Verification of Stereoscopic Projection Systems for Quantitative Distance and Speed Perception Tasks

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***Abstract** – The goal of this paper is to propose a check list and several easy-to-conduct verification procedures in order to verify that a stereoscopic projection system has been set up correctly with respect to properties which might influence distance and speed perception. The paper first introduces the multitude of factors contributing to distance and speed perception in driving simulators, and then discusses the typical technical provisions for providing relevant cues for the perception of a human driver. Verification methods are proposed to assure, that at least some important parameters of the visual system are set up in a physically correct way in order to reduce ambiguous parameters of further research contributions. This should make them more reproducible and finally help to better understand the open issues in distance and speed perception in driving simulators.*

***Keywords:** Stereoscopic projection, distance perception, speed perception, quality assurance*

Introduction

There are many inconsistent and even contradictory results from different authors reporting on the effect of stereoscopic vision on subjective distance and speed perception (Panerai, et al. 2001; Palmisano, 2002; Hurwitz, et al. 2005; Kemeny, 2014; Bos, et al., 2019). Within the driving simulation community, it is well admitted that distance is generally underestimated in virtual environments, and that stereoscopic projection should play a significant role for an improvement (Marsh, et al. 2014; Brooks, et al., 2015; Perroud, et al., 2017; Schmieder, et al., 2017; Ghinea, et al., 2018; Colombet, et al., 2021). However, several studies and approaches could not fully elucidate the reasons for those inconsistencies.

To investigate the reasons for this inconsistency and to pave the way for better future understanding, it needs to be ruled out that this might be caused by deficiencies of the stereoscopic installations. They are implicitly assumed to be correct in the literature papers, but they rely on many contributing parameters with different significance depending on the application. Although these installations may be perfectly suited for the 3D-effects of movies and games, they might not be correct enough for using the same intuitive distance assessments for the driving task as in a real-world environment. The correctness or completeness of the scene projection method has not been a topic in most of the papers, so this effect cannot be traced or even assessed by a literature study.

The goal of this paper is to propose a check list and easy-to-conduct verification procedures in order to verify that the projection system has been set up correctly with respect to properties which might influence distance and speed perception. It should make sure that all well understood effects of optics and physiology are correctly considered (or at least well documented).

This should allow to better analyze the effects of other parameters in future studies, like individual variations of perception and experience among test persons, differences in sound and motion rendering, or further visual rendering effects.

The perception of distances and speeds are the results of complex human perception processes, with physical as well as physiological and psychological aspects involved (Foley, 1978). Additionally, not only the human visual system but several more sensory organs are involved. Currently, there are many driving simulator installations in use, around the world, several even equipped with a 3D stereo visual system. The above-mentioned contradictory results are collected using these different installations, and in most cases, nothing is published about the set-up and the alignment of the simulator and the visual system, in particular. As the correct adjustment of a 3D stereo visual system is a very complex process, which has a major impact on the validity of the collected results

(Banks, et al., 2012), the proposed check list and verification method provide an approach to establish a standardized set-up and alignment process for simulator visual systems, which might help to end up with better comparable and valid simulator experiment results.

Human perception of speed

The goal of a driver-in-the-loop simulator (DIL) is to put a human driver into a virtual environment that induces a driver's behavior as close as possible to the behavior in a real-world driving environment. This is the necessary assumption to assure the portability of results collected in a simulator experiment into real-world behavior, and vice versa.

As several different human perception inputs – among other issues, like the surrounding traffic, the road driven on, or the car being used, for instance – are fundamental for developing a driving experience in real world, it is a common approach to induce the specific perceptions through different technical subsystems within a driving simulator. In real world as well as in a simulator environment, the different perception channels are processed in the human brain and thus generate the overall driving impression.

As with many other brain processes, the resulting impression is additionally influenced by the individual human's expectations, experiences and training conditions (e.g., Barragan and Lee, 2021). Therefore, two different human beings in general end up with two different impressions, even based upon identical physical inputs. These facts have to be considered during set-up and interpretation of results of experiments, especially if they are extracted from questionnaires. If the sensation of speed and distance is used to control behavior, like controlling adequate safety distances, additional ambiguities like the individual driving skills and sense of danger play a further role.

When generating perception inputs using technical systems in a simulator environment, compromises have to be made between the desired realism of the input and the technological capabilities, in most cases. This problem often leads to small or even substantial discrepancies in the impression experienced in real world compared to what can be experienced in the virtual world in a simulator. More philosophically spoken, simulation can only be as good as the sum of all compromises involved.

One important portion of the driving impression is related to the perception of speed. There is no specific sensory organ for speed perception. Thus, the perceived speed is generated using the input of several different sensory perceptions: visual perception, acoustic perception, haptic or vibration perception, accelerating forces perception, in particular (e.g., Caro and Bernadi, 2015). Each component has its specific impact on the resulting perception of speed. A discrepancy in the perceived speed between driving in real world and driving in a simulator might be caused by deficiencies in one, two or even all simulator subsystems involved (Kemeny, 2004).

Even under real world conditions, driving at a certain speed may lead to different speed impressions, depending on the type of car used. Driving in a big, luxury car with a relatively high seating position, equipped with a comfortable air-suspension, a long wheel base, big tires and a very good isolation against engine, transmission, tire and wind noise levels induces a lower impression of speed compared to a ride in a small car with low seat levels, a less comfortable suspension, a short wheel base, small tires, and only pure noise isolation.

Right from the beginning of using driving simulators, and even when using just 2D visual systems, it could be found that many drivers underestimate the driven speed in a simulator (Hurwitz, et al., 2005; Bos, et al., 2019). Despite the fact that this underestimation effect may definitely be caused by deficiencies in more than just one of the involved simulator subsystems - like no or insufficient vibration excitation, limited bandwidth of the motion system and/or the sound system, for example - the following chapter will focus on discussing several well understood aspects of the *visual* perception. This should reduce the parameter space for future investigations of the other factors.

Pictorial distance cues

A human being has two eyes as the sensory organs for any visual perception. When viewing a certain scene in real world, two slightly different images of this scene are projected onto the retina of each eye, depending upon the slightly different position of each eye (right and left eye point). Visual nerves connect each retina to the brain, where the two images are combined to generate the perceived visual impression (Bruce, et al., 2010; Thompson, et al., 2016).

One important aspect in conjunction with the visual impression is the detection of depth or distances within an observed scene. Even a monocular image contains cues for the brain to deduce an impression of distance. The geometry of perspective and projection have been developed since the 15th century in conjunction with Renaissance arts (Edgerton, 2009). Main insights are, for instance,

- the existence of a horizontal plane through the eye level and the horizon,
- an apparent convergence or vanishing point at the horizon for parallel lines,
- a correct occlusion of consecutively positioned objects,

- and the distance-dependent object sizes.

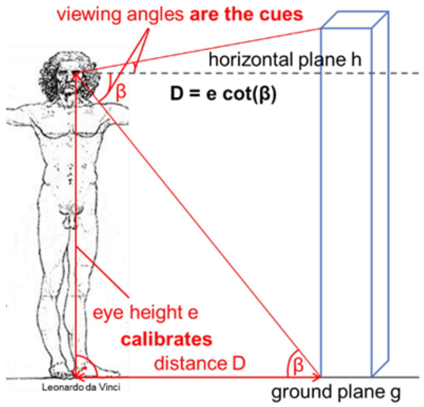


Figure 1: Monocular distance perception

In reference to the implicit knowledge of eye height, the individual can deduce distances to an object on the same ground plane by judging vertical viewing angles between the horizontal plane and the foot point of objects in front (see **figure 1**). Changes in eye height can be deduced from the observed convergence of perspective lines identified or assumed on the ground plane. Humans learn to identify their eye height intuitively, trained for example by the change of perspective between standing and sitting conditions (see **figure 2**). Similarly, truck drivers can swap easily (after some initial training) between truck and passenger car driving positions (see **figure 3**). The effect of eye height has nicely been studied by Larish and Flach (1990). It has to be noted, that (based on the geometry of perspective) all subjective size deductions scale with the known or assumed height of the eye level – as long as there are no other cues for absolute dimensions, such as objects with a well-known size (e. g. doors).

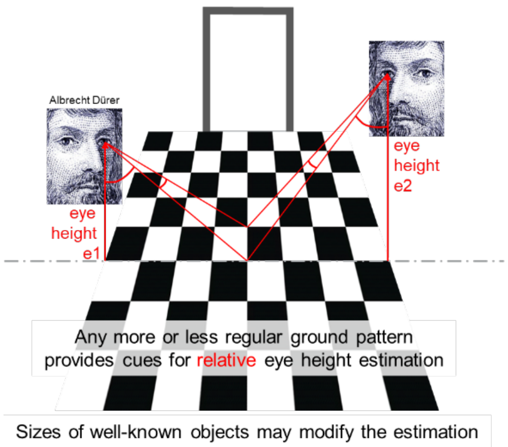


Figure 2: Ground view from different eye heights

Using the slightly different images of the two eyes adds further cues and capabilities based on horizontally structured scenes. This is called spatial or three-dimensional, stereoscopic viewing. The depth perception is extracted from the *disparity* of relative position of corresponding objects in the two images (on the retina or a projection screen), or equivalently the *convergence* (or *squint) angle* between the viewing directions of both eyes (see **figure 4**). The disparity on a screen is largest for very far objects (convergence angle of zero), it decreases for closer objects and turns to zero for objects in the same distance as the projection screen. Objects in front of the screen are projected with negative disparity. The closer the object, the larger is the convergence angle between the two eyes. Stereoscopic viewing only works in a small field of view of approximately ±20° (estimated value, Kletzenbauer, 2006) around the viewing direction (the so-called *panum*); a human who wants to inspect an object with respect to depth outside of this field of view will turn the head into this direction.

Figure 3: Car and truck driver perspectives at same location. Note the different convergence of curb lines, and how the horizon line intersects windows and vertical posts at different heights.

It has to be noted, that all subjective size deductions in stereoscopy scale with the known or assumed distance between the pictures presented to the two eyes. Since in real-world direct viewing this distance is the individual interpupillary distance IPD, humans normally assume their IPD as a scaling factor. A deviation from this base length leads to wrong distance impressions (Renner, et al., 2013).

When using a 3D database for representing the virtual world environment, the pictorial depth cues like linear perspective, dwindling size perspective and occlusion, among others, are intrinsically incorporated in the projection algorithms onto the screen, and thus are already included in a computer-generated 2D visualization. However, this is only correct under the condition, that the eye level and the interpupillary distance IPD are correctly known for the individual person, who finally views the projected scene.

Eye movement distance cues

Additional depth cues, that are not included in the presented image, depend on the presentation to the eyes in a three-dimensional real world.

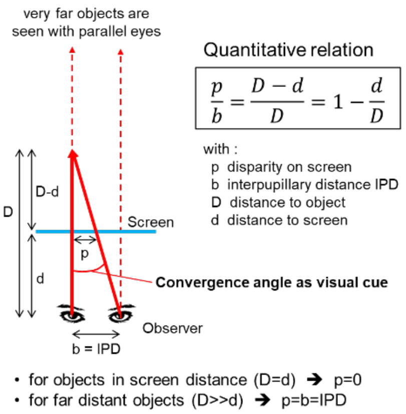


Figure 4: Correct stereoscopic disparity on screen is proportional to the *individual* interpupillary distance

Significant is the *convergence angle* between both eyes when observing a specific object within the scene (see **figure 4**). The brain notices the muscular strength needed to *converge* both eyes in order to look onto the same spot in the scene. This muscular strength decreases with the distance to an observed object. In a natural view of the eyes, there is a fixed relation between the convergence angle and the disparity of the images in the eyes. Human brains should be trained, that these cues always appear jointly. Inconsistencies are reported to result in headaches, and erroneous distance interpretation can be expected (Lambooij, et al., 2007).

A further factor influencing the depth impression is the muscular strength (*accommodation*) needed to *focus* both eyes' lenses when observing a certain object at a specific distance in front of the observer. This strength again is dependent on the distance between the observer and the observed object. The range of acuity (*depth-of-field, DoF*) depends on the illumination of the scene: with a brighter scene the pupils get smaller, and this results in a wider range of acute viewing, measured in diopters (Hainich and Bimber, 2016).

For geometrical and optical reasons, both *vergence* and *accommodation* provide a better distance resolution for short distances than for far distances.

It must be noticed that the described generation of depth impression presume an unrestricted vision of the individual and the capability to interpret stereoscopic images. Humans with not corrected eye defects might not be able to generate a proper depth impression, whilst others do not have the ability for stereoscopic viewing, in general (in the range of 5% of the population, Coutant, 1993). At least there is surely a wide variation among individuals in how far they do effectively use the associated distance cues. Therefore, it is essential to check the visual acuity and stereoscopic viewing capabilities of all subjects prior to their participation in appropriate experiments.

Additional distance cues, resulting from the motion of the eyes with the head, the body or the entire vehicle are *motion parallax* and *optical flow*. They result from changing the relative position laterally or longitudinally to the viewing direction, and they have a strong interaction with the sensation of the motion itself (Ledegang, et al., 2015). The effect of motion parallax may be replicated by a head-tracking system. These complex perception capabilities are the topic of separate research (e.g., Jamson, 2000; Bos, et al., 2021), and they are out of the scope of this paper, which aims mainly at better understanding the effects in stereoscopic viewing systems.

Effects of the projection

In a real-world driver environment, everything to be observed is 3D, including the out-of-the-window traffic scenery. Objects positioned in this scenery each are located in specific distances away from the observer, and therefore the eyes have to *accommodate* and to *converge* according to these distances, when different objects are observed.

In a driving simulator, however, the image (or the two images of a 3D-stereo system) presented to the driver is a 2D image, transformed out of 3D data by a perspective operation (Scratchapixel, 2022), and projected onto a screen surface in front of the observer. This transformation assumes a specific distance, eye-level and viewing direction of the observer with respect to the projection screen. Any deviation of the final observer from these assumptions causes inconsistent viewing angles, which result in unrealistic pictorial distance cues (Colombet, et al., 2010). Furthermore, all objects to be observed are now located on the screen, i.e., in the same screen distance.

For many driving simulator installations, which use complete cars as simulator cabins or a least partial sections of a car, the screen is mounted about 3 m in front of the driver. Typically, all traffic which is important for the driving task, happens *beyond* a distance of 5m, i.e., in a range between 0 and 0.2 diopters, and especially beyond the screen distance.

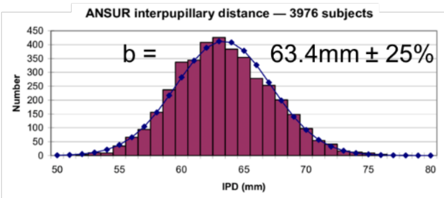
Thus, the driver in a simulator is sitting in a partially real 3D-environment like the cabin with the wind-shield and its frame, the interior of the car including the dashboard with all controls and instruments, the steering wheel and sometimes even the hood. The driver observes both this real 3D-environment in addition to the out-of-the-window traffic scenery, which is generated as one 2D-image (or as two 2D-images for the right eye and the left eye, respectively). As a consequence, for all objects projected onto the screen, the real-world distance cues caused by *accommodation* do not develop. The erroneous accommodation onto the screen can be expected to lead to an underestimation of the distance to traffic objects, since the screen distance is always shorter.

Within a technical 3D-stereo system, additionally an appropriate mechanism must be installed to ensure, that each eye can only see its dedicated image. Stereoscopic glasses for this purpose decrease the already low brightness inside the simulator cabin, which might further influence environment perception.

In Head Mounted Displays (HMD), the viewing distance to the display has to be increased by lenses anyway, which might compensate for the average part of this focus strength; a general distance underestimation might be compensated this way, if accommodation deficits would be the predominant reason. But in a similar way to projection, *accommodation* as cue for distance of a certain object cannot usually be established in HMDs neither, though some solutions have been attempted (Kramida, 2016). Diverse HMD brands apply different optical or virtual screen distances; this might need additional attention for an exact evaluation.

In a monoscopic projection, in addition to the missing *accommodation* cue, the *convergence* (*squint) angle* cue cannot develop correctly, because both eyes observe the identical image point of an object, which is always located on the screen. The consequence of this erroneous cue may also be a consistent underestimation of distance for objects beyond the screen distance.

Interpupillary distance IPD (b):



Eye height *e* of a sitting person:

	DIN 33402-2:2007	percentile					
	(unbekleidete Personen, 18 –65 Jahre)	male			female		
	Abmessungen (in cm)	5.	50.	95.	5.	50.	95.
12	Augenhöhe im Sitzen	74,0	79,5	85,5	70,5	75,5	80,5

e = 78cm ± 7.5cm

Figure 5: Range of individual body measures in a driving simulator setting, Dodgson (2004), DIN 33402-2 (2007).

One of the major benefits of a stereoscopic projection is, that a correct presentation of the two separate images supports the development of a corresponding convergence angle distance cue. The correct calibration of a screen projection can be measured on the screen, using the relations given in **figure 4** (above).

In case of stereoscopic Head Mounted Displays a calibration requires an exact aligning of the optical axes of eyes with the HMD lens system. And of course, also the installations have to ensure the correct convergence angles as well.

The right eye and the left eye image in a technical 3D-stereo visual system are generated based upon the positions and orientation of the two parallel virtual cameras, normally facing straight forward. Thus, the images are only valid for these specific positions and orientation. Viewing to the side is not correctly supported by these camera parameters.

On the other hand, and as mentioned before, the stereoscopic viewing has a limited field of view. In a simulator with a wide horizontal field of view of the entire projection screen, the observer, who intends a closer look at an object beyond this stereoscopic range, is expected to turn his head. A head tracking system, which updates the images according to the new eye positions of the observer, can provide the necessary data. Since in a simulator the observer has a fixed position and approximately rotates his head around a vertical axis, the image generation for different viewing directions might be integrated into the projection system even without head tracker (Schöner and Schmieder, 2016).

Adjusting stereo projection systems during installation

Adjusting a 3D-stereo visual system primarily is done by initially placing and real-time controlling the two virtual cameras used for the generation process of the right eye's image as well as for the left eye's image. These images are then presented separately for each eye, using an appropriate display system.

Placing the cameras means putting them at specific longitudinal (x), lateral (y) and vertical (z) coordinate positions (= observer's or driver's eye point positions for right and left eye) within the virtual environment database (= digital twin of the section of the real-world environment used for the simulation run). These body- or vehicle-related coordinate positions need to be transformed and updated in real-time according to moving around in the world during simulation.

In general, the vertical z-coordinate (= height of the camera above ground or road level for driving simulation) is defined by the actual driver's eye point height in the simulator. For an average passenger car and an average adult driver, the eye point height, when sitting on the driver's seat, is approximately 1350 mm ± 30% (SAE standard is only 1080 mm). Truck drivers have much higher eye point heights, in the range of 2300 mm ± 30% (1800 mm ... 3000 mm) (US-DOT, 2006, Bartlett, 2014). Even for a fixed seat position, the eye height of a sitting 5% percentile female is 15cm lower compared to a 95% percentile male (DIN 33402-2:2007), see **figure 5**. Since a high-end simulator should be designed around a specific eye position, the method of choice is to adjust seat height and longitudinal position of the driver’s seat in order to assure that the eyes (as well as the ears) are in the correct nominal position for every individual driver. By suitable selection of test persons extreme body measures, which cannot be compensated by seat adjustment, should be avoided.

The driver specific interpupillary distance (IPD; between 52 mm and 78 mm for adults with an average of 62 mm for women and 65 mm for men, i.e., 63.4 mm ± 25%, Dodgson 2004) is represented through an +/- offset to the y-coordinates for the cameras. The stereoscopic system should be able to be calibrated for this wide range of different body parameters.

In addition to specifying the x-, y- and z-coordinates, orientation information must be defined in terms of heading, pitch and roll angles for the cameras, as well. These angles specify the specific viewing direction, and might be set up initially to a fixed direction, in most cases the straight forward direction of the visual system's channel. If the simulator is equipped with a head- or even an eye-tracking system, the angles can be updated in real-time, according to the head movements in particular.

Prior to the described camera placing, the aperture angle of the optical system for each camera has to be specified in terms of a horizontal and a vertical field of view, defining the section of the virtual world to be further processed. As the field of view specifications only include fixed and system related parameters, they have to be specified only once, initially.

Based upon the discussed parameters, the image generation process in general performs a perspective transformation from the 3D virtual world database (object space) onto the 2D display screen (image space), both for the right and the left eye image in a 3D-stereo visual system. Depending on the exact shape of the screen, as well as the location and lens type of the projectors, an additional warping of the resulting images might be necessary. The step of warping should compensate for nonlinearities, but it might also leave some residual calibration errors.

The described approach to properly set up a visual system for 3D-stereo is pretty much identical for all potential display devices used to present the generated images (monitors, projection systems, head mounted displays etc.). The set-up process is done by just setting up parameters in the image generator software. It therefore can be done easily and quickly, and no mechanical adjustments are incorporated.

When a projection system is used for 3D-stereo projection, two different modes of operation are available: active and passive stereo. In active stereo mode only one projector is used to sequentially project the right and the left images, one at a time; this way, both images are assured to be projected onto the same area – but in order to avoid flicker, the projector needs to support an increased image frame rate. Synchronized shutter glasses are used to make sure, that each of the observer's eyes can only see it's dedicated image (= image separation). In passive stereo mode two projectors are used, one for each image. Special filters in the projectors as well as in glasses to be worn by the observer guarantee for the image separation. When setting up a passive 3D-stereo projection system, both projectors have to be mounted and initially aligned to make sure that reference points of both presented images are projected onto the same spot on the projection screen. Special glasses are also used for the image separation, if a monitor is used as the display device.

If using a head mounted display as the display device, two adjacent displays are installed, one for each eye. For most implementations, adjusting the center distance between these displays is possible. This distance should match the IPD used in the image generation process, which again should correspond to the IPD of the viewer. Nevertheless, it is worth noting that not all head-mounted displays offer the possibility to adjust the IPD in a wide range.

The so far described approach leads to two different images to be displayed, with an expected offset between each other (measured from a vertical reference line in the normal viewing direction of the virtual cameras) as big as the IPD specified for the image generation process.

Since the projection and screen location may have some installation tolerances, a +/- offset (equivalent to an artificial convergence angle) can be added to the camera's heading angle as an additional calibration parameter. This modification of the image generation process should result in two images where scene objects in the same distance as the observer-to-screen distance are projected onto the same spot (disparity=0). Objects closer to the observer (negative disparity) or further away than the screen (positive disparity) are projected the more separated from each other the more they are off the observer-to-screen distance, respectively. Objects (or special calibration elements) which are located in the far distance, should have a horizontal disparity equivalent to the IPD. This heading offset is a fixed and installation-related parameter, it therefore can be adjusted and then fixed once, initially, as a software parameter.

Intermediate summary

As seen from the above discussion, body measures are supposed to have a significant influence on individual distance perception. Eye height (in monoscopic and stereoscopic systems) as well as IPD (in stereoscopic systems) are parameters which may vary for individuals in substantial ranges. For this reason, the projection system needs to be corrected for every single participant, if distance perception is paramount for the results of the experiment. In consequence, we propose:

1) for future studies, the relevant parameters of the stereoscopic installations should be verified and documented as part of the study, and
2) the key individual body parameters of test persons need to be taken into account and considered as independent parameters for test evaluation.

Features for consideration and documentation

The following independent features which influence monocular and binocular-stereoscopic distance, size and finally also speed perception need documentation and should be considered for recalibration:

1) Horizontal location of the eye point

   depends on the longitudinal position of the observer in the driver's seat. Essential is the resulting distance of the eyes from the screen, which should coincide with the design distance of the 3D-to-2D perspective transformation; it impacts both monocular distance and stereoscopic assessment.

2) Vertical eye location / height of the horizon

   depends on vertical eye position above the ground level; a real-world horizon is always (automatically) on eye level; it impacts both monocular distance and stereoscopic assessment.

3) Left/right image disparity

   depends on IPD (inter-pupillary distance), effects limited by 'ocular pixel resolution'.

4) Left/right eye convergence angle

   depends on IPD (inter-pupillary distance), effects limited by 'ocular pixel resolution' and convergence muscle sensation capabilities; in monocular projections fixation of any point leads to a convergence point on the screen; many stereoscopic installations do not consider this effect correctly.

5) Focusing effort of the eye

   depends on distance of the image screen (with some additional influence from brightness of the picture), effects limited by focus muscle sensation capabilities.

The last effect is more relevant for closer screens than for distant projection screens, and high image brightness can reduce the influence; those parameters should be documented in further studies. Since the feature does not depend on individual macroscopic body parameters, it does not require adaptations to single test persons.

Effects 1 through 4, however, are influenced by body measures of the individual test person in a given simulator: by longitudinal and vertical eye position even on a given seat (or equivalently the resulting screen distance d and eye level e above the ground plane resulting from body and vehicle/simulator dimensions) and by the inter-pupillary distance IPD (i.e., the stereoscopic base b).

If these four features are incorrectly or inconsistently calibrated with respect to the body measures, an individually different wrong distance perception is inevitable. For sound scientific research, body measures need to be taken - at least for checking whether they have an effect. But since their effects can be modelled quantitatively, it can be predicted, verified or even compensated in the experiment.

Test cases for verification of projection systems

Quality of the installation and their adaptation to body parameters of individuals can be checked by some basic tests, and by comparing (and measuring distances between) left and right images on the screen. For this discussion it is important to distinguish between two eye heights:

- Projection eye height e: This is the assumed observer's eye height for calculation of a perspective projection from 3D to 2D; a correct projection has the property that the height of the horizon always matches the projection eye height.
- Observer's eye height v: This is the actual eye height of the observer v while viewing a scene (which may include projections calculated with a different projection eye height e).

1) Is the observer's eye at the correct location?

Verification goal: Make sure, that the location of the eyes of the observer are in the correct distance and on the same level (v) which was assumed as screen distance (d) and eye level (e) for the perspective projection. This is a necessary condition for rays from the observer's eye to elongate from the real world to the virtual scene without a kink.

Method: A simulator without head-tracker is assumed first. Longitudinal eye position: keep a fixed longitudinal seat position, and adjust only steering wheel position and pedal location according to body size. Vertical eye position: Make the horizon visible on the screen; in a correct projection, the horizon appears on the same level as the projection eye level (e).

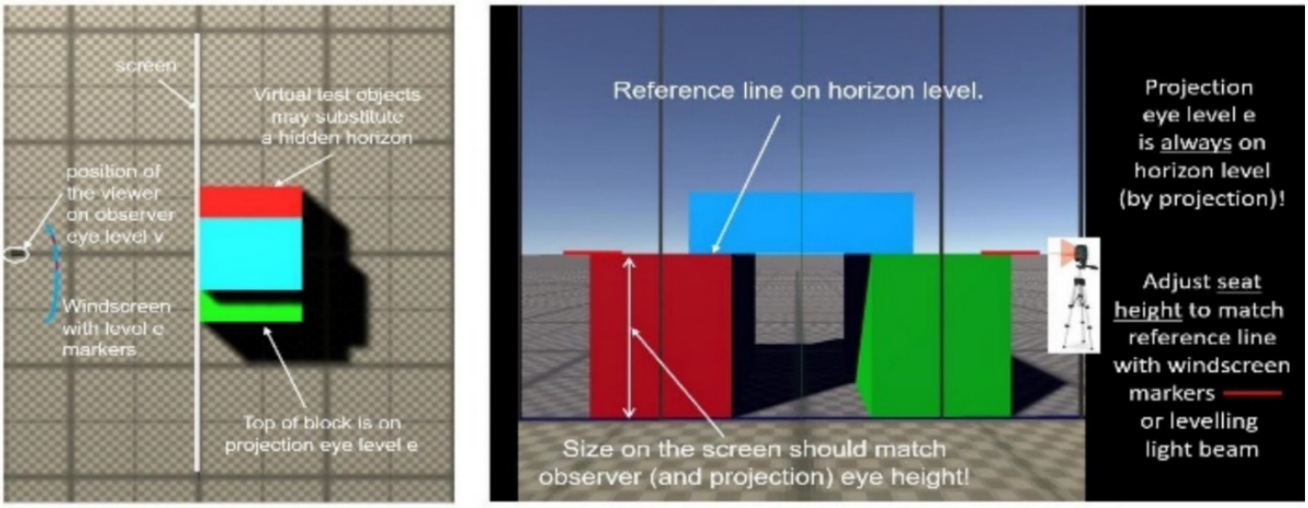


Figure 6: Is the observer's eye height on horizon level?

Since the horizon often is hard to identify correctly, place a virtual object with a distinct reference edge at projection eye level (e), with its front located in screen distance (see **figure 6**). Measure the height of the horizon (or of the reference edge) above the horizontal ground plane. Both should have the same value as the measured eye height (v) of the observer above ground plane.

Methods for comparing eye heights without numeric measurement can be more time efficient, for example by:

- permanent markers on the windshield at the projection eye level; their level has to match with the horizon viewed by the observer.
- projected markers by levelling light beamer adjusted to projection eye level and in screen distance, beaming from the side to the face of the observer; this can be judged by an outside operator, or by the observer himself, looking into a mirror.

<u>Possible re-calibration method:</u> Adjust seat height until observer's eye level and projection eye level match. A suitable selection of test persons should assure, that this is always possible.

<u>Notes:</u> If a head-tracker is installed in the simulator, the horizon matching provides also checking the correct calibration of the head-tracker. The virtual objects should have a reference *plane* (instead of just an *edge*) at projection eye level. The correct head position for the above-mentioned measurements is achieved, when the reference plane turns invisible – because it is seen from its side by the observer. Correcting the vertical offset of the head-tracker provides the additional re-calibration method in this case.

With suitable instruction, the test subject can recalibrate his seat position and the head-tracker projection parameter until the position is correct for his individual perception – no explicit body parameter measurements are necessary. Since horizon level is important also for monoscopic displays, this kind of easy verification and re-calibration should be considered for every simulator installation.

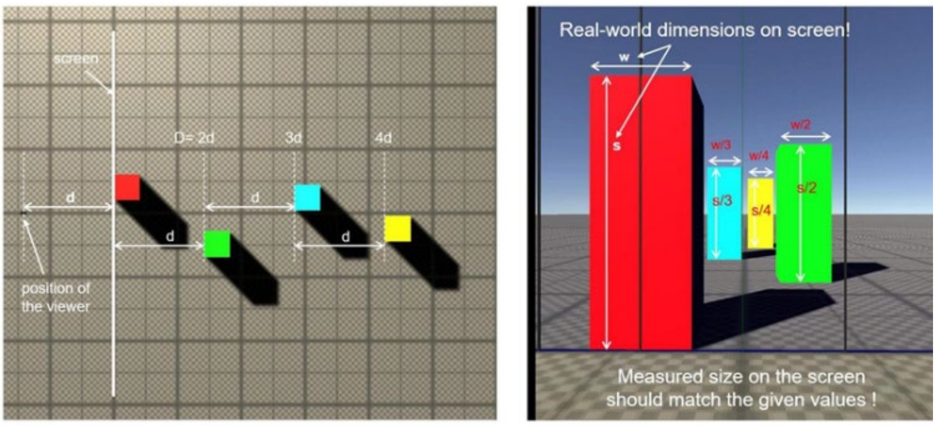


Figure 7: Does size change correctly with varying distance?

2) Does size change correctly with varying distance?

<u>Verification goal:</u> Make sure, that the size of an object decreases with distance in a correct way. Correctly projected objects in n times larger distance should have a 1/n times smaller size on the screen.

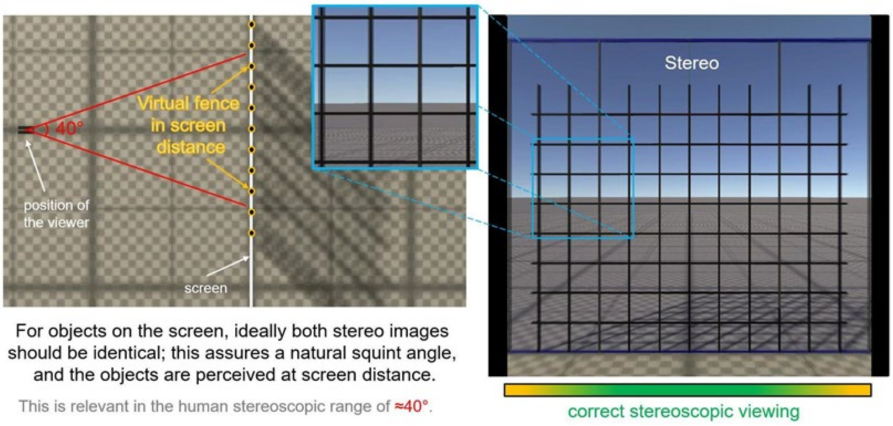


Figure 8: Is the convergence angle correct for objects in screen distance

Method: Place a set of reference objects, all with height s, in multiples of screen distance d. For the distance n x d their size on the screen should be s/n. Measure the size of the objects on the projection screen and compare with their expected size. See **figure 7** for a possible constellation.

Possible re-calibration method: If the change in object size is not as expected, the projection and the warping process needs to be inspected.

Notes: For easy verification, the objects should be labelled with the measurable height as they should appear on the screen (s/2, s/3, s/4, ...) in cm; for completeness the relevant size parameters s and screen distance d should be indicated as text remarks in the projected reference scenery.

This verification checks for issues of the installed projection, which are independent from individual body parameters of test subjects. It is also not restricted to stereoscopic projections. The verification has to be performed only for a new installation.

The set of reference objects should be placed in the region of interest for the distance estimation; this is probably on the road ahead for most driving simulator experiments.

3) Is the convergence angle correct for objects in screen distance?

Verification goal: Make sure, that the convergence angle is correct for at least one location in the relevant field of stereoscopic viewing. A point or object in the virtual world with a distance equivalent to the screen distance d should be projected exactly onto the same point of the screen for both left and right image. An observer should perceive such an object correctly in the distance of the screen.

Method: In the virtual world, a see-through 'fence' of the exact size and location of the (flat or cylindrical) screen with a square pattern on its inner surface ('poles' and 'bars') is placed in front of (or around) the test person; the poles and bars of the fence should not produce any double images on the screen due to the right and left image projection. An observer may check this fact by taking off the stereoscopic glasses. The observer should perceive the fence (in stereo mode) at the same location as the screen (without stereo glasses). See **figure 8** for a possible constellation.

Possible re-calibration method: If there is just a general lateral offset between the two stereo images, the calculated projection of the two images can be shifted by correcting the camera heading angles. For more complex deviations, the projection installation and the warping process needs to be inspected.

Notes: This step verifies the correct relative projection of left and right images in a stereoscopic projection on the screen only. Correct convergence angles at other locations in the virtual world should be assured by a correct 3D to 2D transformation, and size checks as verified with other tests.

This test is only relevant for the stereoscopic viewing angle of the observer without turning the head, i.e., for a similar range as the *panum* (see above). Outside of this range, a different viewing directing for the stereo-projection has to be considered (Schöner and Schmieder, 2016; Schmieder, et al., 2017).

A correct convergence angle for *monoscopic* viewing can only be attained for points located on the projection screen surface; other points have always incorrect convergence angles.

This verification test does not depend on individual body parameters; thus, it has to be performed only for a new installation.

4) Are proportions and size correct for objects in screen distance?

Verification goal: Make sure, that angles as well as the lateral and vertical extent of objects on the screen retain the same as in real world.

Method: Use a virtual 'fence' as in the test before. The square bar pattern of the virtual fence should appear on the screen as squares. A square object of the size s x s in screen distance can be measured on the screen and should have exactly the same vertical and horizontal size s x s in the virtual as in the real world. Pythagoraic triangles are also easy to verify this way. Left and right image should superimpose each other exactly for approximately the range of the

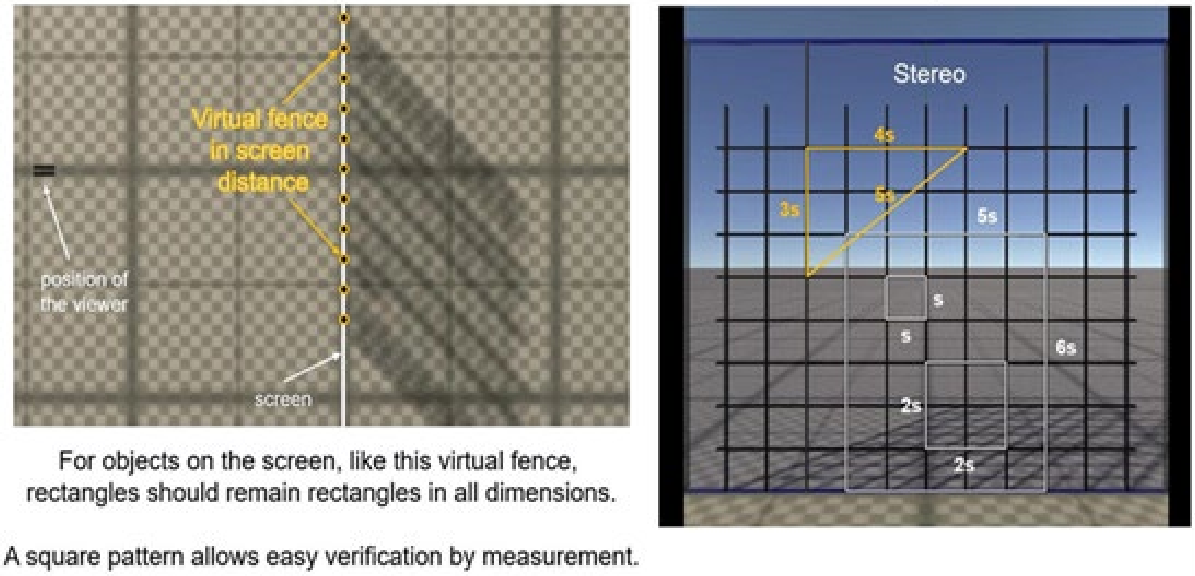


Figure 9: Are proportions and size correct for objects in screen distance?

panum; an observer may check the full overlap of the two pictures when the stereoscopic glasses are shut off or taken off. See **figure 9** for a possible constellation.

Possible re-calibration method: For any deviations within the panum range, the projection installation and the warping process needs to be inspected.

Notes: This verification test does not depend on individual body parameters; thus, it has to be performed only for a new installation.

5) Is the stereoscopic convergence adjusted correctly?

Verification goal: Make sure, that a point (or vertical line) in infinity in the virtual world has a projection on the screen with the right image more to the right than the left image, the distance of the projection points (or vertical lines) being exactly the IPD (equal to the stereoscopic base b). As a result, the eyes of an observer are looking in parallel directions to such a distant point (or vertical line). The observer is expected to perceive an object on the horizon as far outside of the simulator room. The screen itself should turn invisible in stereoscopic mode.

Method: Place distant objects (close to the horizon) in the virtual world, and straight lines on the ground plane from the observer towards the horizon; the objects and projected lines in the two images (viewed without stereoscopic glasses) are inspected and measured with respect to three points:

- Distant objects should have a distance equal to IPD between left and right images, best to verify at objects with distinct vertical lines.

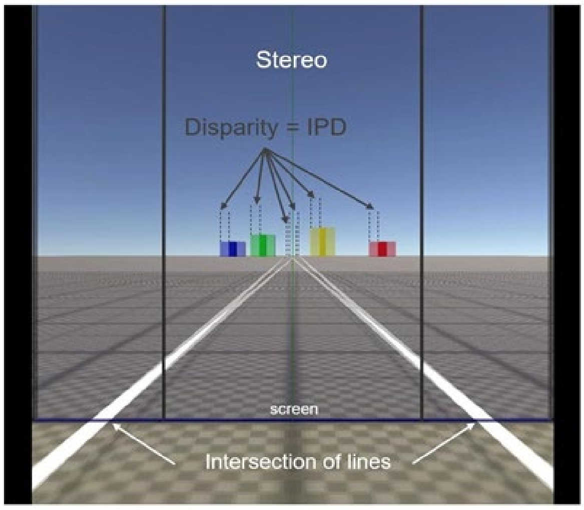


Figure 10: Is the stereoscopic convergence adjusted correctly?

- The lines should cross at screen distance and disappear at the horizon with IPD distance.
- For objects beyond the screen distance, the right image should be farther to the right.

See **figure 10** for a possible constellation.

The observer should experience the expected stereoscopic effects when taking on the stereo glasses:

- an apparent widening of the simulator room,
- a disappearance of the screen position.

Possible re-calibration method: The most frequent reason for incorrect convergence is that the projection eye distance does not match the observer's eye distance. A second reason could be an unintentional interchange of left and right image.

Notes: In addition to testing for correct convergence angle at screen distance (disparity = 0), this test verifies a second projection point of straight lines in the virtual world with disparity = IPD. Both together check the correct calibration of the stereoscopic projection for an individual observer.

Since the interpupillary distance IPD as stereoscopic base for the projection is involved, this test is important for the individual perception of the observer. The verification should be performed for every single participant of a simulator test drive.

Final remarks about the above tests

The importance of a correct stereo base (b=IPD) and eye height (e=v) in the perspective transformation of the projected images (according to the individual values of the finally viewing observer) can be seen from its influence in these simple consistency checks. Some of the verification tests could be done with test persons in place, in order to find out whether all parameters are set correctly. Only two of the tests (#1, #5) depend on individual body measures and should be performed for every single participant of a simulator test drive, prior to starting the drive.

Test #1 actually consists of two parts: The first part verifies that the specified eye-point height is realized with the set-up of the display system and the parameters entered in the image generation process. This part of test #1 has to be performed initially after the system's set-up and it has to be redone from time to time. The second part of the test is to verify, that the actual driver's eye-point position matches the specified simulator's eye-point position, and it has to be performed for every individual driver. The other tests (#2, #3, #4) need to be performed and documented initially for a new installation. They need to be checked and recalibrated from time to time during a regular quality revision of the entire system. Quantitative values for the effect of a false cue due to incorrect calibration can be deduced from geometric analysis of these simple cases via the given formulas.

Expected effects resulting from incorrect distance cues

In general, it can be stated for the accommodation cue (as one example for anticipating the possible results from wrong distance perception cues): in real traffic driving situations, accommodation while focusing a vehicle in front (relevant object distances D are mostly >5m) is close to focusing infinity, with a diopter deficit of accordingly 0.2/m. When focusing on simulator screens, the screen distance d is typically between 0.5m and 5m, equivalent to diopters of 0.2/m up to 2/m. So, the cue to the brain from accommodation to the screen would indicate shorter distances (given all other effects would be correct). That means, subjective distance D_s is expected to be underestimated compared to the objective distance D ($D_s < D$), with stronger under-estimation the closer the screen is placed to the test person.

The missing convergence angle variation of a monoscopic projection should lead to a similar – but even more distinct – effect of underestimation of distance.

Such underestimation of distance should have also consequences for speed perception: Since the time Δt to travel the original distance D in a virtual world is the same as traveling the shorter subjective distance D_s, the subjective speed $v_s = D_s/\Delta t$ is expected to be reduced by the same factor as the perceived distance. However, driving with the goal of keeping the same temporal safety margin should lead (based on this argument) to similarly reduced subjective speeds compared to the real world – although they correspond to the same objective speeds in the virtual world. However, this frontal speed perception should stay inconsistent with lateral speed perception, when at the same time objects passing by in the lateral field of view are perceived with an undistorted angular speed. This is in line with results reported by Correia, et al. (2014).

As a different consequence of underestimated longitudinal distance perception, while driving on a winding road, the curves should appear tighter than in reality. Since in this case the drivers' choice of speed does no longer depend on temporal safety distances, but on a suitable speed for the perceived curve radius. So, drivers are expected to choose a smaller subjective speed than in real world; missing or reduced (lateral and longitudinal) forces might give additional reasons to drive more carefully (i.e., slower) than usually. In total, this might lead to significantly lower produced (objective) speeds.

Solving the quantitative equation for stereoscopic disparity in **figure 4** for object distance D, reveals a strong impact when observing a projected scene with a different IPD compared to the one assumed for the 3D-to-2D transformation. For example, the stereoscopic disparity for an object in 15m distance, correctly projected for an average IPD of 63mm, produces the same distance cue as an object in 10m distance for an observer with an IPD of 78mm, while for an observer with an IPD of 50mm this cue would result from a distance of 103m. And furthermore: objects in very far distance (since they appear on the screen with a disparity of the projection IPD equal to 63mm) would require observers with smaller IPD to use unphysiological negative convergence angles. Such eye divergence does not make sense as a distance cue for such observers. This might explain the unexpected results of experiments with a fixed average projection IPD (Schmieder, et al., 2017).

Results and discussion

The different arguments lead to the observation, that inconsistent distance and speed perception may result from incorrect or incomplete installation, or incorrect operational parameters, depending on the cues the individual driver is using to deduce his behavior in the specific situation. The individual body parameters surely have a significant influence on the perceived distance and speed – in monoscopic as well as in stereoscopic installations. Such parameters need to be adjusted for a precise set-up and dependable scientific evaluation of distance, size and speed perception tasks. Especially the use of an individually adjusted interpupillary distance, IPD, is essential for a correct reproduction of pictorial distance cues in stereoscopic installations.

For this reason, verification of stereoscopy must consider the body parameters of individuals, or at least discuss how much these might have influenced the results. Easy consistency checks and parameter tuning procedures, which might be performed with the individual test person itself, can improve the situation for achieving more consistent and comparable results within in the entire research community in the future. The individual calibration by the test person himself/herself according to his/her individual scene perception might resolve some ethical reservations of collecting body data.

Conclusions

For future quantitative distance and speed perception tasks, the body parameters of test persons should be carefully compensated in the experimental set-up and their correct installation verified by methods like those described above. The paper proposes standard test procedures for verification of correct installations and for correct operational conditions with individual test persons.

It is expected by the authors, that the use of individual body measures for calculation and presentation of stereoscopic projections might resolve a large portion of the previously experienced inconsistencies. Further research on distance perception might focus on *quantitative* theoretical and experimental studies of the specific effects of the single influencing factors discussed in the first part of the paper. The tests proposed in the second part should provide a solid basis for the comparison of results across the entire simulator community.

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