The Role of Stereoscopic Depth Cues in Place Recognition

Bachelorarbeit
der Mathematisch-Naturwissenschaftlichen Fakultät
der Eberhard Karls Universität Tübingen

vorgelegt von
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Tübingen, Februar 2015

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

Tübingen, den

Danksagung

An dieser Stelle möchte ich mich bei Marc Halfmann bedanken, der mich bei jedem Schritt dieser Arbeit tatkräftig unterstützt hat und bei jedem noch so kniffligen Problem einen Ausweg wusste! Vielen Dank natürlich auch an Professor Mallot, der zu den unterschiedlichsten Betrachtungen dieser Arbeit inspirierte und mit seinem Rat aushalf. Ein großer Dank geht auch an Stephan Lancier für die Antwort auf so manche Statistikfrage und an alle aus der Abteilung der Kognitiven Neurowissenschaften für die freundliche Atmosphäre und das schöne Miteinander.

Ich danke auch meiner Familie und meinen Freunden, die mich immer zur richtigen Zeit unterstützt, aufgebaut, abgelenkt und aufgeheitert haben!

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Zusammenfassung

In der Raumkognition spielt die Ortserkennung eine große Rolle. Um sich zurechtzufinden, gibt es zwei grundsätzlich unterschiedliche Methoden der Orientierung. Einerseits gibt es die Möglichkeit, sich anhand von Intensitäts- und Farbinformation zu orientieren, was die Nutzung von salienten Objekten beinhalten kann. Wie Gillner et al. zeigten, ist es aber auch möglich, sich ausschließlich mithilfe eines Farbgradienten zurechtzufinden. Menschen nutzen hierbei gleichermaßen wie andere Tiere ein Schnappschussmodell, indem sie ein im Gedächtnis gespeichertes Bild („Schnappschuss“) vom ursprünglichen Ort mit dem aktuell wahrgenommenen vergleichen und bei Übereinstimmung der beiden Bilder Gewissheit haben, wieder am ursprünglichen Ort angekommen zu sein. Andererseits kann man sich aber auch anhand von Tiefeninformation in einem Raum orientieren. Dazu gehören binokulare Disparität und Bewegungsparallaxe. Im folgenden Experiment wurde geprüft, ob diese Tiefeninformation für eine exakte Navigation und Ortserkennung ausreicht. Dazu wurde mithilfe eines Spiegel-Stereoskops ein virtueller drachenförmiger Raum präsentiert, der in der Kontrollbedingung durch texturierte Wände und in der Versuchsbedingung durch Wände mit sogenannte Random Dots, also flimmernde weiße Punkte auf schwarzem Grund dargestellt wurde. Die Kontrollbedingung stellte beide Arten von Rauminformation zur Verfügung, während es in der Versuchsbedingung durch die Random Dots ausschließlich Tiefeninformation gab. Die Probanden mussten in beiden Bedingungen verschiedene Stellen im Raum wiederfinden. In der Kontrollbedingung gelang es ihnen, in der Versuchsbedingung war ihre Performance jedoch weitaus schlechter. Dies zeigt, dass allein Tiefeninformation nicht hinreichend für eine präzise Ortserkennung ist.

Abstract

Place recognition has an important role in spatial cognition. To orientate, there are two basically different methods. On the one hand there is intensity information to orientate by. This might be the usage of salient objects. Yet Gillner et al. showed that it is possible to orientate only by a colour gradient. For this purpose both humans and animals use a snapshot model by comparing a memorized retinal image of an original place with the current perceived one. When both images match they know that they reached the original place. On the other hand spatial orientation is possible by using depth information. This includes binocular disparity and motion parallax. The following experiment investigates if solely depth information is sufficient for an exact navigation and place recognition. For this purpose a virtual kite-shaped room was presented on a single-mirror stereoscope. In the control condition the walls of the room were textured and in the test condition they were presented as a pattern of flickering random-dots. In this manner the control condition provided both types of spatial information whereas in the random-dot condition there were solely depth cues. Subjects had to recognize and find certain locations in the room. In the control condition they achieved it, however in the test condition their performances were considerably worse. This gives evidence that solely depth information is not sufficient for a proper place recognition and navigation.

1. Introduction

Recognition of places is a highly important issue in spatial cognition. When arriving at a new or barely known environment humans have to be able to find certain locations again to orientate, memorize and to recognize places when getting back to them. Other animals also require this ability. Squirrels, for example, bury their feed in different places in autumn and live on it during the winter. It is essential for them to memorize the sites where they have hidden their nutrition and to recognize them some time later. Only a good spatial recognition ensures orientation and thus a proper navigation in different environments.

In general, there are two fundamentally different ways of place memorization and recognition. On the one hand, there is the usage of intensity information. This may include holistic methods as the descent in image distances which is the quadratic difference or correspondence methods as gradient matching or snapshot model (Möller and Vardy 2006). Guidance is possible by using landmarks, but not necessarily. Landmarks could take several different forms. They could be defined as individual items (Lynch 1960) but also as a configuration of objects (Siegel and White 1975). Even a depth cue can be a landmark, as for instance the angle of two meeting streets (Mallot 2011). There is much evidence that several insect species use a snapshot algorithm which works only with pictorial information. Honey bees for instance, find food sources again by memorizing the respective locations in a pixel-based manner (Cartwright and Collett 1983). They learn "[…] the apparent size and bearing of the landmark as seen from the food source […]" which indicates that they don't build up a Cartesian map of the location but memorize its retinal image (Cartwright and Collett 1982). When searching for it again they recognize it when the remembered target image and the current one match. Relevant features are landmarks which are near the destination. Helpful for memorization of retinal images is also a special form of flight. By flying zigzags, bees can build up an image excluding distant and less important landmarks. Honey bees search locations where snapshots match, not where distances to certain landmarks are correct (Cartwright and Collett 1982). Another Hymenoptera group, wood ants, use a similar system of retinal imagery for navigation. To maintain their paths they learn the retinal elevation of lateral landmarks such as walls. They store these images and try to minimize the differences between these ones and the current perceived images when they walk the same path again (Graham and Collett 2002). When memorizing a goal wood ants begin to recall this stored image before actually reaching it (Durier, Graham et al. 2003). Probably, this is because they start to restore the other snapshots they have made along the route, so that the image of the goal is recalled consequently at approximately the same time. Gillner et al. showed that humans also use the snapshot model under certain circumstances (Gillner, Weiss et al. 2008). Their studies revealed that visual homing can work solely on gradual modulation of colour, even void of featural cues such as landmarks. Subsequently, humans can use spatial information based on image cues only by simply taking a snapshot of the target point and navigating to it by comparing the current retinal images with the target image. It is to say that subjects' accuracy was proportional to colour gradient modulation. This is not surprising as snapshot memory of retinal images requires intensity information which is only given when colour gradient is steep.

On the other hand, place recognition can be realised by a method based on depth cues. Depth cues include motion parallax and binocular disparity. Many insects gain their spatial cognition from motion parallax (Kral and Poteser 1996). Since their compound eyes have an enormous number of single eyes, "multilocular" vision would lead to an equal high number of object images that could hardly be fused. Therefore, they make use of so-called peering-movements to obtain distance information. Particularly in prey capture it is highly important to measure distances exactly. For this purpose, insects, such as praying mantis and locusts, mostly move their bodies from one side to the other but also somewhat for- and backward. In this manner, they can measure the distance to prey precisely before striking. However, mantis apparently do also have stereo vision (Rossel 1983). Their eyes are wide apart which allows them a stereoscopic view on the world, and as they don't have convergence or accommodation binocular disparity is, aside from motion parallax, the only method to perceive depth. In this case, motion parallax is of high importance too.

There is evidence that measuring distances to surfaces is present in pigeons and rats as well (Cheng 2008). Plus, evidence is provided that "geometry and features are not always learned independently" and that by means of combination of those two methods rats recognize places the best. However, Cheng proved that rats mainly rely on geometric information (Cheng 1986). Rats were placed in a rectangular box, as shown in figure 1, and had to memorize the corner where they received food. The results of Cheng's experiment showed that rats confused locations that have the same geometric relations: they searched about equally often for food in both the correct corner and the one located at 180° in the opposite direction. Featural cues, like brightness level, smell or texture, mostly were ignored. This indicates that they especially encode geometric information and that featural information is subordinate. According to Wang and Spelke, the reason for this is that reorientation based on geometric information is an encapsulated system (Wang and Spelke 2002). That means that other cues than the geometric ones are ignored. These rotational errors do not only occur in experiments with rats but also with humans as it will be evident in this study.

1. Introduction

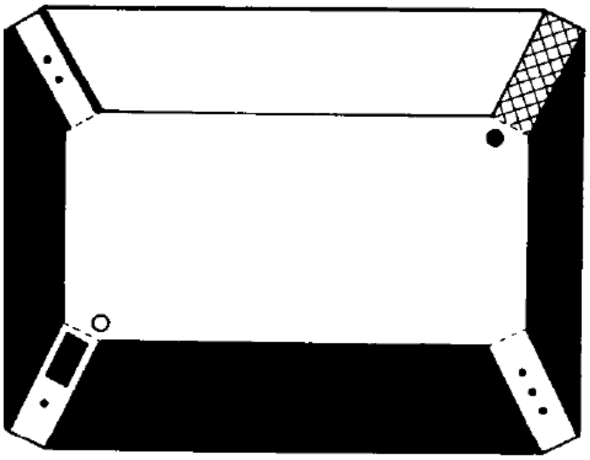

Figure 1: A plan view of the rectangular box in Cheng's experiment. Geometric information as the shape and featural information as the different cues in the corners and the colours of the walls are available for the rats.

However, according to Stürzl et al. relying on geometric relations does not mean a usage of depth information (Stürzl, Cheung et al. 2008). They found that the cause for rotational errors in a rectangular room was a view-based navigation, like a snapshot algorithm, which does not require stereo vision. According to them, the probability of rotational errors increases with increasing salience of the edges and decline of featural details. They proposed that "such an image-matching procedure does not require extraction of edges, objects, or spatial geometry." It works solely on a snapshot model and "the overall view is simply recorded as a panorama of pixel values, which are subsequently used for image comparison, without feature extraction or object recognition".

Sovrano and Vallortigara showed that chicken that were placed in large enclosures relied mainly on featural cues, like coloured walls, whereas when placed in small enclosures they used especially geometric properties (Sovrano and Vallortigara 2005). Both methods of navigation are view-based. The reason for this is that in small rooms they perceive more of its corners in one field of view which enables the animals to orientate themselves by the room's geometric relations. In larger rooms the corners do not fit in one visual field so that they have to use features for spatial orientation. As a consequence the chicken tend to "make more landmark errors than geometric errors when transferred from the large to the small space". Lee and Spelke found out that young children also make use of geometric properties when navigating (Lee and Spelke 2011). They tested children's orientation in enclosed environments. For this purpose they bordered the environment in different ways. When the borders were formed by curved hills that protruded off the floor their orientation was the best. They recognized the environment's shape although the contours of the borders were slightly visible. Thus the study shows that children do not rely on an image-matching method as "children's failure with salient 2D features and success with subtle 3D perturbations in the ground surface do not accord with the predictions of image-matching theories" but are sensitive to floor unevenness.

Normally, we use for navigation both intensity information with all its cues like colour and texture gradient, features and landmarks, and depth information, as motion parallax and binocular disparity. But what if all cues were reduced to depth cues only? This experiment investigates subjects' performances in a virtual environment with two different conditions. In the control condition both depth and intensity information are provided whereas in the other condition only depth information is available. This depth cues are made up of so-called random-dots, that are similar to those described in the study of Sperling and Landy (Sperling, Landy et al. 1989). As they have a limited lifetime they do not provide any constant cues so that subjects cannot make usage of snapshot or featural information and can only orientate by depth cues. In this case, vergence aids the perception of depth too. Yet, accommodation can be ignored as the objects focused are always the two screens in not changing distances. All that remains is binocular disparity and motion parallax. Both conditions, were presented using a mirror stereoscope. This is an optical device which allows a 3-dimensional view on an environment, whether a virtual or a real one. Sir Charles Wheatstone (1802–1875), a British physicist, was the first who found out that two nearly identical pictures perceived on different eyes merge into one spatial image. He developed a device which allowed the observer to have a 3-dimensional view on a virtual image. For this reason he drew pictures which were almost identical, they just differed a little in their horizontal position. Our eyes' perception works on the same principle: as there's a distance of approximately 6 cm between human eyes, each eye sees a little different image. Since the difference is quite small the brain is able to integrate both pictures into one. In this way the generated image appears spatial and tangible. However, the drawn pictures were not easy to make as they were allowed to differ only slightly.

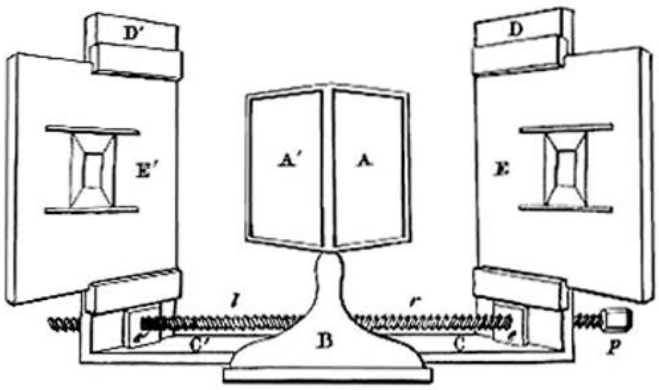

Figure 2: Stereoscope after Wheatstone. In the middle are the two mirrors which reflect the two images on the right and left.

As in Wheatstone's time the photography was just developed they were soon replaced by photographs. Photographs had the advantage that they were highly more accurate than drawings. As shown in Figure 2 those pictures or photographs in the stereoscope are placed on the left and right side of the observer, respectively. In the middle and in front of the observer there are two mirrors, each reflecting another picture. The position of the pictures and the mirrors have to be deployed such that in the observer's view both pictures overlap into one. Therefore, a stereoscope is able to imitate a multidimensional image for an observer.

2. Material and Methods

In this experiment a stereoscope is used which was modified by Joel Kollin and Ari Hollander (Kollin and Hollander 2007). They re-engineered the Wheatstone stereoscope to a 'single-mirror system' by removing the right mirror and placing the right picture, or in this case screen, in front of the observer, as shown in figure 3.

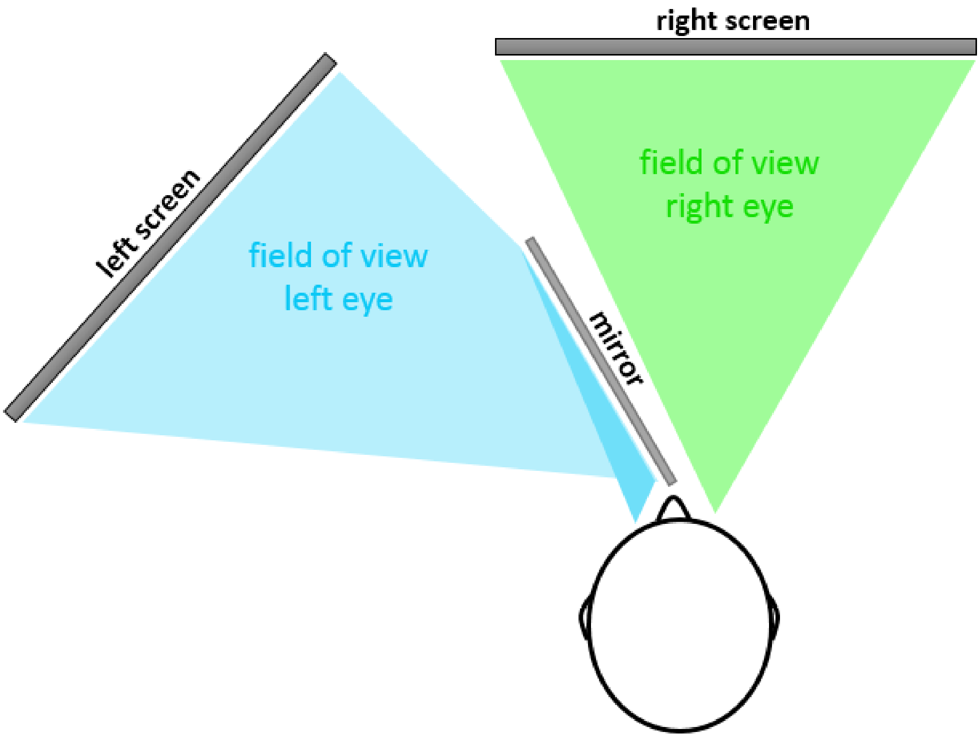

Figure 3: Stereoscope used in this experiment after Kollin and Hollander. The two screens are separated in subject's view by one mirror that reflects the mirror image on the left screen.

The stereoscope used here consisted of 2 screens (each 69 cm diagonal), both connected to one computer. The screens displayed 2 images: the right one depicted the original image and the left one its mirror image. The only difference between the images was that they were shifted horizontally by a small amount. One screen was positioned frontal to the observer at a distance of 82 cm, the angle of vision was 40.19°. The other one was placed diagonally on the left side of the observer. The observer looked at these screens in such a manner that the right eye saw the image on the frontal screen and the left one looked into a mirror which reflected the left screen. The mirror was slanted to the left eye with an angle of 43°. The screens were angled such that in the observer's view both images coincided. As the images for each eye were not completely identical – just like the disparity of both eyes of a perceived real image – the observer seemed to have a 3-dimensional view on a depicted environment. Additionally, in this experiment the stereoscope was draped with black material and some black paperboards were added to hide the screens for the respective eye. Also, the room where the experiment was set up was completely darkened to prevent distraction by incoming daylight.

Figure 4: Set-up of the stereoscope. The mirror is indicated by the red frame.

2. Material and Methods

In this experiment, the environment presented on the stereoscope was a kite-shaped room with dimensions of 21 meters in length, 10 meters in width and 2.5 meters in height, as shown in Figure 5.

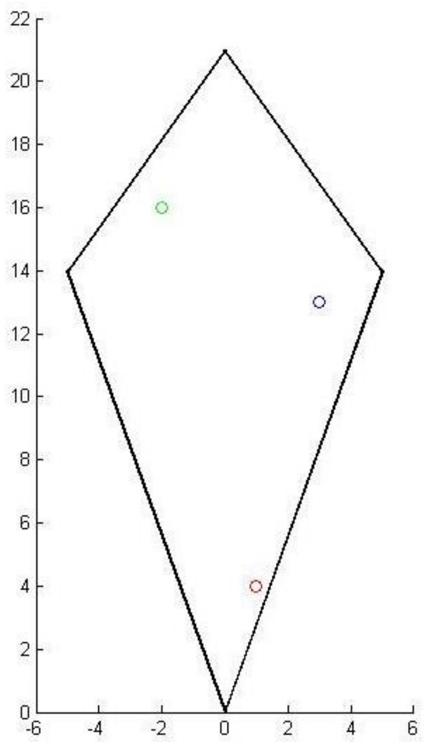

Figure 5: The kite-shaped room with the three different target points, blue target point at (3/13), red target point at (1/4) and green target point at (-2/16).

The experiment consisted of two different conditions. In the control condition, the walls of the room were textured with white circles on a black background, as shown in Figure 6. That way, subjects had both depth and intensity information.

In the random-dot condition, the walls were represented as a pattern of flickering white dots, randomly placed on a black background and with a limited lifetime, as shown in Figure 7. In this manner, the spatial information of the room was restricted to depth information only. No landmarks or other cues were available. In this condition, the maximum number of visible dots was 2000, the dot size was 3 pixels and the minimum and maximum lifetime were set to 100 ms and 200 ms respectively.

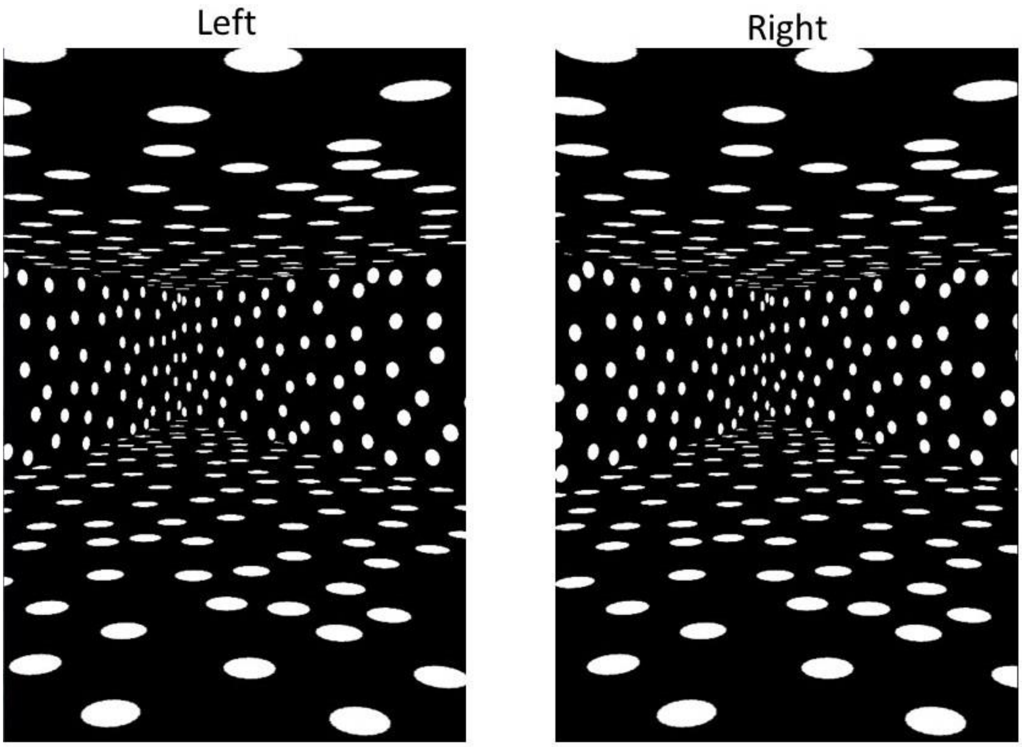

Figure 6: A screenshot of the walls in the control condition. Here, two images are presented, one for the left and one for the right eye. By fusing them a spatial image can be formed.

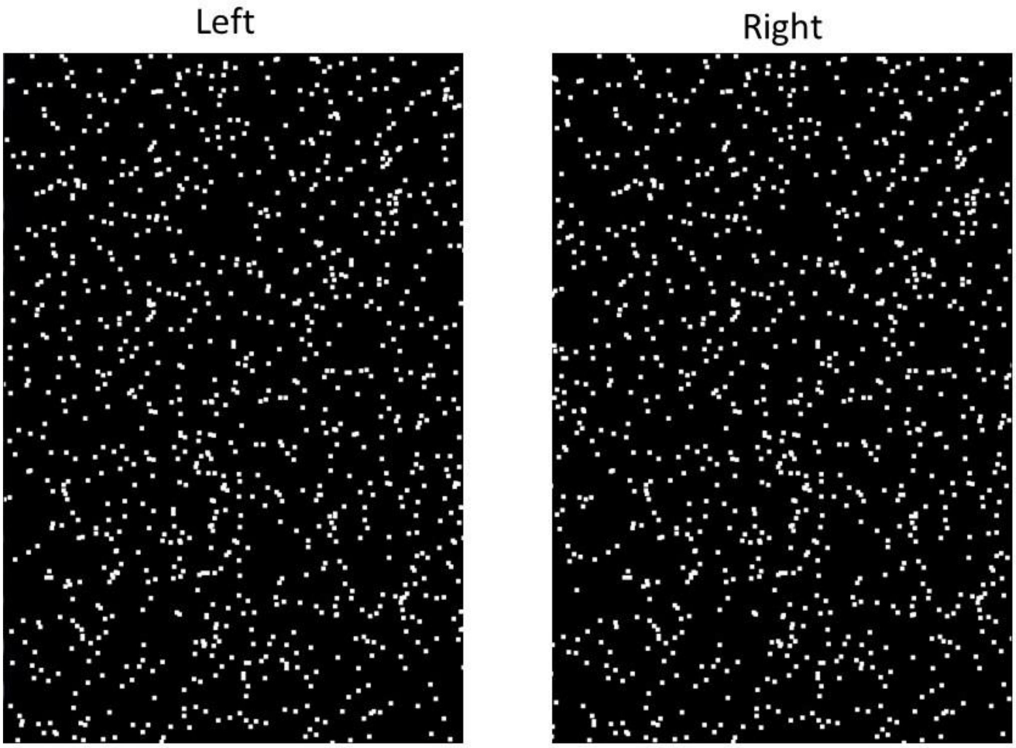

Figure 7: A screenshot of the walls in the random-dot condition. By fusing both images a spatial image can be formed too.

Each condition consisted of 14 trials of which the first 2 ones were for introduction and familiarization. Subjects were shown the shape of the room and were explained the procedure. In each trial, initially, subjects were placed in one of 3 positions in the room, as shown in figure 4. There, their moving space was restricted; they were only allowed to move within a radius of 0.5 meter around this position. They also could turn and look around. Steps were controlled by pressing keys on the keypad, turning around was controlled by moving the mouse sideward. Subjects had to learn this position. When they felt certain that the position was memorized they pressed the spacebar and were beamed to a different place in the room, called starting point. Now, subjects could move freely and their task was to walk back to the previously learned position, the target point. When assuming that the initial position is found subjects again pressed the spacebar to confirm their decision. Subsequently they were driven to the correct target point which was the only feedback subjects were given. This was now the end of one trial. After that they could repose and when feeling ready for the next trial they started it by pressing the spacebar. In the next trial, they were placed at another position, so that they had a new target point. The previous target point was now the starting point to which subjects were beamed. The procedure was the same in all trials.

The 20 subjects did each condition on a different day. This had the effect that whole experiment did not take too much time and subjects did not run out of motivation. They started with the control condition which took about 20 minutes. Before the experiment, they were given a written information to read and sign. It included short facts about the experiment in general, such as the experimental set-up, the 3D-effect, a note of potential vertigo, data collection and a consent form. To test subjects for normal stereo vision, they were shown some 3D-pictures in a book (Hirsch and Kramer: Neuroanatomy 3D-Stereoscopic Atlas of the Human Brain, Springer, 1999) with usual red-green 3D-glasses. All subjects saw a 3D-effect which made them suitable for the experiment. In addition, to test if subjects correctly perceived depth information from looking at the stereoscope, a pre-test was carried out which is described later. After that subjects were instructed to the procedure in written form and verbally. They were shown a sketch of the room so they knew it was kite-shaped. Emerging questions were answered. After the experiment was finished the subjects got a questionnaire including questions about fun factor, motivation, level of difficulty and the positions that were easier for them to find. Moreover, they had to draw the target points they remembered within a sketch of the kite-shaped room.

On another day, they had to do the random-dot-condition. Prior to that, a pre-test was done to test a subject’s stereoscopic vision. This pre-test was done with the stereoscope as well. Subjects were presented two squares on a black background. The squares were also presented as random dot patterns (same parameters as in the control condition). The squares appeared equal sized to the observer, however, they were placed at different distances. The pre-test was composed of 24 trials of which in 12 the right square and in the other 12 the left square was closer to the observer. There were 3 different constellations: the squares were 10.125 m and 9.875 m, 10.5 m and 9.5 m, 12.5 m and 7.5 m, respectively, away from the observer (at intervals of 0.25 m, 1 m, 5 m, respectively, of each other). Each constellation appeared 4 times. The subjects were asked to decide whether the left or right square appeared closer by left- or right-clicking, respectively (forced choice). Subsequently they were allowed to repose. Then they started with the main experiment, the random-dot-condition. This time the walls of the room presented by the stereoscope were made up of a random-dot pattern but the procedure was exactly like in the control condition. They could repose after every trial but not during it. Pre-test and main experiment also didn't take more than 30 minutes which ensured a relatively high concentration of the subjects. Finally subjects again had to answer the same questionnaire as after the the control condition.

3. Results

In general the received results are just as expected. It can be said that subjects made more errors in the random-dot condition than in the control condition.

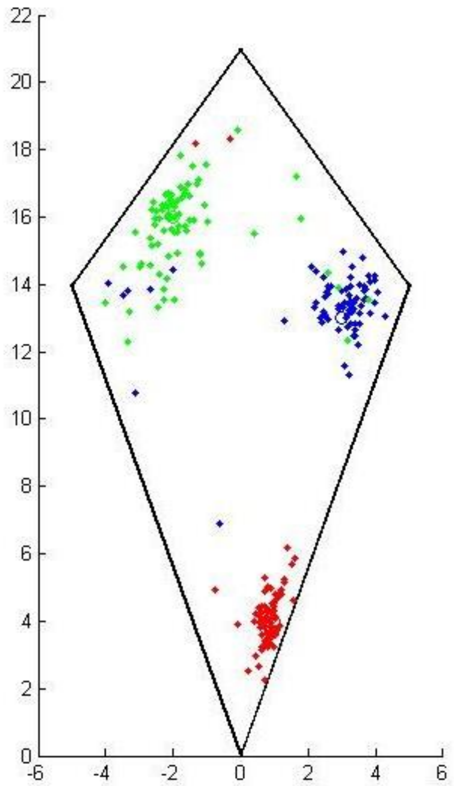

Figure 8: All decisions in the control condition.

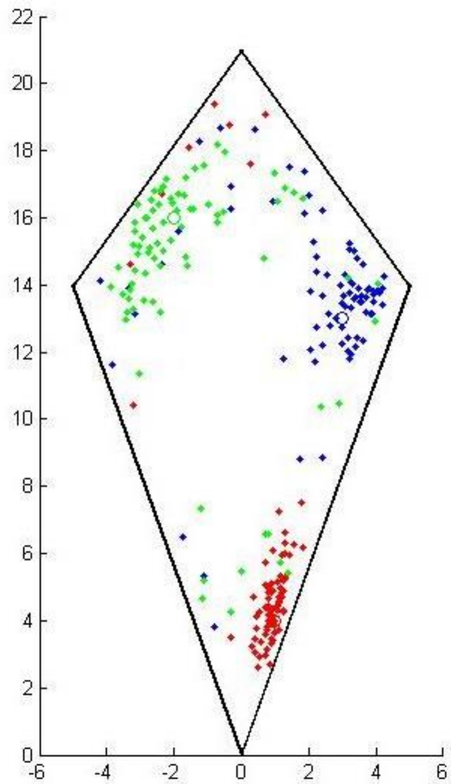

Figure 9: All decisions in the random-dot condition.

The confirmed points in the random-dot condition shown in figure 9 are dispersed much more broadly than those in the control condition as shown in figure 8. In the control condition the points are more concentrated in different spaces, even when lying in wrong spots. In the random-dot condition the points are scattered more all over the room.

3.1. Frequency distribution of distances from the target points

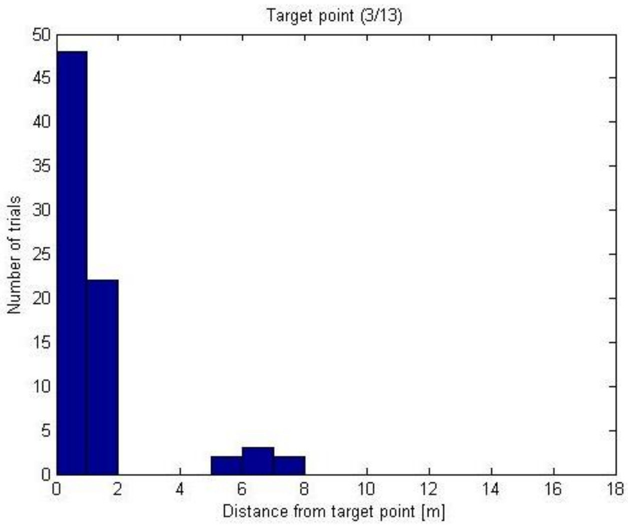

Figure 10: Frequency distribution of distances from the blue target point (3/13) in meters in the control condition.

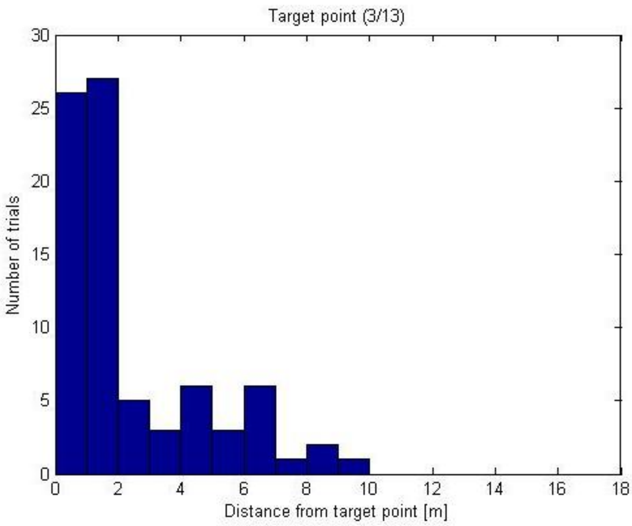

Figure 11: Frequency distribution of distances from the blue target point (3/13) in meters in the random-dot condition.

In the control condition, in 48 trials the assumed target point was under 1 meter, and in 70 trials it was under 2 meters away from the correct target point. Further assumed target points all were at a distance between 5 and 8 meters.

In the random-dot condition, in 53 trials the assumed target point was less than 2 meters away from the correct target point. In only 8 trials the distance was between 2 and 4 meters. Distances with more than 4 meters were found in 19 trials.

3. Results

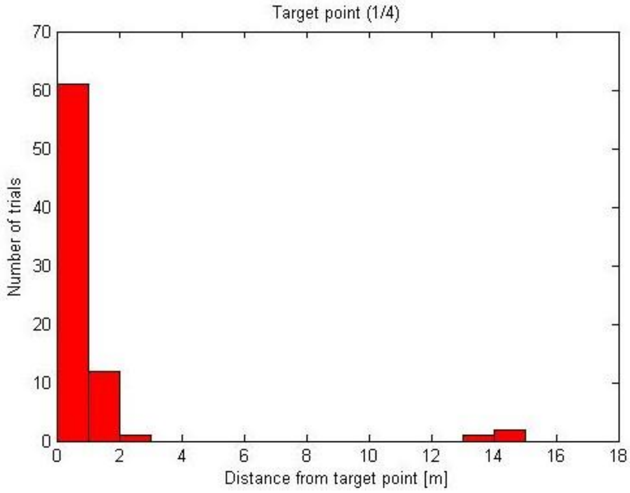

Figure 12: Frequency distribution of distances from the red target point (1/4) in meters in the control condition.

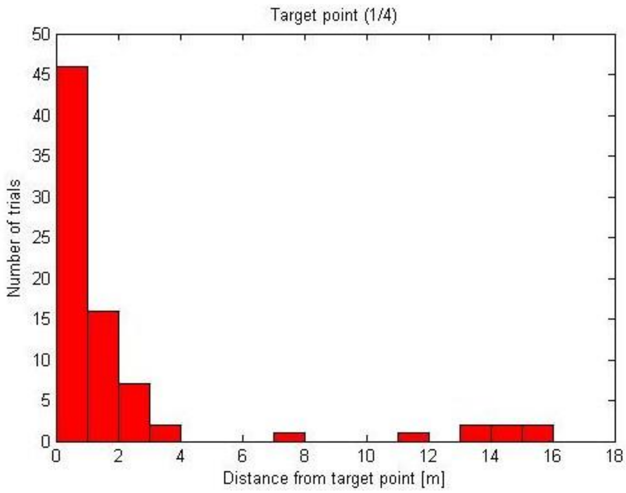

Figure 13: Frequency distribution of distances from the red target point (1/4) in meters in the random-dot condition.

In the control condition, in 73 trials subjects assumed the target point very close to the correct target point (2 meters or less). In 3 trials the assumed target point was between 13 and 15 meters away from the correct target point.

In the random-dot condition, in 62 trials the assumed target point was less than 2 meters away from the correct one. In 9 trials the distance was from 2 to 4 meters. In one trial a subject confirmed the target point at a distance of approximately 7 meters and in 7 trials subjects assumed the target point at a distance of 11 to 16 meters from the correct target point.

3. Results

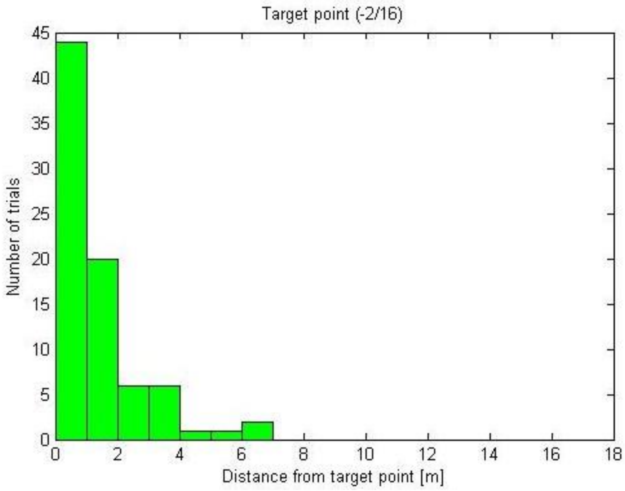

Figure 14: Frequency distribution of distances from the green target point (-2/16) in meters in the control condition.

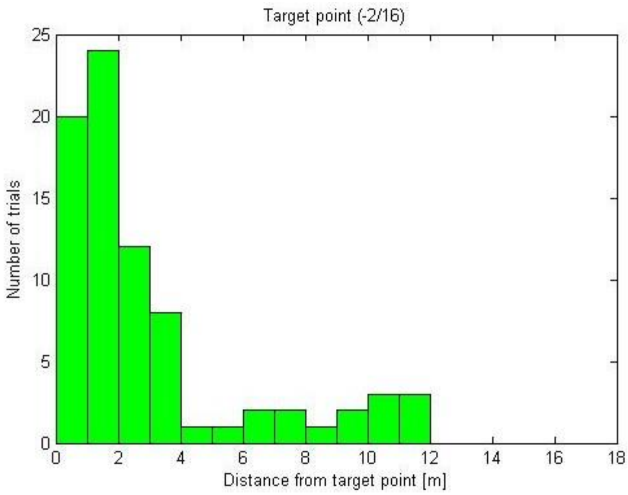

Figure 15: Frequency distribution of distances from the green target point (-2/16) in meters in the random-dot condition.

In the control condition, in 64 trials the assumed target point was under 2 meters away from the correct one. In 16 trials the target was assumed at a distance between 2 and 7 meters.

In the random-dot condition, in 44 trials the assumed target point was between a distance of 2 meters and in 20 trials the assumed target point was between 2 and 4 meters. In 35 trials the assumed target point was at a distance from 2 to 12 meters.

3. Results

As the majority of assumed target points lie within a distance of 4 meters from the true target 4 meters were defined as a threshold. Target points confirmed less than 4 meters away from the correct target were considered correct, the other ones were considered errors.

Additionally, the numbers of trials are distributed differently over the distances, depending on the condition and target point. In the control condition the numbers of trials are concentrated on few different distances. There is one group found under 4 meters and another found at a considerably higher distance, and nothing in between. At least this is the case within the blue and red target point. In contrast to that, the numbers of trials in the random-dot condition are distributed over much more distances. There is no such clustering as in the control condition.

3.2. Comparison of errors in the control and random-dot condition

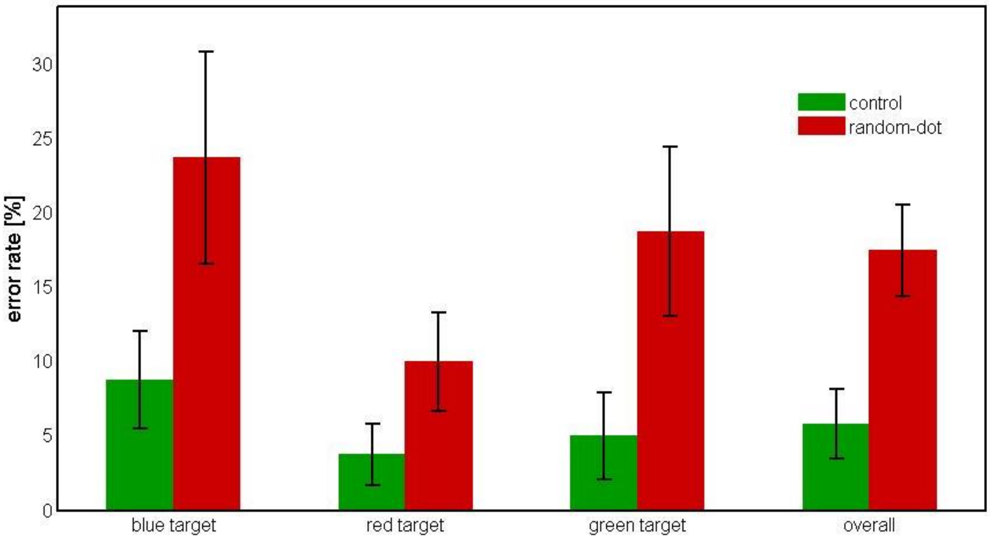

Figure 16: Errors with SEM.

The “target” bars in figure 16 show the percentage of errors for each target point. 100% are equivalent to the number of trials where the respective target points appeared, that means 4 trials for each target point. For example subjects in the random-dot condition made on average one error in one trial with the blue target point (that means 1 error trial per 4 trials = 0.25). Therefore the error rate for the blue target point is about 25%. The last bars show the percentage of errors over all target points.

In general the error rate is higher in the random-dot condition. It differs significantly for the blue target (Wilcoxon, one-sided U(19)= -1.705, p=0.049), the green target (U(19)= -1.977, p=0,032) and the average of all targets (U(19)= -2.442, p=0,006). There is no significant difference for the red target (U(19)= -1.508, p=0,117). The highest error rate is found in trials with the blue target, both control and the random-dot condition (8% and 23% respectively), followed by the error rate for the green target in both conditions (5% and 18% respectively). The smallest error rate is for the red target in both conditions (4% and 10% respectively).

3.3. Error ellipses

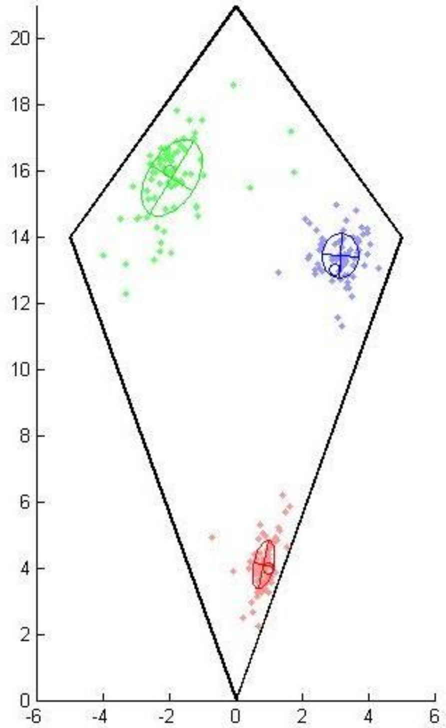

Figure 17: Correct decisions in the control condition.

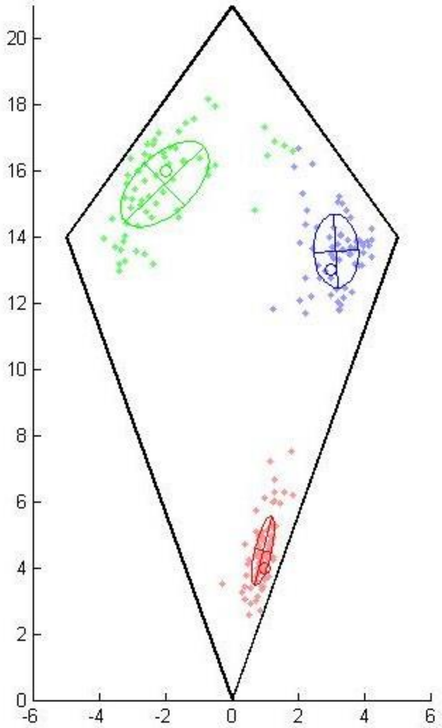

Figure 18: Correct decisions in the random-dot condition.

Table 1: Areas of error ellipses of correct decisions in m² in the control and random-dot condition

	control condition	**random-dot condition**
blue target point	1.1513	2.3506
red target point	0.7145	0.8365
green target point	2.9319	4.5005

Figure 17 and figure 18 show the areas of error ellipses excluding all points that are further than 4 meters away from the respective correct target points. Again, the ellipses in the control condition are smaller than those in the random-dot condition. As shown in Table 1 the ellipse around the blue target point in the control condition has an area of 1.1513 m², compared to 2.3506 m² in the random-dot condition. Yet, there is solely a small difference between the ellipses surrounding the red target point: 0.7145 m² in the control condition and 0.8365 m² in the random-dot condition. The area of the ellipse around the green target point is 2.9319 m² in the control condition, whereas in the random-dot condition it is 4.5005 m².

3.4. Absolute error: mean of all distances to the target points

Table 2: Mean of all distances to the target points and respective t-test for independent samples

	control condition	**random-dot condition**	**t-test**
blue target point	0.87 m	1.29 m	p=0.0035
red target point	0.68 m	0.96 m	p=0.0465
green target point	1.17 m	1.64 m	p=0.024

Table 2 shows that the absolute error for all target points is significantly higher in the random-dot condition. In both conditions the highest absolute error is found for the green target point: on average subjects assumed the target point at a distance of 1.17 m from the correct target point in the control condition and 1.64 m in the random-dot condition which has statistical significance (t-test, $t(19)= 2.046$, $p=0.024$). Trials with the blue target point have the second highest absolute error: 0.87 m in the control condition and 1.29 m in the random-dot condition. This is significant too ($t(19)= 2.889$, $p=0.0035$). The lowest absolute error is found for the red target point: in the control condition it is 0.68 m, which is 0.19 m below the value of the blue target point in the respective condition, and in the random-dot condition it is 0.96 m, 0.33 m less than within the blue target point in the respective condition. Here, the difference between control and the random-dot condition is also significant ($t(19)= 1.739$, $p=0.0465$).

3.5. Comparison of angles

Circular histograms in figures 19 - 24 show the frequency of confirmed target points plotted against the direction. The centre of the histogram corresponds to the centre of the kite-shaped room and with 0° facing the right corner of the room. 30° around the target point's position was accepted as being in the correct direction. Points in the opposite direction were considered rotational errors, here again 30° around the point turned by 180° was accepted.

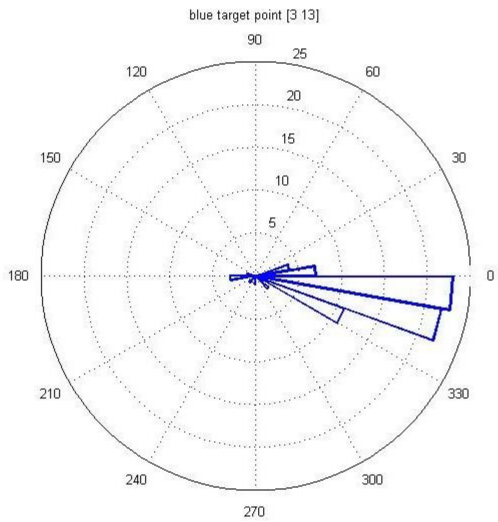

Figure 19: Frequency of confirmed blue target points in the control condition against the direction in degree.

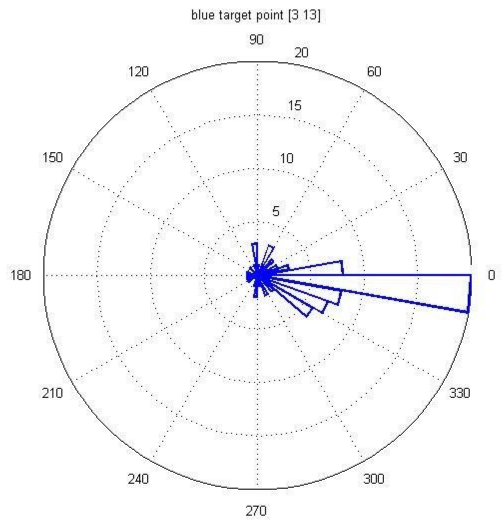

Figure 20: Frequency of confirmed blue target points in the random-dot condition against the direction in degree.

Table 3: Frequency of confirmed blue target points

blue target point	**control condition**	**random-dot condition**
correct angle 341°|accepted range: 330°-360°	56	25
opposite angle: 160°|accepted range: 150°-180°	2	2

The blue target point is at an angle of 341°, the accepted range is between 330° and 360°. In the control condition in 56 trials subjects confirmed the target point there. In the random-dot condition the number of trials was only 25. The opposite angle is found at approximately 160°, the respective accepted range is between 150° and 180°. Both conditions have 2 trials in this area, thus 2 rotational errors in each condition.

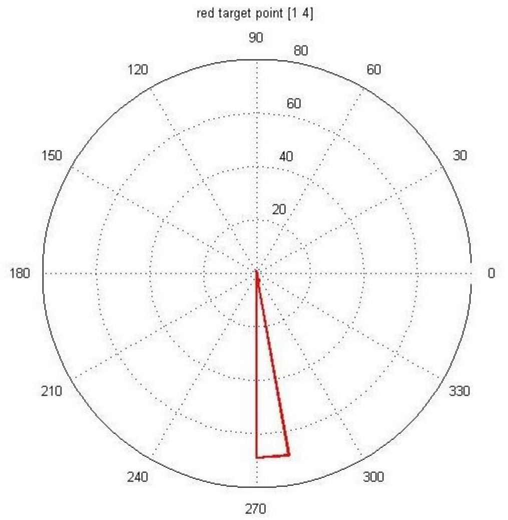

Figure 21: Frequency of confirmed red target points in the control condition against the direction in degree.

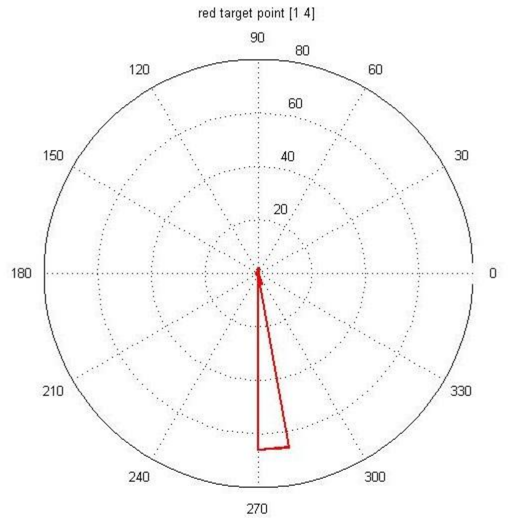

Figure 22: Frequency of confirmed red target points in the random-dot condition against the direction in degree.

Table 4: Frequency of confirmed red target points

red target point	control condition	random-dot condition
correct angle 275°|accepted range: 270°-300°	72	70
rotational angle: 95°|accepted range: 90°-120°	2	3

The red target point is at an angle of 275°, the accepted range is between 270° and 300°. In the control condition in 72 trials subjects confirmed the target point there. That are 16 more than for the blue target point. In the random-dot condition the number of correct trials was 70. The angle turned by 180° is found at 95°, the respective accepted range is between 90° and 120°. In the control condition there are 2 trials in this area, thus 2 rotational errors. In the random-dot condition there are 3.

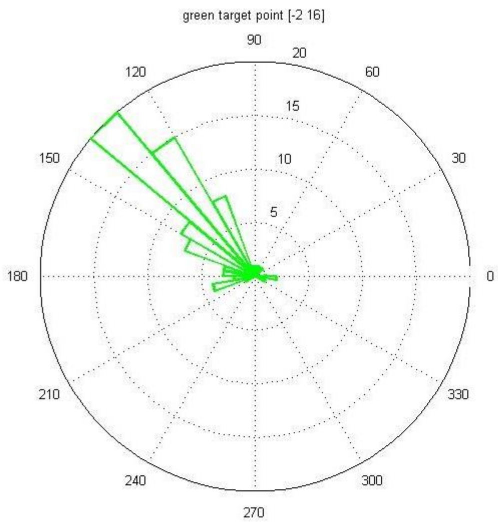

Figure 23: Frequency of confirmed green target points in the control condition against the direction in degree.

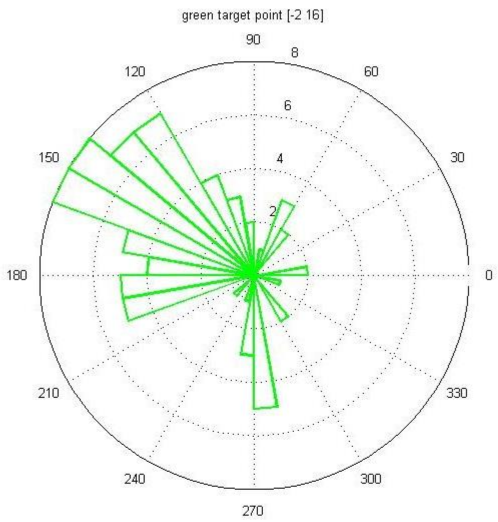

Figure 24: Frequency of confirmed green target points in the random-dot condition against the direction in degree.

Table 5: Frequency of confirmed green target points

green target point	control condition	random-dot condition
correct angle 135°|accepted range: 120°-180°	43	22
rotational angle: 315°|accepted range: 300°-330°	0	2

The green target point is at an angle of 135°, the accepted range is defined between 120° and 180°. In the control condition in 43 trials subjects confirmed the target point there. That is the lowest value of all target points. In the random-dot condition the number of trials there was 22, which is also below the other values. The angle turned by 180° is found at 315°, the range where confirmed target points were accepted is between 300° and 330°. The control condition has no confirmed target points in this area. In the random-dot condition there are 2.

3.6. Comparison of time

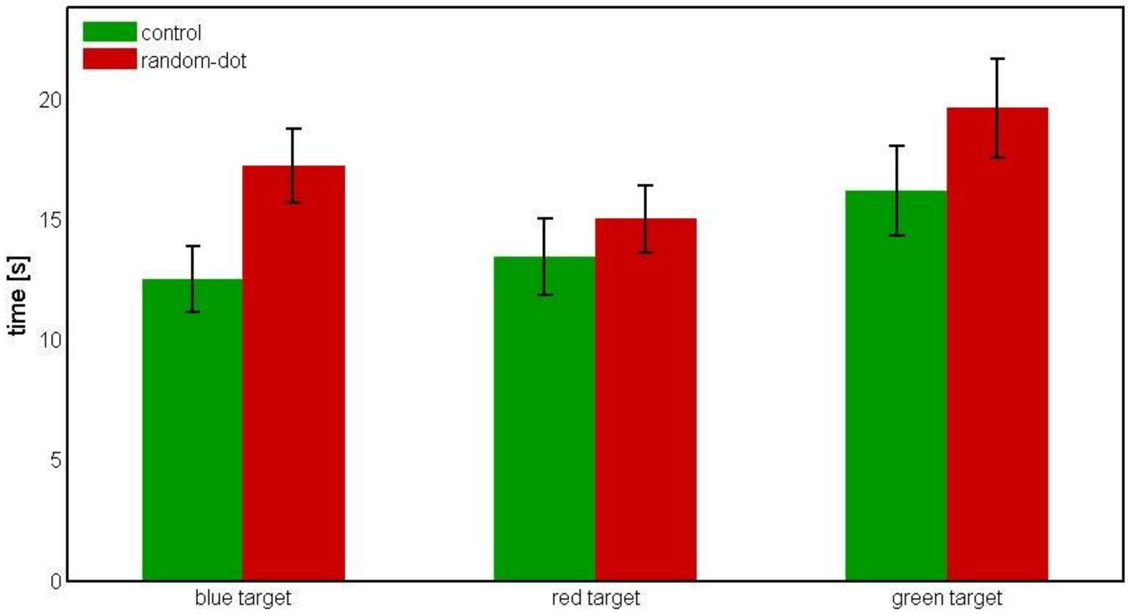

Figure 25: Comparison of time split up in the control and random-dot condition.

On average, trials in all target points took longer in the random-dot condition as shown in figure 25. For the blue target point subjects took on average about 12.46 sec in the control condition, whereas in the random-dot condition the average time is 17.29 sec. The difference is significant (t-test for paired samples, $t(19)= 3.47$, $p=0.0015$). In trials with the red target point subjects took on average 13.41 sec in the control condition and 15.09 sec in the random-dot condition, which is not significant ($t(19)= 1.23$, $p=0.117$). For the green target point the average time is 16.22 sec in the control condition and 19.72 sec in the random-dot condition, which is significant again ($t(19)= 1.808$, $p=0.043$).

Taking both conditions together, subjects took the longest time in trials with the green target point (on average 17.97 sec), followed by trials with the blue (14.92 sec) and red target point (14.26 sec). A two-factorial ANOVA shows statistical significance between the walking times to the different target points ($F (2, 17) = 17.694$, $p<0.001$).

A subsequent post-hoc analysis based on a Bonferroni correction shows significant difference between the green and blue target point ($p=0.001$), and between the green and red target point ($p=0.000$), yet no significant difference between the blue and red target point ($p=0.880$).

3.7. Correlation of pre-test and random-dot condition

3.7.1. Pre-test

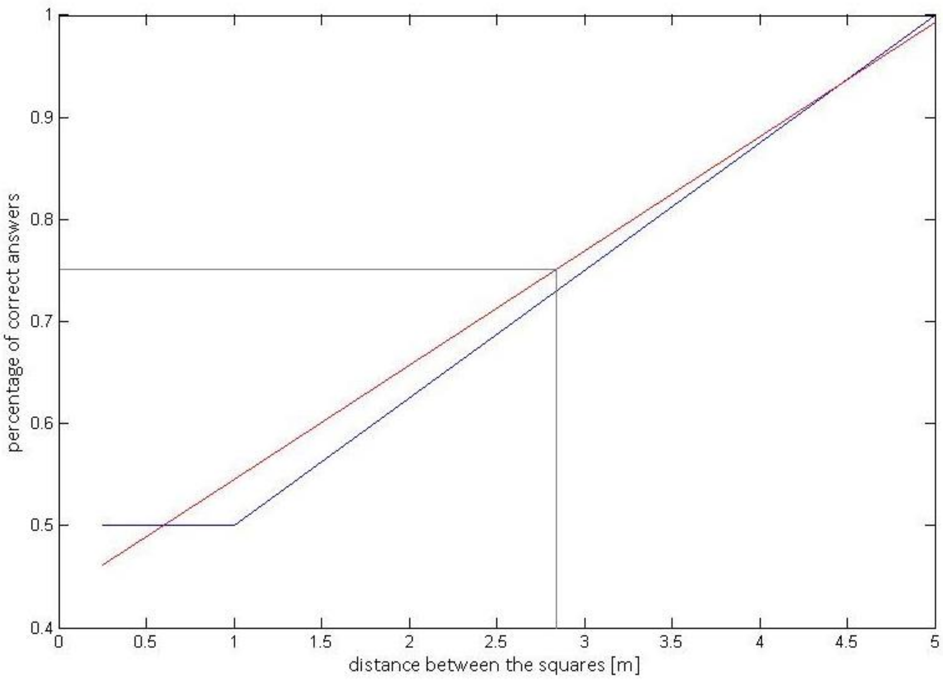

Figure 26: Distance between the squares against percentage of correct answers (subject 01). The threshold of this subject is at approximately 2.8 meters.

The intervals between the squares in the pre-test were plotted against the percentage of correct answers and a trend line was plotted through as shown in figure 26. The threshold where they answered 75% correctly was taken as a measurement of subject's performance in the pre-test, i.e. the interval where they could determine the nearer square with certainty.

The performance of the subject shown in figure 26 thus indicates a threshold of about 2.8 m, i.e. this distance is necessary for the subject to determine the nearer square with certainty.

3.7.2. Correlation of pre-test and random-dot condition

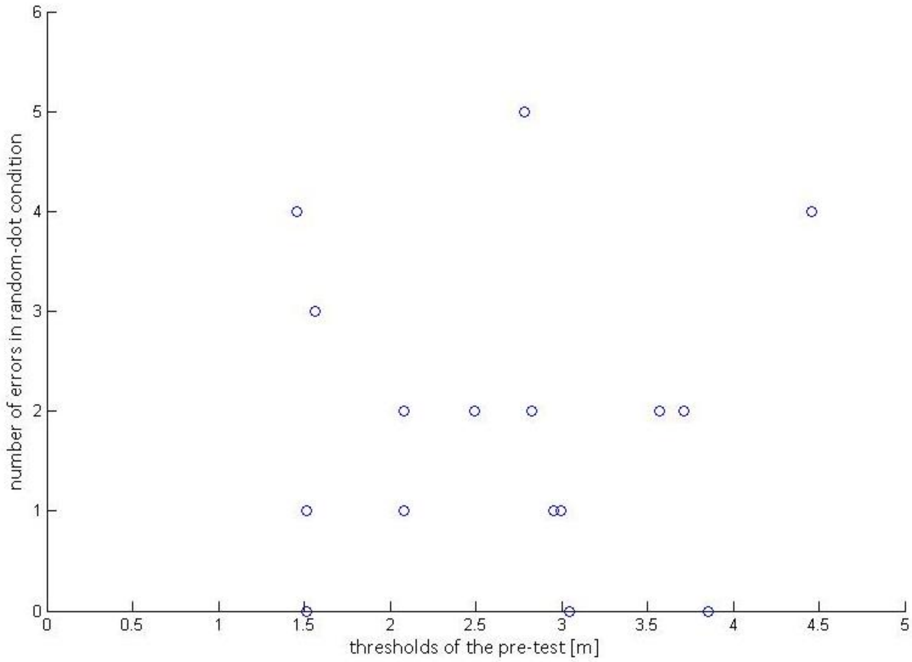

Figure 27: Results of pre-test and random-dot condition without outliers.

There is no correlation found between results of the pre-test and those of the random-dot condition (figure 27). Subjects who performed well in pre-test, i.e. have a low threshold, for example between 1 m and 2 m, don't necessarily perform well in the random-dot condition. Conversely, there are several subjects whose thresholds are relatively high, e.g. about 4 m, yet they perform well in the random-dot condition.

3.7.3. Outliers

As some subjects had an extraordinarily different performance in the pre-test the trend line is located too high and the 75%-threshold gets a too high value. One example is shown below.

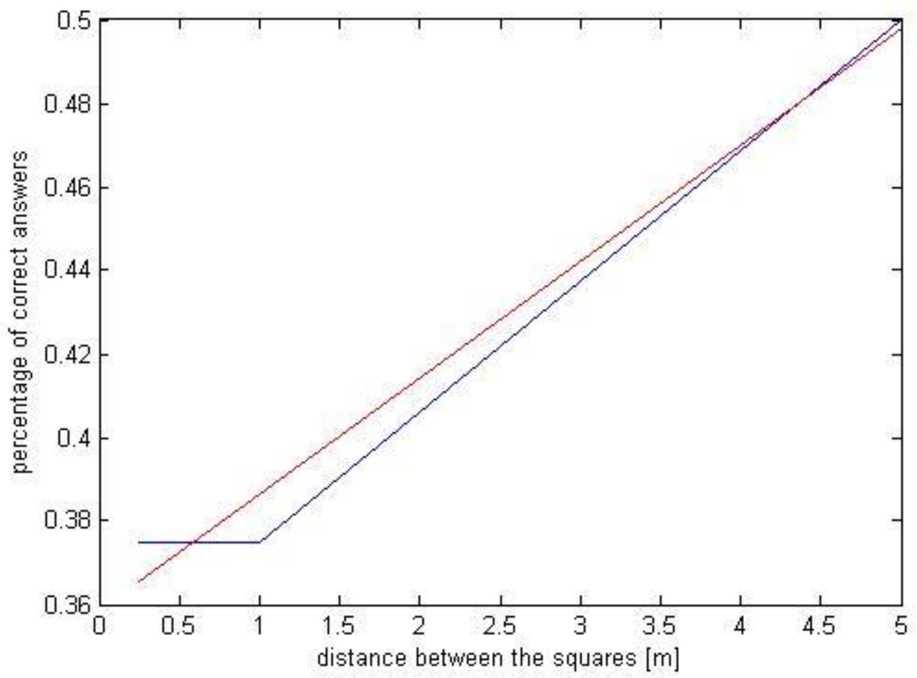

Figure 28: Outlier. Not even a distance of 5 meters between the squares was sufficient to lead to certainty of answering correctly. The threshold of 75% would be at 14 m.

4. Discussion

Regarding the overall comparison of errors in the room, it is conspicuous that, unlike in the random-dot condition, in the control condition there are first greatly less errors and second more concentrated in single locations in the room. This low number of errors in the control condition is already explained above. The fact that in the control condition errors are more accumulated than in the random-dot condition suggests that here subjects did not search for a particular spot. They seem to confirm any location regardless of the cues they were given. In contrary to the control condition where they at least appear to assume the target points in the opposite sites – which means that they definitely memorized and recognized the respective surroundings – in the random-dot condition the confirmed points are far more dispersed over the room. This indicates an unassertive and disoriented manner of searching due to reduced spatial information.

Contrary to expectation the results of the pre-test differ extremely from each other. There are several subjects whose performances were just as expected – their threshold was about 1 meter and at a distance of 5 meters they recognized the nearer square with certainty. This is due to the fact that disparity of an object increases with rising distance and allows subjects to recognize its depth. However, there were several subjects whose performance differed highly from the expected. These subjects were at chance level (50%) for all distances, i.e. they did not recognize the nearer square but simply guessed. Therefore, those results are not included in the subsequent analysis of the correlation between pre-test and random-dot condition. Nonetheless, there is no correlation found. There were both subjects who performed well in pre-test but had low results in the random-dot condition and subjects who performed badly in pre-test whereas performed well in the random-dot condition. The phenomenon of performing well in pre-test and at the same time doing poorly in the random-dot condition might be explained with the fact that in pre-test subjects had to determine solely which square is nearer, that is the relative distance of an object. In the random-dot condition however, their task was to determine exactly the respective target point, i.e. is the absolute distance to the walls which is a lot more difficult. The fact that subjects who performed badly in pre-test accomplished well in the random-dot condition could be due to the fact that in the random-dot condition, unlike in pre-test, subjects had the possibility of using motion parallax. This is considerably helpful, probably more helpful than binocular disparity. This is coincident with the findings of Sperling et al.: They tested subjects' abilities to identify the shapes of objects that were formed only by random-dots. There was evidence that "changing dot density was neither necessary nor sufficient to account for accuracy; motion alone sufficed" which shows that usage of binocular disparity is subordinate in contrast to motion parallax (Sperling, Landy et al.

1989). This pre-test also reveals that stereo vision is graduated; it ameliorates the greater the distance between the both squares becomes.

Comparing the results of the frequency distribution of distances from the blue target point in control and the random-dot condition, the vast majority of trials in the control condition that ranges between 0 and 2 meters gives evidence of how much simpler it is to locate the target point in the control condition than to do so in the random-dot condition. The difference between the numbers of trials for the red and green target point in the same range leads to a similar conclusion. This is due to the fact that the walls in the control condition contain more spatial information than those in the random-dot condition.

The difference between the frequency distributions of distances in the individual target points depends on the localization of the respective target points. Some are more peripheral, particularly the red target point. Thus the maximum distance to this target point in the room is greater than the maximum distance to a target point more in the middle of the room, e.g. the blue one. For this reason there are trials for the red target point in which the assumed target point is more than 14 meters away from the correct one, whereas for the blue target point the maximum distance does not exceed 10 meters. The values of the green target point are in between. This is why trials for the red target point occur at a much higher distance than for the blue target point.

The frequency distribution of distances is mostly divided into two parts; one is under 4 meters and the other at a greater distance. This is because subjects confused the correct corner with the opposite one. This comes by the fact that both the correct and the opposite corner have similar geometric relations. This occurrence is also found in rats' performance of finding places in a rectangular box (Cheng 1986). These so-called rotational errors are very common in task performances with reduced spatial information. As subjects in this experiment couldn't rely on feature information as landmarks in both control and the random-dot condition, it was hard for them to distinguish the individual corners. Although in the control condition they had parts of intensity information, those were obviously not sufficient to determine the target point in the correct corner in every trial. According to Stürzl et al. rotational errors can be explained by view-based navigation, that means a snapshot model (Stürzl, Cheung et al. 2008). However, in the random-dot condition there are theoretically no cues that could provide such a snapshot-based method. A snapshot model requires constant cues which are not given by flickering random-dots. Though, there are indeed constant cues and those are the edges of the corners. They remain the same and in this manner they could serve as cues for a snapshot navigation. Besides, there are considerably less trials in the control condition that fall under rotational errors. This once more gives evidence of how much easier it was for subjects to find the respective target points again in the control condition than in the random-dot condition.

The fact that in the random-dot condition the numbers of trials are distributed more broadly than in the control condition gives evidence of where and how subjects searched for the target point. In the random-dot condition they sought randomly all over the room. They seemed to walk aimlessly through the room without having an idea of where to go. Contrary to that, subjects searched more systematically in the control condition. Either they searched in the right spot or corner which occurred notably more frequently or they sought at the opposite site which was much more rarely. Apparently, subjects in the random-dot condition felt disoriented which is due to the fact that sole depth information was insufficient to localize the target point properly, whereas in the control condition they at least seemed to have an idea of where to walk, even if it was not the right corner but the opposite one. Plus, it's likely that subjects were confused by the random-dots in the random-dot condition which lead to an aimless performance. The reason that for the green target point in the control condition the numbers of trials are not as clumped as for the other target points is that the green target point is more in the middle of the room and thus has no salient corner in immediate proximity to orientate by.

Regarding the comparison of errors, it's clear that it was a lot more difficult for subjects to orientate in the random-dot condition. As subjects numerously confirmed especially the blue target point in places far away from the correct target point it is evident that it was hard for them to find this position again. Trials with the red target point have considerably less errors which is due to the fact that the red target point is positioned near a more salient corner. This makes it easier for subjects to memorize the spot. As the blue and green target point are at places near corners that resemble each other closely those corners are not salient cues. This makes it difficult for subjects to memorize the respective sites. The reason why there is such a low number of errors in trials with the green target point – despite the fact that it has no salient cues that could help subjects to remember it – is its position, as it is mentioned above. The errors subjects made here are simply not considered errors as they don't exceed the 4 meter threshold.

Regarding the comparison of the error ellipses it is evident that in the random-dot condition subjects walked more aimlessly through the room, although the difference between the ellipses of both conditions is not too great. The reason for this might probably be that subjects only had to estimate their position within the room and find out where to head. Once they achieved this the difficulty in the random-dot condition became irrelevant and they accomplished this condition similar to the control condition.

4. Discussion

Regarding the error ellipse of the red target point, it is to add that the scatter of the correct decision points stretches along the wall. There is no high dispersion in terms of broadness but a lot higher one in the slanting longitudinal axis. The reason for that is that subjects' estimation of the distances to the walls is unequally good. The nearer the walls, i.e. the smaller the space to be estimated, the more properly subjects are able to estimate the distances to the walls. This is consistent with the results of Waller, Loomis, Golledge and Beall. They showed that imprecision in distance estimation increases with the distance to be estimated (Waller, Loomis et al. 2002). These results are in accordance with Weber's law of psychophysics. Plus, Loomis showed in another study (Loomis, Klatzky et al. 2013) that subjects perceived glowing objects in a dark environment more than 3 meters away as closer as the things actually were. This might be comparable with the fact that most of the subjects estimated the red target point farther away from the wall than it actually was. Perhaps here again they perceived it as closer as it actually was.

Concerning the absolute error, that is the mean of all distances to the respective target points, it is clear that in the random-dot condition the absolute error is higher which is not astonishing after all, as well as the fact that the absolute error is the lowest in trials with the red target point. What is remarkable yet is that the smallest difference between control and the random-dot condition is found for the red target point. The explanation for this is that the position of the red target point is near cues such salient that it does not make a difference if intensity information is available or not. This is suggested not only by the fact that this target point is within the unique sharp corner but also by the fact that from this viewpoint subjects were able to see all the other 3 corners in one field of view, provided that they really turned around after arriving at the red target point. This is an important detail that was also focused in the work of Sovrano and Vallortigara (Sovrano and Vallortigara 2005). Their results are coincident with those of this study: Like the chicks in the said experiment, it was easier for subjects to recognize places from which they had a view on several corners, e.g. on the overall geometric relations of the room. Hence, if this was not the case they could use featural information but as at least in the random-dot condition there was completely no featural information available subjects felt and acted disoriented. It presumably explains the great difference in performances with red and blue target point. Thus, in general, subjects always accomplish trials with the red target point well – regardless of the condition. This once more shows how necessary a unique corner is for a proper orientation in this condition but as well the importance of all cues being in one field of view. The fact that the highest absolute error is found in trials with the green target point is not surprising. First the green target point is placed of all target points in the least salient spot in the room. Second, in contrast to the red and blue target point, there is no corner in immediate proximity that could help memorizing the spot. The fact that the highest statistical significance between control and the random-dot condition is found in trials with the blue target point suggests that this target point can virtually only be properly determined in the control condition. That is that here intensity information is essential in particular. The peculiarity with the blue target point is probably again due to the issue with the field of view. From the blue target point's position all corners of the room do not fit in one visual field. Thus subjects could not perceive all cues at the same time, they had to turn around. In the control condition this proved to be no problem at all. In the random-dot condition however, such a motion had a negative effect on subjects' orientation. When subjects rotated their head in the random-dot condition, this quickly lead to confusion and disorientation as the movement of the flickering dots distracted them. Moving was only useful when subjects stepped sidewards. Then they could perceive depth information through motion parallax. Besides, the effects of a subject's movement in the random-dot condition also depend on the arrangement of cues. If one had all cues in a visual field, as it was the case with the red target point, sidestep moving was extremely useful to figure out one's position in the room. Yet, if a visual field did not contain all cues, so that subjects had to turn around to perceive the other cues, movement was far from helpful. This was due to the fact that by spinning around certain cues disappeared from one's visual field which was disadvantageous to subjects' orientation. Plus, the required movements had to be large and that was another factor that distracted subjects. If one turns around so that he or she gets a complete new visual field, he or she has to start again spatializing this new visual field in the room. Therefore, big movements in the random-dot condition did not serve orientation as well as slight movements did. However, subjects' heading was not documented so there is no absolute certainty about whether subjects used the visual field with all cues for orientation or not. Further experiments that trace subjects' direction are required to determine the role of all cues in one visual field. In trials with the green target point there is no such considerable difference in performance in the control and random-dot condition. This is because subjects performed moderately in both conditions. This shows that even in the control condition it was hard for subjects to determine the green target point properly. The reason for that is evidently the target's position. It is difficult for subjects to estimate the distances to the corners between which the target point lies. Unlike the other target points where subjects confirmed the points more or less right as long as they stood near the respective corner, here it was far harder to find the correct position since the corners were farther away.

The comparison of angles again shows the different difficulties to find the respective target point. Recognizing the red target point is not hard both in the control and random-dot condition. Subjects confirmed the red target point even properly. However, it is to mention that transferring the room into a circle is not an adequate comparison as the kite-shape is clearly not symmetric with respect to a point. Thus, the target points are in different distances to the centre and the same ranges around the target points differ in their size. Therefore the confirmed points around the red target point are in a wider range than those of the blue or green target point. In random-dot trials with the blue or green target point it is evident that subjects felt more disoriented which explains why so many confirmed points are beyond those accepted ranges. In contrast to that, subjects in the the control condition, even if they mistook the correct target point, searched more properly in the opposite corner. This again shows that there is different spatial information in both conditions and gives evidence of how salient the cues need to be when only depth information is available.

The comparison of the time subjects took to confirm the target points indicates which target points were faster, i.e. easier to find and thus, on which target points they were certain. It shows that difficulty of a trial and the time to find the respective target point are correlated. It is not surprising that trials in the random-dot condition took longer than in the control condition as subjects had more difficulties to orientate and navigate here. The fact that there is no significant difference in trials with the red target point leads to the conclusion that in the random-dot condition subjects recognized the position of this target point nearly instantly – almost as fast as in the control condition. Consequently, the highest difficulty here was not finding the red target point but orientating in the room in general. For this reason there are significant differences between control and the random-dot condition in trials with the blue and green target point. Here, it was not only hard for subjects to orientate but also to find the respective target points as salience was barely given there. Moreover, there are differences in the ranking between control and the random-dot condition. The target point for which subjects took longest time in both conditions is the green one. However, the second longest time they took for is the red target point in the control condition and the blue target point in the random-dot condition. It is understandable that for the blue target point, as it is harder to find, subjects took a long time in the random-dot condition. However, it is more difficult to clarify why in the control condition subjects took slightly longer time for trials with the red target point. A plausible explanation might be that subjects recognized the blue target point as fast as the red one. Yet, to get to the blue target point, they took less time because one of the respective starting points – the green one – is not far away from the blue target point. In trials with the red target point, however, both starting points – the blue and green one – have a greater distance to the target point. Though, the duration of the trials does not indicate how well subjects performed. It only points out how long they took to feel more or less certain on a target point but that does not give evidence about accuracy.

Subjects' answers of the questionnaire give evidence that performing in the random-dot condition was not only much more difficult but also lowered motivation and the perception of fun which is a consequence of a task that is hard to perform. Also due to perceived difficulty level subjects could reproduce the position of the target points within a sketch less properly after performing in the random-dot condition.

4.1. Conclusion and Outlook

In summary, orientating and navigating in an environment containing only depth information is possible, yet it is considerably more difficult. For a proper orientation humans need both intensity and depth cues. Only when perceiving this two different kinds of information humans are able to recognize places accurately. When given solely depth information it is highly important that cues are salient. Salience is given when certain cues stand out so that they can be perceived well with sole depth information too. This is the only way to enable subjects a proper spatial navigation. On the whole, the usage of binocular disparity and motion parallax is not sufficient to orientate properly, unless the surrounding cues are greatly salient. Additionally to the results of this experiment, the trajectories could be analyzed. They could give more evidence of how subjects searched in the respective condition, of the direction in which they started to walk and probably reaffirm the conclusion that searching in the random-dot condition was much more aimless. Plus, the direction in which subjects looked when confirming the target point could be analyzed. It would show whether subjects orientated themselves by having all cues in one visual field or not. What could be focused in future is to reduce even depth information to either binocular disparity or motion parallax and to test subjects' performances in these conditions. What would to be expected is that it would become even more difficult with only one kind of cues as it is already shown in a study about perceived distance of Philbeck and Loomis that "monocular parallax, binocular parallax and absolute motion parallax all were relatively weak cues to egocentric distance, especially beyond 2 m" (Philbeck and Loomis 1997). Besides, it could be tested how subjects would perform when in an environment with sole depth information constant cues as the edges of the corners would be eliminated. What if the corners would become round and thus would be less salient? All this and many other points are impulses for further analyses and studies. Place recognition is still an interesting and not entirely solved field of spatial cognition.

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6. Appendix

6.1. Questionnaire

Table 6: Evaluation of different factors by the subjects

	evaluated higher in…
Fun Factor	control condition
Motivation	control condition
Level of difficulty	random-dot condition

Subjects answered questions about fun factor, motivation and level of difficulty in the two conditions differently.

They drew their supposed target points within a sketch of the kite-shaped room and it became evident that in the random-dot condition subjects more rarely recognized how many target points there were. Additionally they considered this target point easier to find that was near the sharp corner, i.e. the red one. Also, they found that corners in general were helpful cues.

Fragebogen

Geschlecht:

Alter:

Studiengang:

Kreise die Zahl die Deiner Antwort am ehesten entspricht:

- Hat Dir das Experiment Spaß gemacht?

  sehr wenig 1 – 2 – 3 – 4 – 5 – 6 – 7 sehr viel

- Warst du motiviert?

  sehr wenig 1 – 2 – 3 – 4 – 5 – 6 – 7 sehr viel

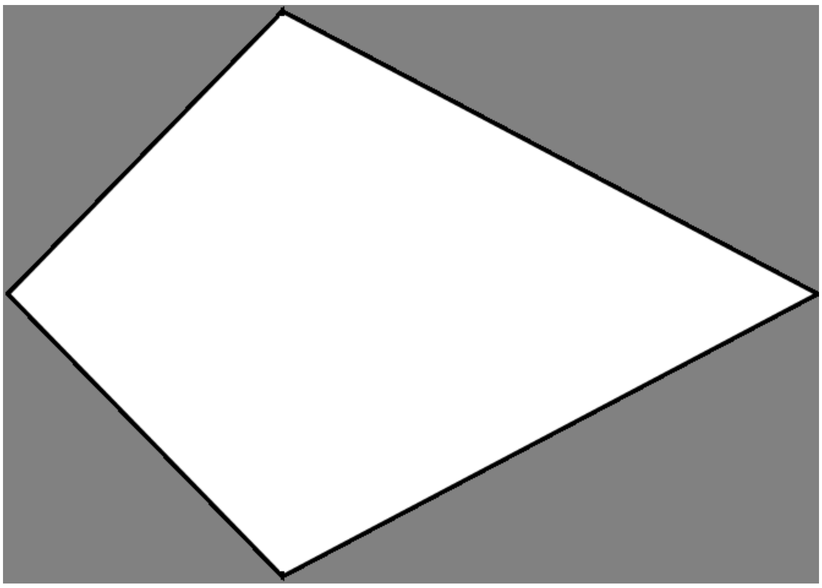
- Wie schwierig fandest du das Experiment?

  sehr leicht 1 – 2 – 3 – 4 – 5 – 6 – 7 sehr schwer

- Gab es Positionen bei denen Du es einfacher fandest, sie wieder zu finden?

  ____
  ____
  ____
  ____
  ____

- Kannst Du Deine Zielpunkte in den dargestellten Raum eintragen:



Vielen Dank für Deine Teilnahme!

6.2. Sketches from subjects

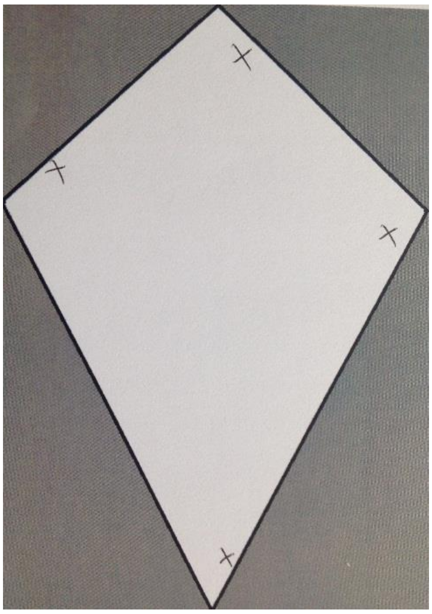


Figure 29: Sketch of the kite-shaped room with the target points drawn in by a subject after the control condition. The subject had almost all target points right, yet there is an additional one in the upper corner. This indicates a rotational error.

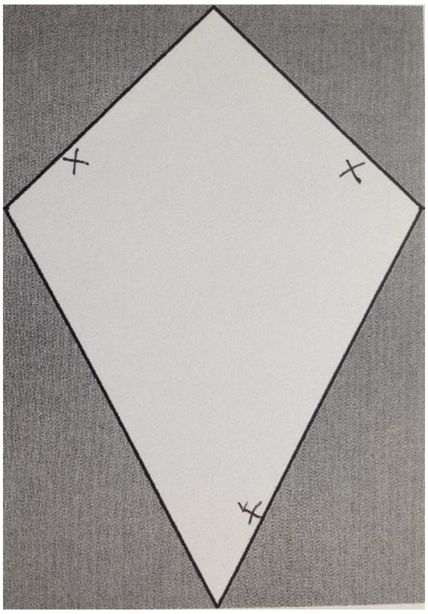


Figure 30: Sketch of the kite-shaped room with the target points drawn in by a subject after the random-dot condition. The subject could not determine the blue target point's position properly. The green target point is positioned too near to the corner.

6. Appendix

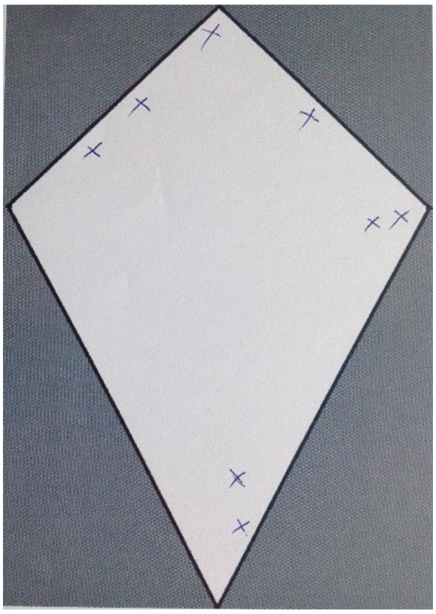


Figure 31: Sketch of the kite-shaped room with the target points drawn in by a subject after the control condition. The subject thought there were more than three target points, yet the correct target points are included.

6.3. Subject information

Liebe(r) Proband(in),

die beiden heutigen Experimente bestehen aus einem graphischen Programm welches vor Dir auf den beiden Bildschirmen präsentiert wird. Dabei solltest Du während der Experimente nur auf den Bildschirm vor Dir blicken. Der Spiegel vor Dir wird dabei so positioniert, dass Du nur mit einem Auge auf den vorderen Bildschirm schaust und mit dem anderen Auge auf den Spiegel.

Im ersten Experiment wirst Du zwei unterschiedlich weit entfernte Quadrate zu sehen bekommen, welche durch flimmernde Punkte auf schwarzen Grund dargestellt werden. Dabei sollst Du jeweils entscheiden, welches Quadrat Dir ***näher*** erscheint und dies durch Drücken der jeweiligen Maustasten (linke Taste = linkes Quadrat, rechte Taste = rechtes Quadrat) bestätigen.

Im zweiten Experiment wirst Dich in einem drachenförmigen Raum wiederfinden, dessen Struktur, ebenso wie die Quadrate aus dem ersten Experiment, durch flimmernde, weiße Punkte auf schwarzem Grund festgelegt ist.

Zu Beginn jedes Versuchsdurchganges kannst Du den Durchgang durch Drücken der Leertaste starten. Du befindest Dich nun an einem Platz (Startpunkt) innerhalb des Raumes. Hier kannst Du Dich durch Bewegen der Maus im Raum umdrehen und Dich in einem kleinen Bereich vorwärts (“W“), rückwärts (“S“) und seitwärts (“A“, “D“) bewegen. Dabei sollst Du Dir die Position genau anschauen und merken. Bist Du Dir sicher, dass Du Dir die Position gemerkt hast, kannst Du den zweiten Teil durch erneutes Drücken der Leertaste beginnen. Jetzt befindest Du Dich wieder erneut an einem Ort im Raum. Ziel ist es nun, zum zuvor gezeigten Startpunkt zurückzulaufen. Dabei kannst Du Dich mithilfe der Maus drehen und Dich vorwärts (“W“), rückwärts (“S“) und seitwärts (“A“, “D“) bewegen. Dabei solltest Du Dich zu Beginn wieder umschauen und <u>dann möglichst zügig und ohne Umwege zum Startpunkt zurücklaufen</u>. Bist Du Dir sicher den Startpunkt gefunden zu haben, bestätige dies durch Drücken der Leertaste. Damit ist ein Durchgang abgeschlossen. Der nächste Durchgang beginnt mit einem schwarzen Bildschirm und den Worten „Durchgang starten durch Drücken der Leertaste“. Möchtest Du eine Pause einlegen, ist dies die Gelegenheit. Die anderen Teile des Experimentes führe bitte zügig aber genau aus.

Der Versuchsleiter wird Dir die einzelnen Teile nochmal genau erklären.

Viel Spaß! :)