $F(2.28) = 11.09$, $p < 0.001$, $\eta_p^2 = 0.44$). Post-hoc comparisons between the three groups showed a significant difference only between the lowest and the highest modulation frequency (see figure 12).

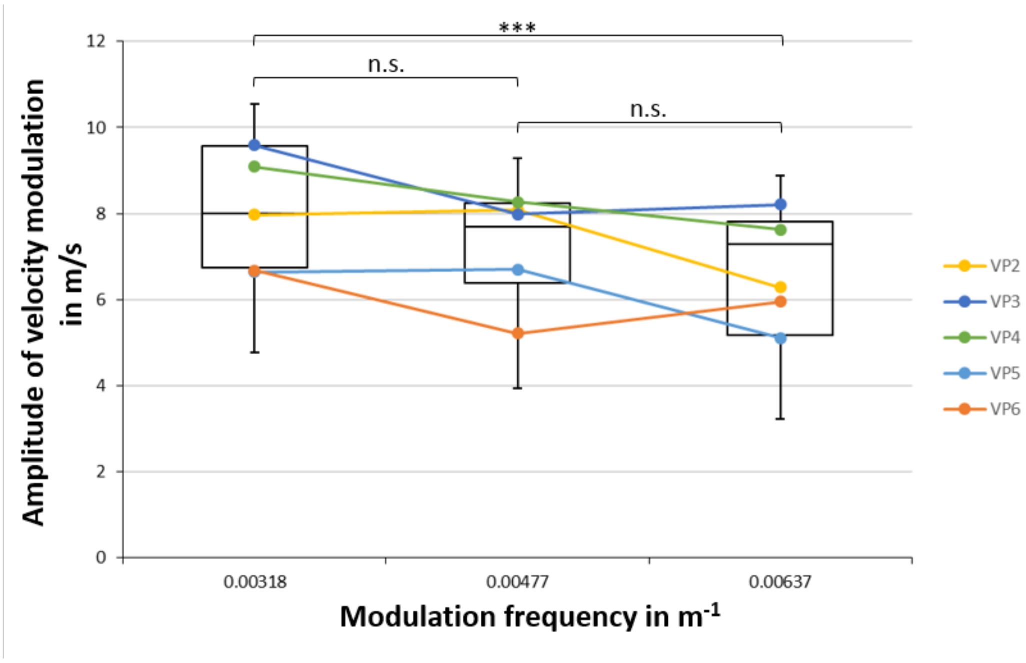


Figure 12: Boxplot of the amplitude of velocity modulation for all three modulation frequencies 0.00318, 0.00477, and 0.00637. Colored lines show the individual data for every subject (VP2 to VP6). Colored dots show the means of the three runs through each tunnel of each subject. Asterisks indicate the statistical significance between the groups (n.s.: not significant, * p < .05, ** p < .01, and *** p < .001).

3.1.3 Changes in Velocity

In figure 13, the average velocities are shown for each of the five periods of the tunnels in Experiment 1. The highest average velocity in this experiment was obtained for the second period with 12.94 m/s. The lowest velocity was found for the fourth period with an average of 12.07 m/s. Although there were no large differences between the values, there was a noticeable trend of a decreasing velocity from the first (12.81) to the last period (12.14). This temporal order effect was confirmed significantly by a repeated measurement one-way ANOVA ($F(4.56) = 2.83$, $p < 0.05$, $\eta_p^2 = 0.17$). Post-hoc analysis between the 5 periods was not significant at all. There was no significant influence ($p = 0.23$) of the factor modulation frequency on the velocity as tested with a repeated measurement one-way ANOVA.

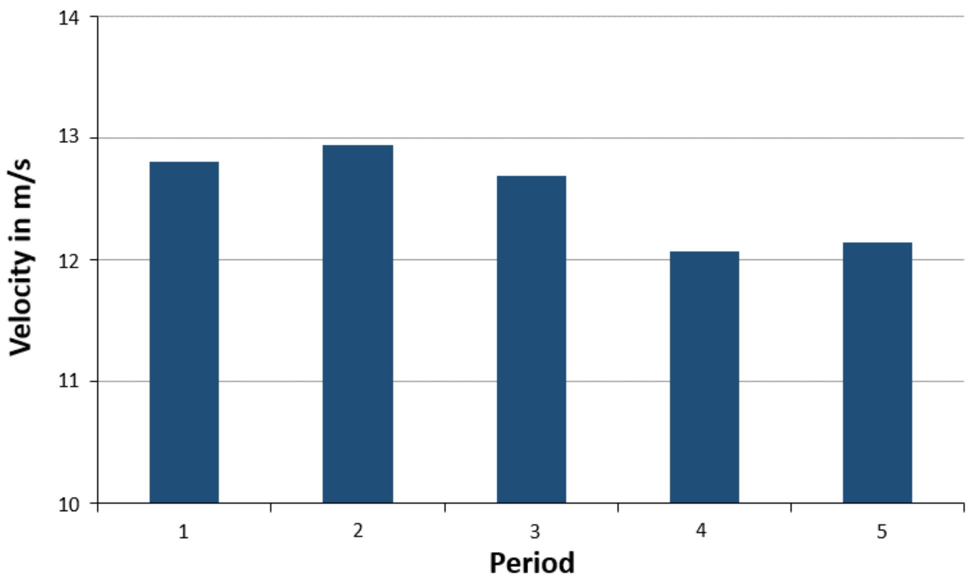


Figure 13: Bar plot of the average velocity for the 5 periods of all frequency modulated tunnels in Experiment 1. Note: Significance levels are not shown because the paired comparisons between each period were always not significant.

3.1.4 Residues

To assess the scope of applicability regarding the sine wave fitting, the residues between the raw data and the fitted sine wave were calculated for each quadrant of the period. However, there was no obvious difference between the residues indicating an adequate fitting over the whole length of the tunnel.

3.2 Experiment 2

Experiment 2 was designed to characterize the correlations between (i) the offset and the modulation amplitude and (ii) the amplitude of velocity modulation and modulation amplitude of the three test tunnels. An additional tunnel segment with changing amplitudes of the sine wave within the tunnel was used to check for potential linking effects (i.e., alignment to the continually perceived same amplitude of a test tunnel) to the test tunnels. Also, in the additional tunnel, the correlation between amplitude of velocity modulation and modulation amplitude was investigated.

3.2.1 Offset versus Modulation Amplitude

The relation between the offset and the modulation amplitudes is presented in figure 14. Overall, there was a small tendency towards lower offsets for increasing amplitudes. The offset of the smallest modulation amplitude had a median of 15.00 (min = 6.68, max = 24.07). The offset of the medium modulation amplitude had a median of 14.37 (min = 8.42, max = 27.23), and the offset of the largest modulation amplitude had a median of 13.02 (min = 3.50, max = 24.02).

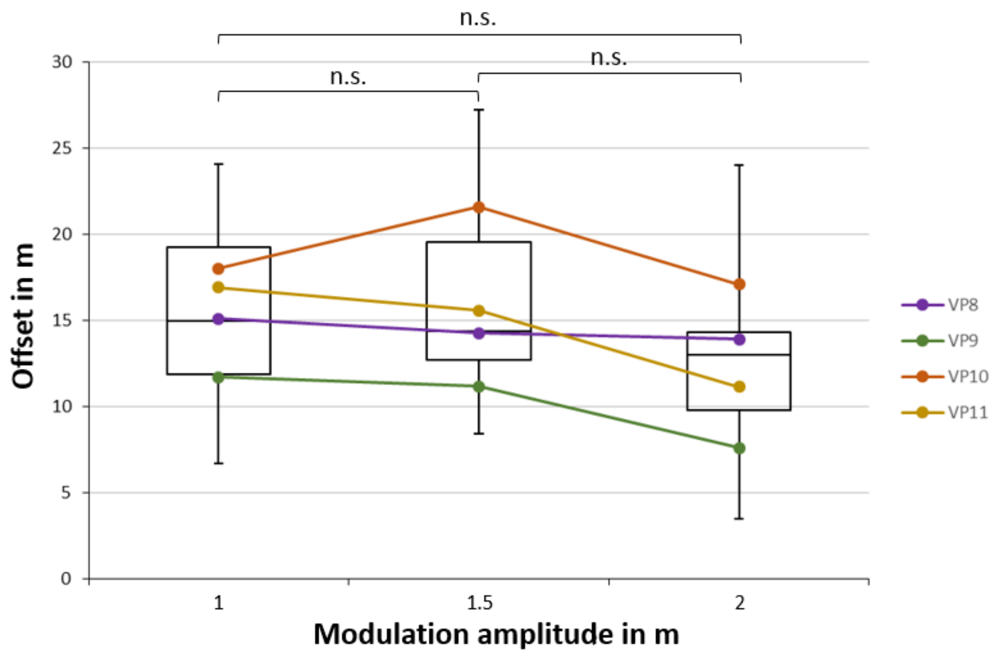


Figure 14: Boxplot of the offset for all three modulation amplitudes 1, 1.5, and 2. Individual data of every subject (VP8 to VP11) are shown in different colors. Colored dots show the mean values of the three runs through one tunnel for each subject. Asterisks indicate the statistical significance between the groups (n.s.: not significant, * p < .05, ** p < .01, and *** p < .001).

The influence of modulation amplitude on offset was not significant (repeated measurement one-way ANOVA: $F(2.22) = 2.84$, $p = 0.08$, $\eta_p^2 = 0.21$). Additionally, post-hoc comparisons between the three groups showed no significant differences (see figure 14).

3.2.2 Amplitude of Velocity Modulation versus Modulation Amplitude

Figure 15 shows the relation between the amplitude of velocity modulation and the modulation amplitude of the three test tunnels. For all subjects, a positive correlation between the variables was found. Here, for the smallest modulation amplitude, the smallest amplitude of velocity modulation with a median of 2.70 (min = 1.02, max = 3.64) was found. The largest modulation amplitude induced the highest values in amplitude of velocity modulation with a median of 5.16 (min = 3.42, max = 8.21). The influence of modulation amplitude on the amplitude of velocity modulation showed significance when applying a repeated measurement one-way ANOVA ($F(2.22) = 34.91$, $p < 0.001$, $\eta_p^2 = 0.76$). Post-hoc analysis revealed significant differences between all three groups (see figure 15). The individual data (i.e., means of all three runs through the test tunnels with the same amplitude) show comparable adaptations concerning the modulation amplitude for each subject (small amount of overlap between the colored lines in figure 15).

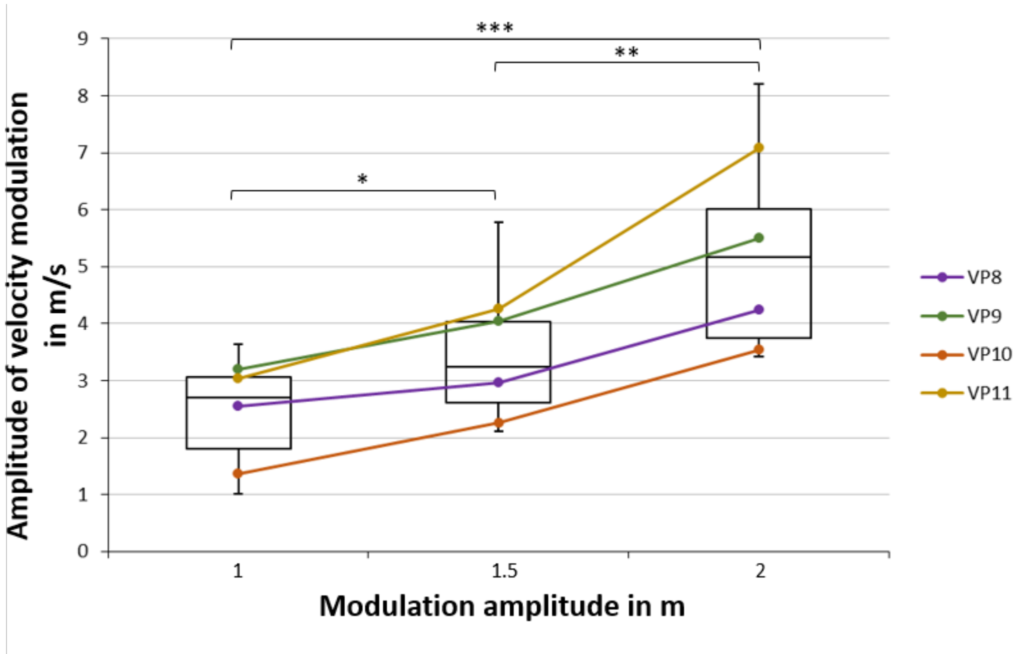


Figure 15: Boxplot of the amplitude of velocity modulation for all three modulation amplitudes. Colored lines show the individual data for every subject (VP8 to VP11). Colored dots show the means of the three runs through each tunnel of each subject. Asterisks indicate the statistical significance between the groups (n.s.: not significant, * p < .05, ** p < .01, and *** p < .001).

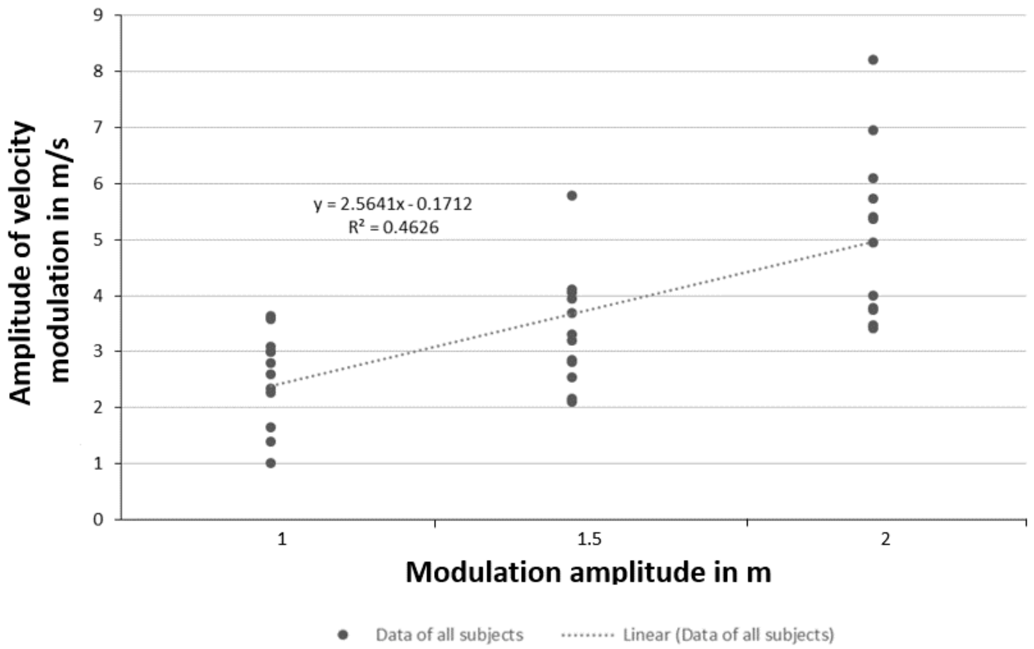


Figure 16: Regression analysis of the single data points (amplitude of velocity modulation) of all runs for each test tunnel of all subjects. Linear regression was calculated with R^2 = 0.46.

Considering all individual responses (three runs per test tunnel amplitude) of all subjects, the positive correlation between modulation amplitude and amplitude of velocity modulation could be confirmed (figure 16). The data were fitted best by a linear regression with f(x) = 2.56x – 0.17 and R^2 = 0.46.

3.2.3 Additional Tunnel

With the additional tunnel, it was intended to investigate potential linking effects of the subjects to the uniform progression of the test tunnels with always the same amplitude. As a consequence of no such linking effects, the amplitude of velocity modulation should vary for each particular amplitude of the additional tunnel and should be similar to the results described in section 3.2.2.

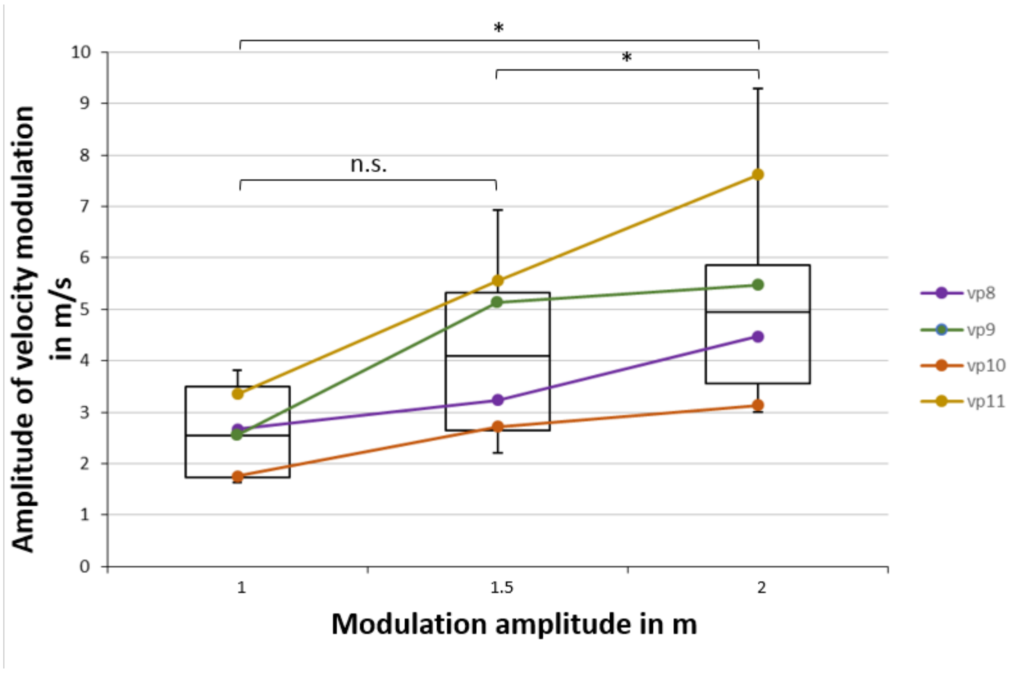


Figure 17: Boxplot of the amplitude of velocity modulation for all three modulation amplitudes in the additional tunnel. Colored lines show the individual data for every subject (VP8 to VP11). Colored dots show the mean values for the different amplitudes. Asterisks indicate the statistical significance between the groups (n.s.: not significant, * p < .05, ** p < .01, and *** p < .001).

The results for the additional tunnel are shown in figure 17. There was an obvious positive correlation between modulation amplitude and amplitude of velocity modulation. This observation is similar to the results in section 3.2.2. The smallest modulation amplitude had a median of 2.55 (min = 1.64, max = 3.81). The medium modulation amplitude increased with a median of 4.10 (min = 2.21, max = 6.93). The largest modulation amplitude of a = 2 had a median of 4.94 (min= 3.01, max = 9.29). The ANOVA showed a statistical significance with $F(2.14) = 12.20$, $p < 0.01$, and $\eta_p^2 = 0.64$. The paired group comparisons between the smallest and the largest, and the medium and the largest modulation amplitudes were significant (see figure 17).

Considering all individual responses (twice the same amplitude per additional tunnel) of all subjects, the positive correlation between modulation amplitude and amplitude of velocity modulation could be confirmed (figure 18). These data were fitted best by a linear regression with $f(x) = 2.60x + 0.08$ and $R^2 = 0.35$. The slopes and interceptions of the linear regressions from the data of the additional tunnel and the test tunnels (3.2.2) were highly similar (slope: 2.60 versus 2.56, interception: 0.08 versus -0.17; figure 19).

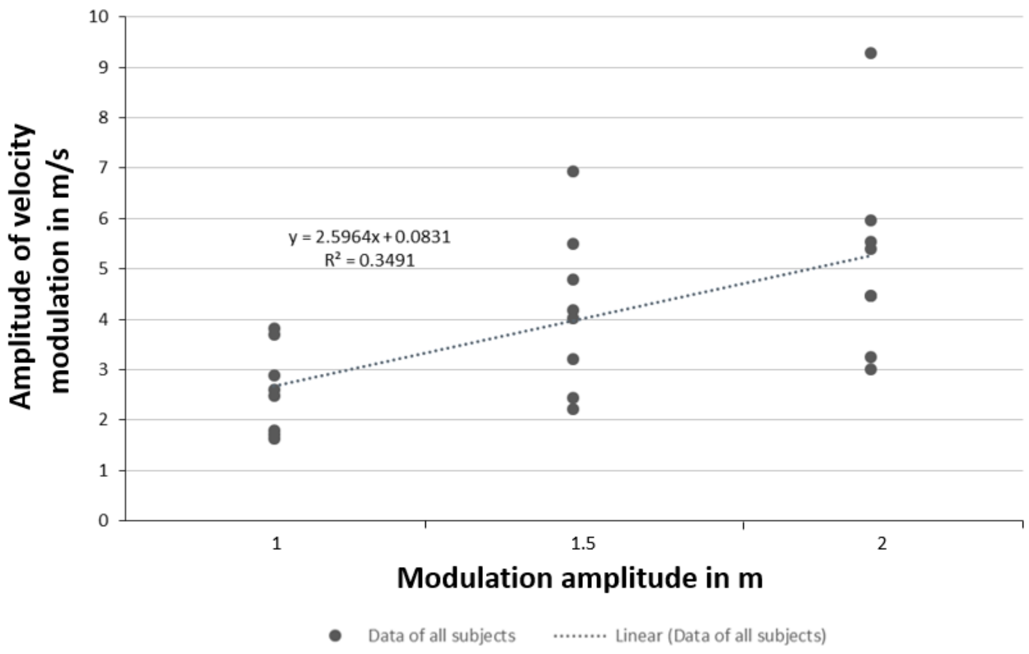


Figure 18: Regression analysis of the single data points (amplitude of velocity modulation) for each modulation amplitude obtained from the run through the additional tunnel of all subjects. Linear regression was calculated with $R^2 = 0.35$.

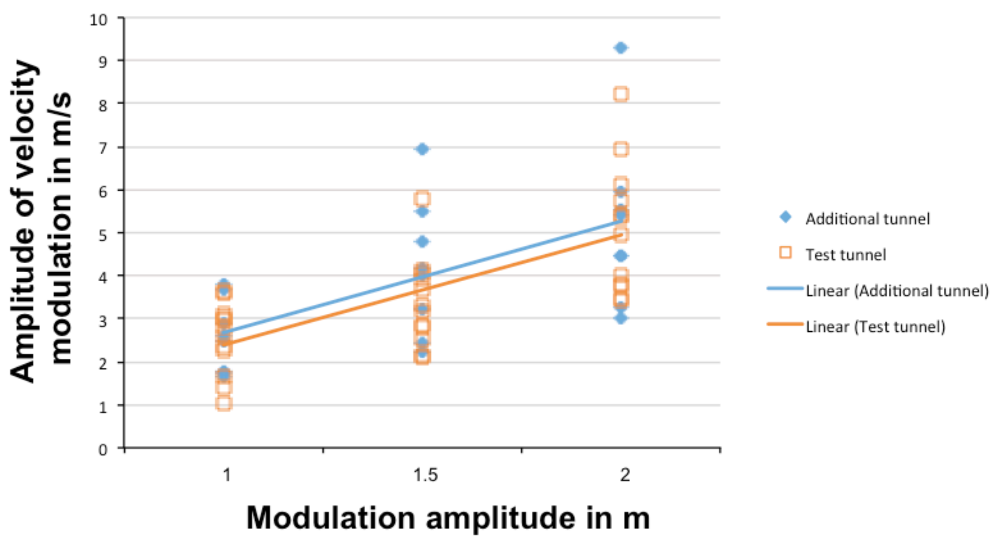


Figure 19: Comparison between the amplitudes (of velocity modulation) of the test (cf. figure 16) and the additional (cf. figure 18) tunnel for all three tunnel amplitudes of Experiment 2. Linear regressions are given for the test tunnel (orange line) and the additional tunnel (blue line).

3.2.4 Changes in Velocity

In figure 20, the average velocities are shown for each of the five periods of the tunnels in Experiment 2. The highest average velocity in this experiment was obtained for the first period with 10.34 m/s. The lowest velocity was found for the fourth period with a mean value of 9.50 m/s. Although there were no large differences between the values, as in Experiment 1, there was an effect of the temporal order on the velocity from the first (10.34 m/s) to the last period (9.51 m/s). This effect was confirmed as significant by a repeated measurement one-way ANOVA ($F(4.44) = 3.29$, $p < 0.05$, $\eta_p^2 = 0.23$). Post-hoc analysis between the 5 periods was not significant at all. The influence of the factor modulation amplitude on the velocity was not significant but with $p = 0.08$ slightly below the criterion of significance. Furthermore, the effect size (η_p^2) was relatively strong with a value of 0.21 supposing that modulation amplitude might have an influence on the average velocity in the progression of the tunnel.

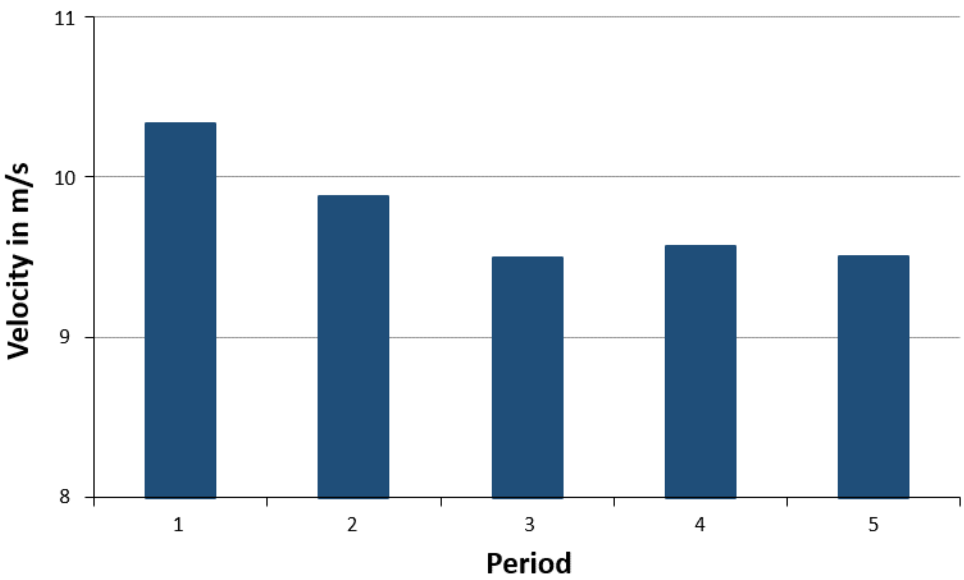


Figure 20: Bar plot of the average velocity for the 5 periods of all amplitude modulated tunnels in Experiment 2 (except the additional tunnel). Note: Significance levels are not shown because the paired comparisons between each period were always not significant.

This effect was also confirmed by the additional tunnel. In figure 21 the average velocities are shown for the 6 periods of the additional tunnel. The highest velocity was found for the first period with an average value of 11.85 m/s. The lowest velocity was obtained for the fifth period with a mean value of 8.47 m/s. The order of amplitudes presented in this tunnel are reflected in the mean velocities (large – medium – small – medium – small – large, see also 2.3.2). Additionally, the effect of temporal order on the overall velocity was obvious. Here, the second presentation of each amplitude caused a decrease in the value of the average velocity. The velocity for the largest amplitude decreased from 11.85 m/s to 10.42 m/s, for the medium modulation amplitude from 10.19 m/s to 9.58 m/s, and for the smallest modulation amplitude a decrease from 8.71 m/s to 8.47 m/s was obtained. The influence of order as well as amplitude could not be tested to significant effects, because of the small number of four observations per period.

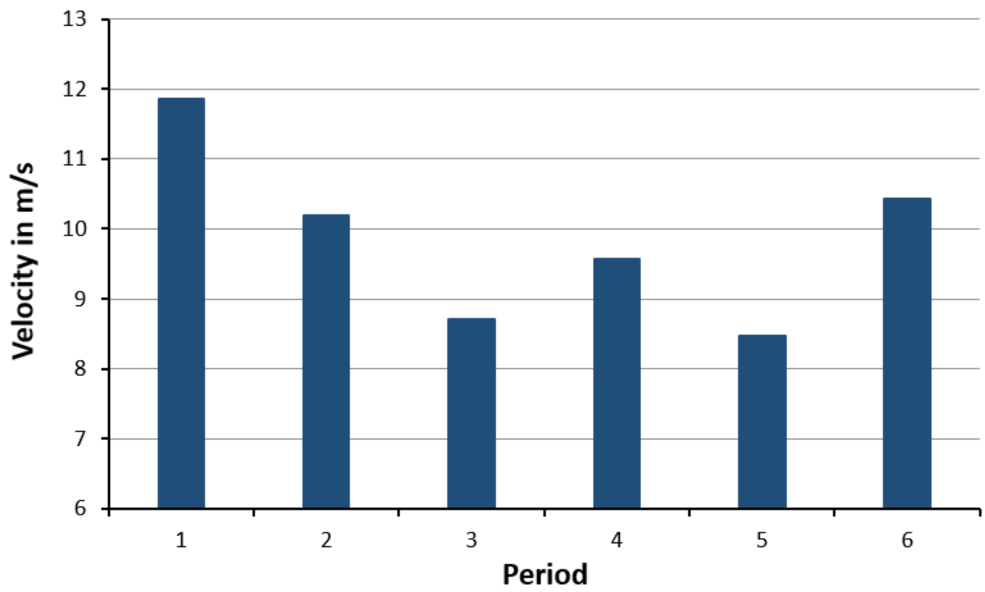


Figure 21: Bar plot of the average velocity for the 6 periods of the additional tunnel in Experiment 2. Note: Significance levels are not shown because the paired comparisons between each period were always not significant.

3.3 Questionnaire Evaluation

A subjective questionnaire was given to the subjects after each experiment with general questions about the experiment including questions with an important informative effect for the analysis of the experiment.

Question 1: I was motivated during the Experiment.

Subjects had to choose their level of motivation on a scale from 1 to 7 where 1 was not at all motivated and 7 fully motivated. The overall level of motivation in Experiment 1 was rated high with a mean value of 6.60 ± 0.80. The overall level of motivation in Experiment 2 was compared to Experiment 1 lower with a mean value of 5.25 ± 1.09.

Question 2: I had fun with the Experiment.

Subjects had to choose their level of fun on a scale from 1 to 7 where 1 was not at all fun and 7 highest level of fun. The overall level of fun was rated as good with a mean value of 5.20 ± 0.98 in Experiment 1. In Experiment 2, the level of fun was rated a bit lower with a mean value of 4.00 ± 1.23 compared to Experiment 1.

Question 3: I would participate again in a psychophysical experiment of this kind.

Subjects had to choose their willingness of re-participation on a scale from 1 to 7 where 1 was not at all willing to re-participate and 7 confirmed participation. The overall level of willingness to participate again in a psychophysical experiment of this kind was rated high with a mean value of 6.60 ± 0.80 in Experiment 1. Subjects rated lower with a mean value of 6.25 ± 1.30 regarding the overall level of willingness to participate again in a psychophysical experiment after passing Experiment 2.

Question 4: I am familiar with the use of a game controller as I often play video games in my leisure time.

Subjects had to estimate their level of knowledge in using a game controller on a scale from 1 to 7 where 1 was no experience at all with a game controller and 7 the highest level of knowledge. In Experiment 1, the overall level of knowledge was rated with a mean value of 3.40 ± 2.25. Here, 40% of subjects had no experience with a game controller. In contrast to Experiment 1, the mean value of Experiment 2 was lower with a mean value of 2.25 ± 2.17. Here, 75% of all subjects had no experience with a game controller.

Question 5: I got the feeling to pass the experiment positively.

Subjects had to estimate their level of positive feeling on a scale from 1 to 7 where 1 was poor feeling and 7 the highest level of positive feeling. The overall level of perceived feeling was rated medium with a mean value of 3.80 ± 0.75 in Experiment 1 and a mean value of 2.75 ± 0.83 in Experiment 2.

Question 6: During the course of the experiment, I realized the purpose of the experiment.

Subjects had to choose their level of understanding the purpose of the experiment on a scale from 1 to 7 where 1 was no understanding of the purpose of the experiment and 7 the highest level of understanding. In both experiments, the overall level of understanding was rated high with a mean value of 6.80 ± 0.40 (Experiment 1) and 6.50 ± 0.50 (Experiment 2).

Question 7: a) I felt that I noticed changes between the different test tunnels.

b) If YES, please specify the changes.

a) In Experiment 1, 60% of all subjects answered with YES and 40% with NO.

In Experiment 2, 50% of the subjects answered with YES and 50% with NO.

b) In Experiment 1, VP2 reported changes in the size of the central black disc. In contrast, VP4 and VP6 perceived changes in the ground speed. VP6 additionally mentioned that the tunnel seemed to differ from trial to trial but was not able to specify his feelings.

In Experiment 2, VP8 reported that the visual focus differed between the tunnels. VP9 perceived, as VP4 and VP6 in Experiment 1, changes in the ground speed.

Question 8: During the experiment, where did you orientate to or where did you look at?

In Experiment 1, VP2 orientated on the number of dots, searching for areas with more than two dots. VP3 mentioned that he focused his eyes to infinity and, in some parts, he did not look to a specific point in the tunnel. However, VP3 reported that he looked sometimes at the lower right edge of the screen. VP4 reported changing fixation points during the course of the experiment. Within the first trials, VP4 directed his gaze on the center of the black disc. Later, he looked on the upper or lower edge of the disc and tried to orientate on the length of the lines (which were formed by the optical flow of the dots). VP5 looked to the upper right part of the screen and orientated likewise VP4 on the form of the dots and lines respectively. VP6 looked, as VP4, at the middle of the black disc and orientated on the flying dots.

In the beginning of Experiment 2, VP8 looked at the dots above the black disc. Later, he fixated on the dots on the left side of the black disc. The dots strayed to lines in this area. 3 out of 4 subjects focused on the central part of the black disc. VP9 always focused on the middle part of the black disc for orientation. VP10 predominantly looked to the center of the black disc. VP11 looked also to the central part of the black disc but also to the lower right edge of the screen.

After the questionnaire was filled in, the following question was asked: “Can you describe the form of the cloud of dots you passed in the test trials?” This question was not part of the written questionnaire. No subject was able to describe the form of the “cloud of dots” in either experiment. Although the clouds of dots were sine waved tunnels, subjects perceived it as changes in velocity.

4 Discussion

In the following sections, the results of Experiment 1 and Experiment 2 will be discussed focusing on the hypotheses of the study. For Experiment 1 the hypothesis was "There is an influence of different sine waved tunnel frequencies on the offset and the phase shift of the response by the subjects and, there is no influence on the amplitude of velocity modulation.", and for Experiment 2 "There is an influence of the different sine waved tunnel amplitudes on the subject's amplitude of velocity modulation, but no influence on the offset or phase shift.". Furthermore, the pros and cons of the experiments will be discussed. The last paragraph will give an outlook towards potential future investigations and regarding changes and improvements for the experimental paradigm.

As a general result it has to be mentioned that all subjects reacted on the changes in optic flow. They were not only able to react but every subject reacted nearly the same. Apparently they perceived the changes equal so that there were no great differences in the average speed of all subjects, which besides amounted to almost 15 m/s. At least also on changes in amplitude or frequency the subjects answered with very similar reactions. This shows that stereo vision is not used to disambiguate ego-motion and depth in optic flow. Based on this result the results of the two experiments will now be further discussed.

4.1 Experiment 1

In Experiment 1, changes in perceived optical flow were evaluated in relation to changing frequencies of the sine waved tunnels. These tunnels were built with a constant amplitude but changing modulation frequencies. With the help of a controller, the subjects had the task to maintain their perceived velocity constant during the flight through the tunnels.

Regarding the influence of modulation frequencies on the offset and the phase shift, the results were statistically highly significant (see figure 8 and 9). For the offset (measured in meters), the highest value was obtained for the smallest frequency. The medium and the largest frequency revealed a lower offset. Furthermore, for the phase shift (calculated in degrees), two maxima were obtained for the smallest and the largest frequency with a local minimum for the medium modulation frequency. It is obvious that there is an effect of decreasing offset as well as phase shift, from low to medium frequencies. Subjects responded faster to the sine waved tunnel changes when the tunnel frequency increased to the medium level. However, it seemed that the offset increased only slightly from the medium to the largest frequency. As the difference between the medium and the largest frequency was statistically significant, even with the small number of subjects, it can be concluded that subjects reacted slightly slower when confronted with high tunnel frequencies compared to the medium frequency. Analyzing the phase shift, it supported this effect. It increased from the medium to the largest frequency up to a similar height as for the smallest modulation frequency. Consequently, the medium modulation frequency might be the easiest frequency to react adequately. Because of the fastest responses in terms of offset and phase shift in these tunnels the (response) time delay for the smallest and the largest modulation frequency could be related to the visual processing of the subjects. In the smaller frequencies, changes in optical flow were more difficult to perceive and in larger frequencies, the changes appeared too fast.

The influence of modulation frequencies on amplitude of velocity modulation was also found as significant when comparing low and high sine waved tunnel frequencies. This means that the deflection of the joystick was slightly greater with low frequencies compared to the high frequency tunnels. For the medium frequency, the deflection level was in between low and high frequencies. In the tunnels with a low frequency, subjects might perceive changes easy resulting in a well adjustable deflection of the joystick. For higher frequency changes, the lower deflection could be correlated to a Low-Pass Filter phenomenon where subjects might be not able to address these changes in the tunnel with a normal adjustable deflection of the joystick compared to low frequencies.

As a consequence, the hypothesis can be confirmed that there is a dependency between offset as well as phase shift and frequency modulation. In addition, there seems to be evidence that the frequency modulation has also an effect on the amplitude of velocity modulation. This part of the hypothesis needs to be questioned or even be falsified.

4.2 Experiment 2

In Experiment 2, the perception of optical flow patterns through changing amplitudes of the tunnels was investigated. The used sine waved tunnels had a constant frequency but changing amplitudes. Furthermore, the sine waved tunnels contained the additional tunnel segment (***ADD***). As in Experiment 1, subjects had the task to maintain their velocity constant during the flight through the tunnel.

There was neither a clear trend nor a significant change of the modulation amplitude regarding the offset (see figure 14). This might be associated with the same frequency used in all tunnels resulting in constant stimuli during the flight through the tunnels. It seems that subjects reacted in amplitude modulated tunnels very similar in each tunnel.

However, subjects responded with an increase in amplitude of velocity modulation with increasing modulation amplitude (see figures 15-16). All subjects showed an increase in the amount of deflection of the joystick with increasing changes in amplitude of the test tunnels. These findings were also confirmed by analysis of subject's raw data resulting in a positive correlation between modulation amplitude and amount of deflection of the joystick (amplitude of velocity modulation). When analyzing the behavior of subjects while passing the additional tunnel segment these findings are confirmed as well. All subjects reacted on each of the amplitude modulated sine waved tunnel segments in the same manner as found for the test tunnels (figure 17). The result was a stronger acceleration in tunnel segments with larger amplitudes compared to segments with smaller amplitudes. Furthermore, by comparing the regression lines from the normal tunnels to the additional tunnel, a high similarity became obvious. This finding indicated that the effect is not bound to an entire tunnel but to the height of a single amplitude.

These results confirm the hypothesis that the amplitude of velocity modulation increases with increasing modulation amplitude but with no effect on the offset. It seemed that increasing amplitudes in different tunnels resulted in a perceived increase of optical flow causing a larger deflection of the joystick. All subjects perceived the velocity of the dots decelerated when reaching the periphery of the sine waved tunnel. As a fact, subjects responded with a larger deflection on larger amplitudes resulting in an acceleration of their velocity.

4.3 Changes in Velocity

The aim in analyzing the velocity was to elaborate how the adjusted velocity changed over the length of a tunnel. Therefore, the average velocities were calculated for each of the five sine waved periods of the tunnels. In Experiment 1, although the effect was really small, a significant decreasing effect with increasing number of periods was obtained, meaning that the average velocity during the flight through the tunnel was slowed down. The same effect was also found in Experiment 2 and could be attributed to irritations by the perceived optical flow on the subjects. The narrowing parts of the tunnel, where the optical flow and the perceived velocity increased, might perceived as more salient changes compared to the widening parts of the tunnels where optical flow and perceived velocity decreased. Another effect might be that subjects adjusted the original perceived velocity in each period again and new. This might have resulted in more difficulty to remember the original velocity. With such a time effect together with an enhanced perception of the velocity in narrowing parts of the tunnels (resulting in deceleration), the overall decreasing effect could be explained. Moreover, the amplitude heights of the sine waved tunnels had also an effect on the velocity. In tunnels with smaller amplitudes, the average velocities were also slower. In tunnels with higher amplitudes, the average velocity increased to higher levels. This was also confirmed in the additional tunnel, where the velocities changed steadily with changing amplitude heights. In periods with higher amplitudes, the mean velocity was faster than in those with smaller amplitude heights. The decreasing average velocity effect, caused by the increasing number of periods, may be again exemplified with the additional tunnel. Here, each second passage of a given amplitude height period lead always to a slower average velocity than in the first passage.

4.4 Questionnaires

The outcomes of the subjective questionnaires were very similar in both experiments. All subjects from both experiments responded indifferent to positive to questions number 1 to 6. In these questions, subjects had to score their fun, motivation, willingness of re-participate in such an experiment, familiarity with a game controller, positive feeling during the experiment, and knowing about the purpose of the experiment.

Similar answers were obtained when asking where subjects did orientate during the experiment. The responses indicated, that the main orientation was on local flow patterns of dot areas in both experiments. This means that the subjects concentrated on a specific point where they watched the changes of the dots (e.g. the dots turned into longer lines in case of “acceleration” than in “deceleration”). No subject was able to describe the sine waved construction of the cloud of dots. All subjects perceived the optical flow as changes in velocity irrespective of the shape of the structure. The assumption that a stereoscopic set up would ease the perception of the sine waved form of the tunnel was not confirmed. Under the assumption that the results would be the same under monocular viewing, it would be necessary to repeat such an experiment by using just one stimulation screen.

4.5 Future Opportunities

Although the number of subjects was small in each experiment, general effects became obvious. This might be promoted by the triple repetition of tunnels per subject. Achieved mean values with standard deviations allow better calculation of cohort sizes for future experiments. Especially for the amplitude of velocity modulation versus modulation frequency, a larger number of subjects would have been beneficial to calculate larger effects. By using tunnels with higher frequencies as enrolled in this experiment, a further decreasing effect on the amplitude of velocity modulation could have been achieved.

The effect of the offset in frequency modulated tunnels increased from medium to high frequencies. Although a low significance was obtained, it would be helpful to clarify this context by repeating the experiment with more frequencies in between medium and high and also higher ones to find out whether there is an optimal (in terms of perception) offset for a specific sine frequency. Additionally, frequencies above the highest frequency used in this experiment could clarify a linking effect.

The present investigation should be understood as a pilot study in which we obtained clear effects and descriptive statistical results. These discoveries can be used to conceive future experiments. A study design under monocular condition could lead to similar results as described by Becker (2013). He used narrowing and widening tunnels in a monocular and binocular setup and monocular results were different from binocular data.

There is ongoing research in the department of cognitive neuroscience in Tübingen, with similar experiments. The experiments will give more structure information (e.g. houses instead of dots) to the subjects. This might enable a better discrimination whether there are changes in velocity or in structure.

4.6 Concluding Remarks

Summarizing and after looking on the different results, the question from the beginning, whether it is possible to disambiguate if there are changes in velocity or in space, can be answered. In this kind of experiment, with the setup of a random dot pattern in stereo vision, subjects were not able to characterize the changes. Comparing the experiments and findings from Festl et. al. (2012), and Becker (2013) results like this could be expected. However, the subjects were able to react on the changes. As in the previous studies, changes in optical flow were perceived as changes in velocity. The difference between this experiments and the previous ones was that in the prior studies the subjects had to determine deceleration or acceleration and in this experiments they had to react on the changes with deceleration or acceleration. Hence, subjects reacted with acceleration on the widening parts of the tunnels and with deceleration on the narrowing parts of the tunnels. The velocity slowed down in the course of the tunnel because it was apparently difficult to remember the original velocity. As consequence the subjects tended to decelerate more than to accelerate. Most probably, as in previous experiments of this kind (e.g. limited-life-time dots), also the current results based on a similar processing mechanism (i.e., template matching). According to Lange (2009), with this experiments we were not able to explain anything about factors that have a positive influence on the ego-motion perception in humans and further investigations are needed to answer such a question.

5 Bibliography

Becker, Till 2013. Detection of linear ego-acceleration from optic flow in stereoscopy

Festl, Freya 2011. Erkennung der Eigenbeschleunigung durch optischen Fluss

Festl, Freya, F. Recktenwald, C. Yuan, H. A. Mallot 2012. Detection of linear ego-acceleration from optic flow. Journal of Vision 2012

Hannig, Matthias D. 2012. Entwicklung und Validierung eines spiegelstereoskopischen Virtual-Reality Aufbaus.

Kollin, Joel, A. Hollander 2007. Re-engineering the Wheatstone stereoscope.

Lange, Rene 2009. Eigengeschwindigkeitsschätzung einer Flugdrohne mittels optischen Flusses.

Mallot, Hanspeter A. 2013. Datenanalyse mit MatLab, Lecture notes University of Tübingen.

Ott, Florian 2013. Detection of linear ego-acceleration during 3D-shape perception

Warren, W.H., M. W. Morris, M. Kalish 1988. Perception of translational heading from optical flow.

Wikipedia. Optical flow. http://en.wikipedia.org/wiki/Optical_flow

6 Attachment

6.1 Probandeninformation – Experiment 1

Im folgenden Versuch geht es darum, beim Flug durch eine Punktwolke die Geschwindigkeit möglichst konstant zu halten. Dies wird mit Hilfe eines Controllers ermöglicht. Durch Drücken des linken Joysticks am Controller nach vorne kann beschleunigt und durch Ziehen nach hinten abgebremst werden.

Der Ablauf besteht aus 2 Phasen:

> Der erste Teil ist die Übungsphase. Hier kommt es darauf an den Umgang mit dem Controller zu üben und auszuprobieren wie die Punktwolke auf positive und negative Beschleunigung durch den Joystick reagiert. Außerdem soll eine gewisse Vertrautheit mit der Umgebung und der geflogenen Geschwindigkeit entstehen. In der Übungsphase bleibt die geflogene Geschwindigkeit ohne Verwendung des Controllers konstant.
>
> Der zweite Teil des Versuchs stellt die Testphase dar. Wiederum erfolgt ein Flug durch eine Punktwolke. Hierbei ist nun darauf zu achten, dass die Geschwindigkeit beim Durchflug durch die Punktwolke immer konstant bleibt. Um dies zu erreichen muss mit Hilfe des Controllers beschleunigt (Joystick nach vorne) oder abgebremst (Joystick nach hinten) werden.

Es erfolgt 9mal nacheinander eine Übungsphase im Wechsel mit einer Testphase.

Viel Spaß beim Fliegen!

6.2 Probandeninformation – Experiment 2

Im folgenden Versuch geht es darum, beim Flug durch eine Punktwolke die Geschwindigkeit möglichst konstant zu halten. Dies wird mit Hilfe eines Controllers ermöglicht. Durch Drücken des rechten Joysticks am Controller nach vorne kann beschleunigt und durch Ziehen nach hinten abgebremst werden.

Der Ablauf besteht aus 2 Phasen:

> Der erste Teil ist die Übungsphase. Hier kommt es darauf an den Umgang mit dem Controller zu üben und auszuprobieren wie die Punktwolke auf positive und negative Beschleunigung durch den Joystick reagiert. Außerdem soll eine gewisse Vertrautheit mit der Umgebung und der geflogenen Geschwindigkeit entstehen. In der Übungsphase bleibt die geflogene Geschwindigkeit ohne Verwendung des Controllers konstant.
>
> Der zweite Teil des Versuchs stellt die Testphase dar. Wiederum erfolgt ein Flug durch eine Punktwolke. Hierbei ist nun darauf zu achten, dass die Geschwindigkeit beim Durchflug durch die Punktwolke immer konstant bleibt. Um dies zu erreichen muss mit Hilfe des Controllers beschleunigt (Joystick nach vorne) oder abgebremst (Joystick nach hinten) werden.

Es erfolgt 10mal nacheinander eine Übungsphase im Wechsel mit einer Testphase.

Viel Spaß beim Fliegen!

6.3 Questionnaire

Fragebogen Experiment

Dieser Fragebogen enthält Aussagen zu Verhaltensweisen beim Zurechtfinden im optischen Fluss. Wir bitten Sie, für jede Aussage anzuzeigen, inwieweit Sie der Aussage zustimmen. Die Möglichkeit zur Ablehnung bzw. Zustimmung hat die folgende Form:

trifft gar nicht zu 1 2 3 4 5 6 7 trifft voll und ganz zu

Bitte markieren Sie für jede Aussage diejenige Position durch Einkreisen, die dem Grad ihrer Zustimmung am besten entspricht. Markieren Sie bitte die Mittelposition (4), wenn Sie weder zustimmen noch ablehnen.

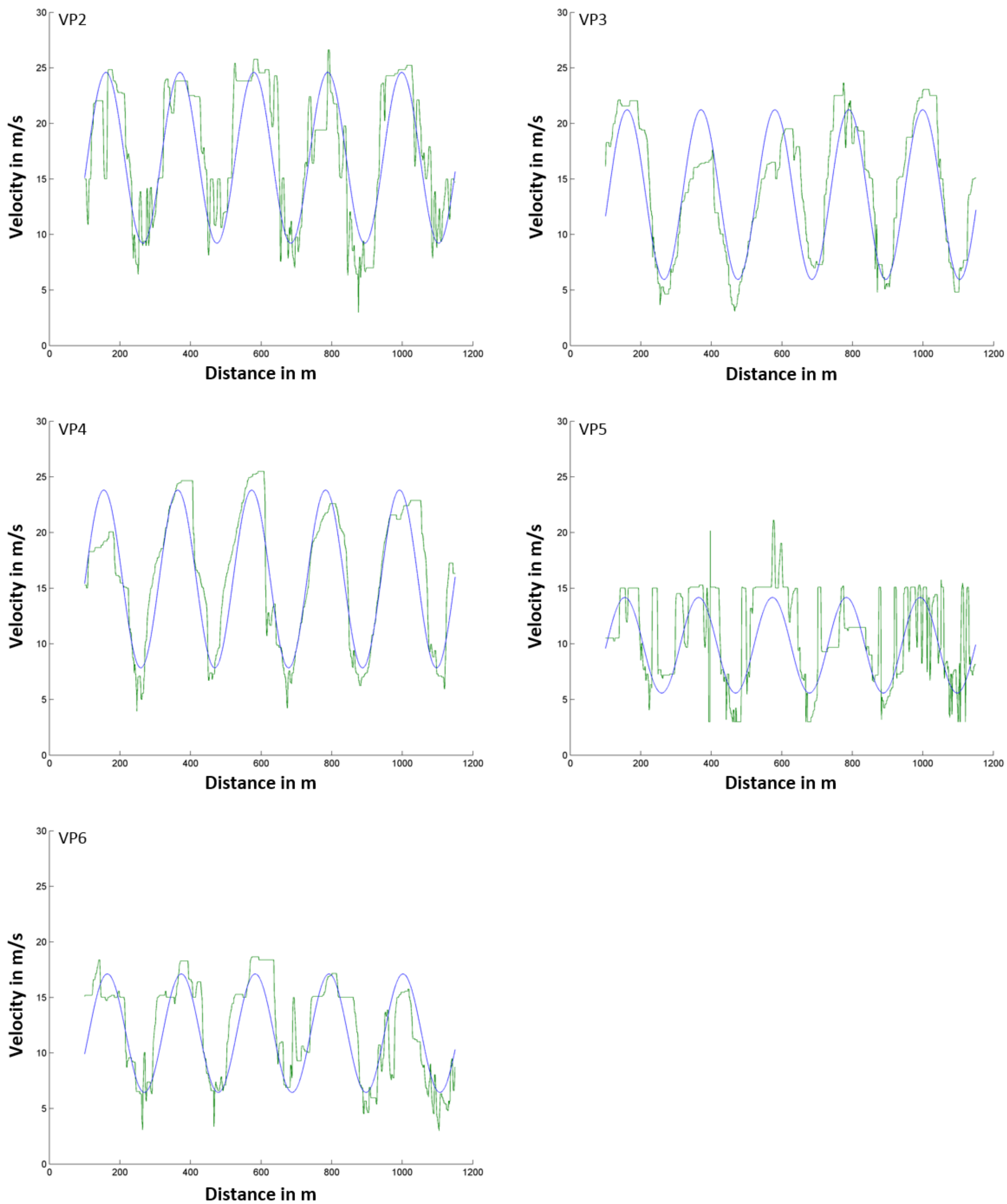
1 Während des Experiments war ich motiviert.	**1**	**2**	**3**	**4**	**5**	**6**	**7**
2 Das Experiment hat mir Spaß gemacht.	**1**	**2**	**3**	**4**	**5**	**6**	**7**
3 Ich würde wieder an einem psychophysikalischen Experiment teilnehmen.	**1**	**2**	**3**	**4**	**5**	**6**	**7**
4 In meiner Freizeit spiele ich häufig Videospiele, in welchen der Umgang mit einem Controller normal ist.	**1**	**2**	**3**	**4**	**5**	**6**	**7**
5 Ich habe das Gefühl im Experiment gut abgeschnitten zu haben.	**1**	**2**	**3**	**4**	**5**	**6**	**7**
6 Während des Versuches war mir klar, welches Ziel ich verfolgen sollte.	**1**	**2**	**3**	**4**	**5**	**6**	**7**
7a Ich hatte das Gefühl zwischen den einzelnen Durchläufen der Testphasen Veränderungen bemerkt zu haben.	**Nein**						**Ja**
7b Wenn ja, welche Veränderung/en?							
8 Woran haben sie sich während des Versuchs orientiert, bzw. wohin haben sie geschaut?							

6.4 Printout of a Standard Data Set

Table 1: Printout of a standard raw data set. velocity: subject's selected velocity, radius: actual radius of the sine waved tunnel, y: passed distance (m), time: time required (s) up to that point in the tunnel.

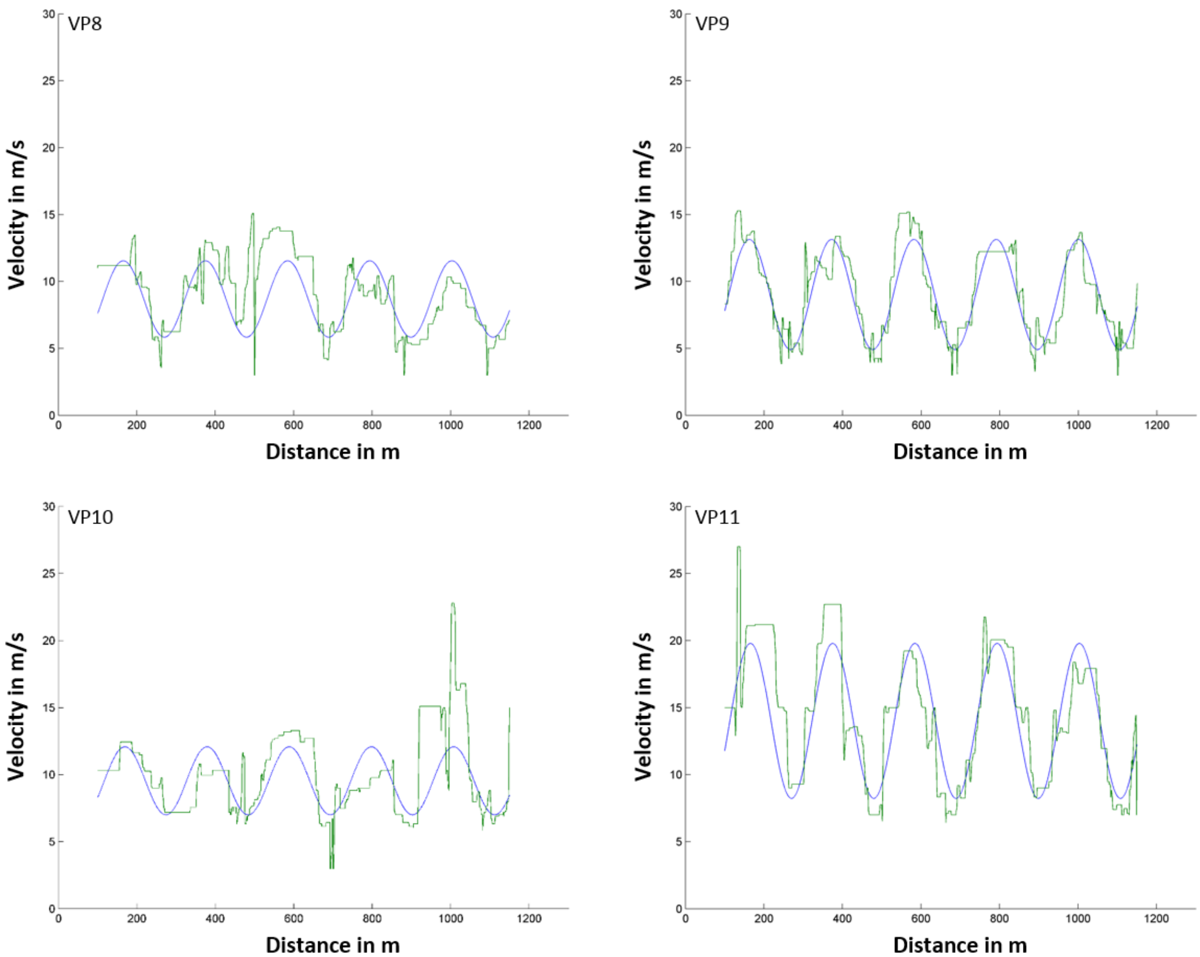
velocity	radius	y	time
24.2816	7.18789	156.017	10.5752
24.2816	7.19888	156.422	10.5919
24.4691	7.20996	156.83	10.6086
24.4691	7.22104	157.238	10.6253
24.5629	7.23217	157.647	10.642
24.5629	7.24329	158.056	10.6586
24.8441	7.25454	158.47	10.6752
24.8441	7.26579	158.885	10.692

6.5 Raw Data - Experiment 1



Panel 1: Panel of the run in a tunnel (frequency: 0.03) of Experiment 1 of each subject (VP2-VP6). The green line shows the raw data, the blue line shows the fitted line.

6.6 Raw Data - Experiment 2



Panel 2: Panel of the run in a tunnel (amplitude: 1.5) of Experiment 2 of each subject (VP8-VP11). The green line shows the raw data, the blue line shows the fitted line.