Exploring depth and distance perception in strabismus

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A thesis submitted for the degree of PhD
at the
University of St Andrews

2019

Identifier to use to cite or link to this thesis:

DOI: https://doi.org/10.17630/10023-18959

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General acknowledgements

I would like to thank my supervisor, Dr Dhanraj Vishwanath, for his guidance and support throughout my PhD research and the preparation of this thesis. It was his exceptional supervision during my undergraduate project and his innovative approach to vision research, which inspired me to begin my PhD. Thank you for this opportunity and a number of honest conversations that have helped me to grow not only as a researcher, but also as a human being. I am very grateful to Verity Brown and David Tait, for employing me as a research inter after my second year of undergraduate studies and laying the foundation to my interest in academia.

The end of my PhD research also marks the end of 10 years of being with the School of Psychology and Neuroscience. Thank you everyone for your encouragement and infective enthusiasm. The School quiz nights, chats after Friday seminars, Ines Jentzsch at psycholoquias, and garden parties all will be well remembered. I would like to give special thanks to the technicians and the administration office, who are the heart of this school. Karen, Toni, Helen, Mary, Shona, Roy, Brian, Mike and Keith thank you for helping me to solve issues as they come along in a cheery way.

I would like to thank everyone in the Vision Lab group, for their insights, comments, and support. Particularly Andrew Mackenzie, Phil Cammack, David Hunter, Justin Ales, Olivier Penacchio and Marlene Poncet, who always found time to listen about my research and who gave me invaluable advice. I am very grateful to all of the PhD students who were there with me at the start of my PhD, as well as at the end. Thank you Jennie, Bobby, Benjamin, Alonzo, Sonny, Charles, Fraser, Antonio, Arin, Mizuki and Francesca.

I am incredibly grateful to Dr Kenneth Scott-Brown for not only being an amazing collaborator, but also for inviting me to give guest lectures to both undergraduate and postgraduate students at the Abertay University.

I would like to thank my family for always pushing me to achieve more than I would dream, and supporting me along the way. Aciu! Thank you to Adam and Fiona Brooks, and particularly Elliott for helping me to survive the birth of this thesis. I am very grateful to the Ritchies, especially Barbara and Aikmans, Lauren Biermann, Olia Generalova, Tamara Kosikova, Jonathan Jouty, Marjorie Gourlay and all the other unnamed people, who reminded me to have a life outside PhD.

Funding

This work was supported by the Engineering and Physical Sciences Research Council [grant number EP/M506631/1].

Research Data/Digital Outputs access statement

Research data underpinning this thesis are available at https://doi.org/10.17630/dd47de98-b469-42c4-b3de-d0cf733158f6

Abstract

Strabismus can be defined as the inability to coordinate the eye muscles that ordinarily fixate the two eyes on a single target, resulting in lack of a single binocular vision. Strabismus as a disorder has been known since the times of Hippocrates. However, the exact extent of the limitations in depth and distance perception in strabismic individuals with limited or no binocular stereovision in comparison to typically developed binocular individuals remains unclear. This thesis aimed to explore differences in depth perception between strabismic and non-strabismic individuals by examining qualitative aspects of depth perception, egocentric distance perception, and relative depth perception. These aspects were examined by conducting two experiments for each. The first two experiments revealed that feeling of immersive and tangible depth (a.k.a. stereopsis) is not uniquely linked to binocular disparities and may be experienced by individuals with varying levels of binocular stereovision under monocular aperture viewing (evoking monocular stereopsis). The next two experiments explored egocentric distance perception by measuring familiar object size judgments (as a proxy for distance perception) under monocular, binocular, and stereoscopic viewing. All subjects made similar size judgments under all viewing conditions. The last two experiments showed that observers with no/limited stereovision do not have deficits in the perception of relative depth from perspective cues. They showed similar levels of susceptibility and capacity to make depth judgements from the perspective cue to those of stereonormal individuals. The results of this thesis add systematic insight into understanding the way individuals with strabismus perceive depth and distance in comparison to typically developed binocular individuals. Overall, it suggests that there are more similarities between these two groups in the perception of 3D space than suggested by anecdotal reports and conjecture. This emphasizes the need for further systematic exploration to determine the specific limitations strabismics face whilst performing everyday tasks.

Contents

Chapter 1

General introduction

1.1. Strabismus

Strabismus, derived from the Greek word strabizein, meaning to strabismus, (Online Etymology Dictionary) can be defined as the inability to coordinate the eye muscles that ordinarily fixate the two eyes on a single target (Schiffman, 2001). Strabismus, as a disorder of eye position and its movements, was mentioned by Hippocrates in approximately 480 BC alongside amblyopia (a term for diminished visual acuity, from the Greek for “dull vision”) (Loudon & Simonsz, 2005). Immediately focus was placed on treating strabismus, as the Greeks considered strabismus to be a symptom of other bodily illnesses, while during the Byzantine Empire the first known treatment aimed to realign strabismic eye took place (Loudon & Simonsz, 2005). The first recorded description of occlusion therapy to treat strabismus appeared in the work of Arab scientist Thabit ibn Qurrah ibn Marwan al-Harrani (836-901): "Strabismus should be treated by patching the normal eye. Once you do that the visual power will go in its entirety to the deviating eye and vision in that eye will return to normal. You should not release the normal eye until the vision in the strabismic eye has completely returned to normal" (Loudon & Simonsz, 2005). While advances in understanding the role of ocular muscles in strabismus led to the development of surgical treatments in the XIX Century, the occlusion therapy was reintroduced during the first of half of the XX century and remains to be the prime treatment of amblyopia and strabismic amblyopia to the current day (Loudon & Simonsz, 2005; Rutstein et al., 2011; von Noorden & Campos, 2002; Wright, Spiegel, & Thompson, 2006).

It is quite a common disorder, as about five percent of the adult population are diagnosed with it (von Bartheld, Croes, & Johnson, 2010; Wright et al., 2006). There are a number of syndromes and conditions associated with strabismus, however, in all cases it is a result of damages to the extra-ocular eye muscles or aberrant innervation of these muscles (Motley, 2018; von Bartheld et al., 2010; Wright et al., 2006). Overall, there are six extra-ocular eye muscles, each of which is responsible for a different eye movement (Motley, 2018; Wright et al., 2006). Thus, if any of the six extra-ocular eye muscles is damaged or ineffectively innervated, it will manifest in a corresponding misalignment between eyes, i.e., a misalignment of the eyes may occur in the horizontal or vertical direction, or along a torsional axis (Motley, 2018; von Bartheld et al., 2010). Based on the way the various causes and associated visual impairments manifest themselves, strabismus is classified into many different types and subtypes.

1.1.1. Types of strabismus

The foremost classification of strabismus is based on the visual system's ability to bring the two eyes into alignment when they are intended to focus on a single point in a three-dimensional (3D) space – motor fusion (von Noorden & Campos, 2002; Wright et al., 2006). The first type of strabismus, known as heterotropia or simply tropia, is a manifest strabismus, which is evident under normal everyday viewing conditions, because in this case, even though both eyes are intended to focus on a single point, due to a number of different possible causes, the eyes are still misaligned (Motley, 2018). The second type, known as heterophoria or simply phoria, is a latent strabismus, which is a tendency for the eyes to become misaligned when they are in a resting state (i.e., are closed), but when both eyes are working (i.e., neither of them is closed) motor fusion is used to maintain proper alignment and focus on a single point in space (Motley, 2018; von Noorden & Campos, 2002; Wright et al., 2006). Large angle phorias (i.e., large deviation) over time can develop into tropias, if extra-ocular eye muscle strength is inadequate to maintain alignment, or visual stimulus is weak (e.g. blurred vision due to astigmatism), or there is a problem with the neurological pathway (Motley, 2018; von Bartheld et al., 2010; Wright et al., 2006). However, orthophoria, i.e., an ideal condition of balance of the ocular muscles resulting in perfect eye alignment even when the eyes are in a resting state, is rarely seen clinically and a small phoria is normal (von Noorden & Campos, 2002; Wright et al., 2006). Therefore, commonly only heterotropia is considered to be a disorder that requires treatment or monitoring. As a result of which, in North America the term strabismus is used as a synonym to the term heterotropia. However, in the United Kingdom the term strabismus refers to both heterotropia and heterophoria, the specific NHS term for heterotropia being a strabismus (NHS Choices; von Bartheld et al., 2010; von Noorden & Campos, 2002).

Secondly, strabismus can be classified into three different types depending on the age of onset. The first type is congenital strabismus, which is linked with pregnancy traumas and genetic, developmental or acquired syndromes, such as Down syndrome or Fetal alcohol syndrome (von Bartheld et al., 2010). The second type is infantile or early childhood strabismus, which is the most common type, as, usually, strabismus develops in children under the age of five, whose visual system is unable to maintain the eyes alignment, often, due to untreated visual impairments in one of the eyes, such as hyperopia (far-sightedness) (Motley, 2018; von Bartheld et al., 2010; Wright et al., 2006). The final type of strabismus, also known as acquired strabismus, typically happens later on in life, commonly, due to a direct damage of the extra-ocular eye muscles or head traumas resulting in neurological damage (von Bartheld et al., 2010; Wright et al., 2006).

Strabismus can be classified further based upon the differences in manifestations, which are linked to its cause being either direct damage of an extra-ocular muscle, or aberrant neurological pathway controlling the muscles. Orthoptists investigate this using cardinal gaze positions, as each of them is controlled by a different pair of muscles, according to the Hering's Law, called Yoke muscles, shown in Figure 1.1 part A (von Noorden & Campos, 2002). If one of the extra-ocular eye muscles lacks innervation or is paralysed, the angle of deviation will depend on the direction of gaze, i.e. misalignment will be noticeable only in the gaze positions that involve the paralysed extra-ocular eye muscle, as it is shown in the example in the Figure 1.1 part B (von Noorden & Campos, 2002; Wright et al., 2006). This type of strabismus is called incomitant (paralytic) strabismus, while in the case of (con)comitant (non-paralytic) strabismus the deviations are the same in all directions of gaze, as it is not caused by an extra-ocular muscle paralysis or neurological problems, but rather is found in most types of infantile or early childhood strabismus (von Noorden & Campos, 2002; Wright et al., 2006). Additionally, strabismus can be identified as constant, in this case the deviation is present under any circumstances and all the time, or intermittent, when the deviation manifests only at certain times, when a person is tired, ill, or in particular test situations that break the motor fusion between the two eyes, or requires fixation at the near or far viewing distance (Motley, 2018; von Noorden & Campos, 2002).

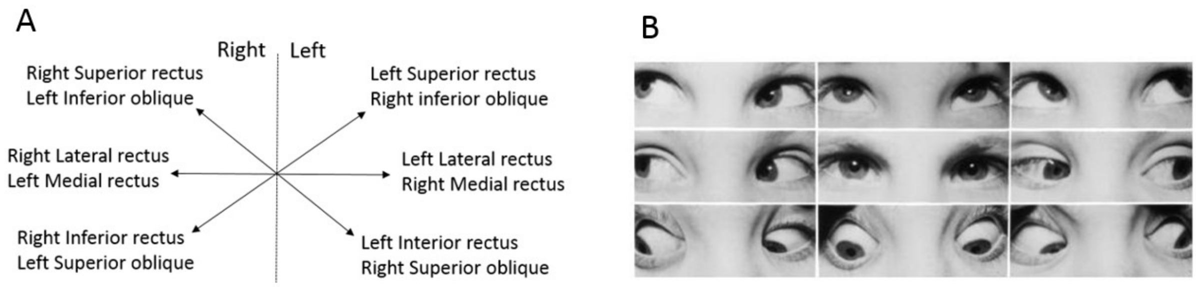


Figure 1.1. The cardinal gaze positions. A) Yoke muscles linked to each of the six cardinal gaze positions. B) An example of a patient's eyes observed under the cardinal gaze positions, revealing left inferior oblique paralysis in the top left photograph (Reprinted from Binocular vision and ocular motility: theory and management of strabismus, 6th edition, van Noorden & Campos, p 432, Mosby (2002), with permission from Elsevier).

Both tropias and phorias can be distinguished into subtypes based on the direction an eye deviates or has a tendency to deviate when covered. Typically this is identified using a Cover test for heterotropias and a Cover-Uncover test for heterphorias (see Figure 1.2 Panel A and B respectively). During the Cover test a patient is asked to fixate on an object, firstly at a near distance of about 30cm (Near Cover Test), then at a distance of about 6m away (Distance Cover Test), and one eye is observed while the other eye is covered (Motley, 2018; von Bartheld et al., 2010). If there is a small angle tropia, when the dominant eye is covered there will be a noticeable movement in the misaligned eye as it will be forced to correct its position in order to fixate on the intended point in space. Consequently, if there is no deviation in the observed eye there are no tropias. If the eye moves outwards, inwards, downwards or upwards to fixate there is esotropia, exotropia, hypertropia or hypotropia, respectively (see Figure 1.2 Panel A). By convention, vertical deviation is referred to as either right or left eye hyper/hypotropia (Wright et al., 2006). In the Cover-Uncover test we also try to detect any corrective movement in the eye that has phoria, only in this case are we observing the eye that was covered, because if there is a tendency for an eye to be misaligned in a resting state once we remove the cover and force it to fixate again there should be a noticeable movement as the eye's position is corrected. Thus, in the Cover-Uncover test, as in the Cover test, if there are no deviations, there are no phorias. If the observed eye moves outwards, inwards, downwards, or upwards to fixate, there is esophoria, exophoria, hyperphoria, or hypophoria, respectively (see Figure 1.2 Panel B). Both tests are used for both tropias and phorias in order to accurately determine the deviations, for instance, the Cover test can be used to determine dissociated vertical deviations in phorias. If the Cover-Uncover test reveals that an individual has both heterotropia and heterophoria, it is classified as either exodeviation or esodeviation based on the direction of the corrective eye movements (von Noorden & Campos, 2002).

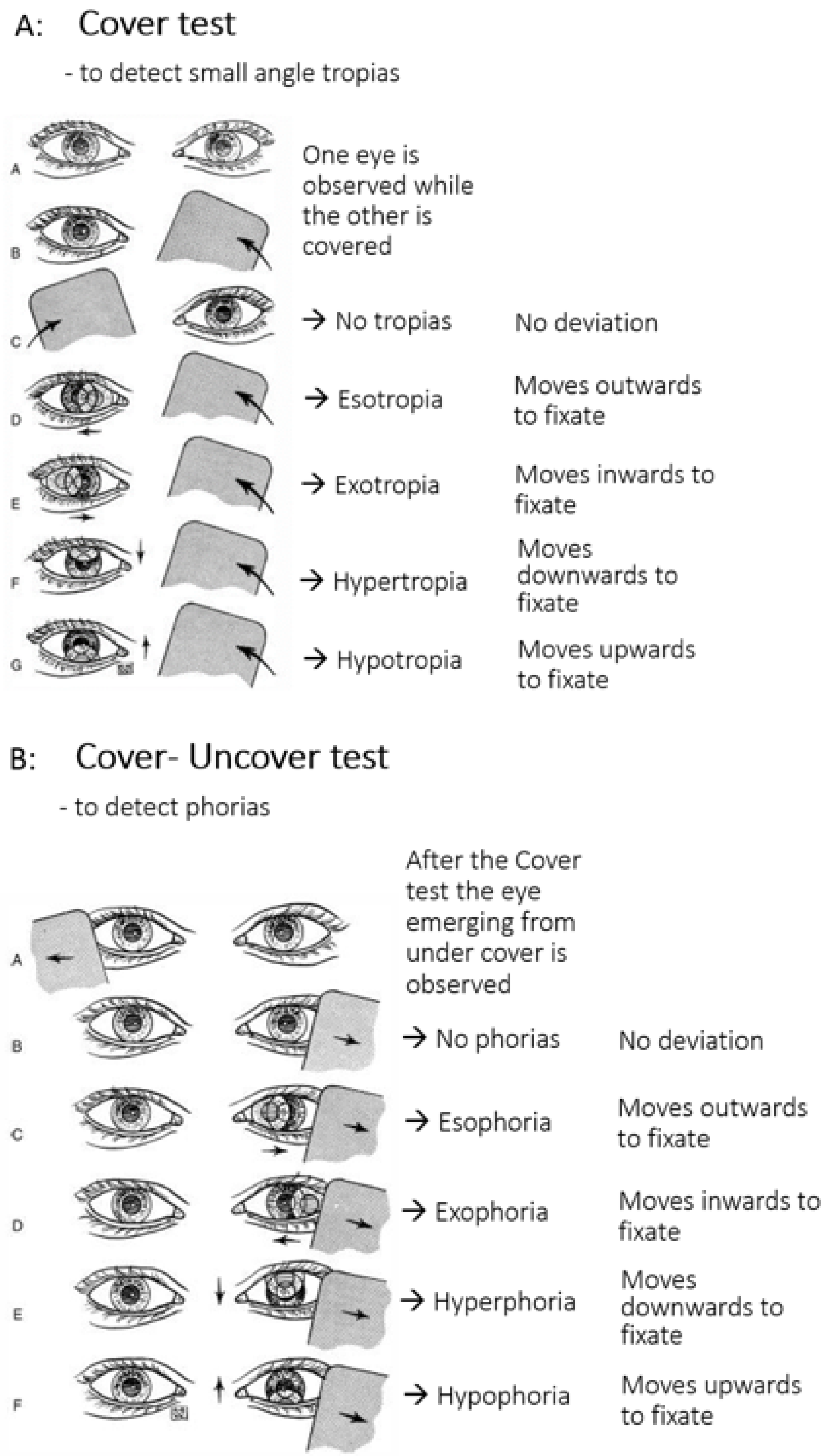


Figure 1.2. Illustrations of Cover (Panel A) and Cover-Uncover (Panel B) diagnostic tests (Reprinted from Binocular vision and ocular motility: theory and management of strabismus, 6th edition, van Noorden & Campos, pp 174-175, Mosby (2002), with permission from Elsevier).

Lastly, strabismus is frequently observed with the presence of amblyopia, which according to Hess and Daw (2010) is defined as “a loss of visual acuity of three lines or more on a clinical letter chart that is not optically correctable or is not due to an opthalmoscopically observable pathological cause”. However, amblyopia, similar to strabismus, is caused by a number of conditions. Roughly a third of all amblyopes are strabismic amblyopes, a third are anisometropic amblyopes (caused by unequal refractive power), a third are the combination of the prior two (Hess & Daw, 2010), and a relatively small number of cases are stimulus deprivation amblyopes. It is considered to develop during the critical period, i.e. up to the age of seven, during which the blurred image affects neurological development, and leads to the constant cortical suppression of the amblyopic eye (Hess & Daw, 2010; Wright et al., 2006). Strabismic amblyopia is largely associated with infantile esotropia, as it occurs in approximately 50% of patients with infantile esotropia (von Noorden & Campos, 2002; Wright et al., 2006). This high prevalence is due to the early onset of esodeviations which usually manifest in constant tropias, thus affecting binocular vision development during infancy or early childhood. In contrast, exodeviations are usually acquired or intermittent, and thus do not have a large influence on binocular vision development and are rarely associated with amblyopia (von Noorden & Campos, 2002; Wright et al., 2006).

1.1.2. Perceptual implications of strabismus

Strabismus disrupts sensory fusion - the cortical process of joining the images from the two eyes into a single binocular image (von Bartheld et al., 2010; von Noorden & Campos, 2002; Wright et al., 2006). This fusion starts in the chiasm where optic nerve fibers from the two eyes join to then project to the lateral geniculate nucleus and then on the striate cortex (von Noorden & Campos, 2002; Wright et al., 2006). Within the striate cortex there are binocular cortical cells, and when a person has accurate eye alignment corresponding retinal points project on the same binocular cortical cells (Wright et al., 2006). However, when the eyes are misaligned, and motor fusion is disrupted, the retinal points reaching the binocular cortical cells do not correspond, thus affecting sensory fusion (Hubel & Wiesel, 1965; Motley, 2018; von Noorden & Campos, 2002; Wright et al., 2006). The main ensuing perceptual implications are lack of single vision, and lack of binocular depth perception.

In the case of strabismic amblyopia there are additional perceptual implications, such as crowding (letters presented together are harder to discriminate than isolated letters), deficits in contrast detection, spatial uncertainty, impaired visual acuity, and impaired binocular stereovision (Hess & Daw, 2010; Levi, Knill, & Bavelier, 2015). The key characteristic of all types of amblyopia is the cortical suppression of the amblyopic eye, leading to individuals with this condition being effectively monocular under binocular viewing conditions (Hess & Daw, 2010; Wright et al., 2006). On the other hand, recent research has shown that amblyopia is highly responsive to stereo training (e.g. using virtual reality headsets), and adult amblyopes can recover not only visual acuity but also at least partial stereopsis (Cleary, Moody, Buchanan, Stewart, & Dutton, 2009; Ding & Levi, 2011; Levi et al., 2015; Li et al., 2015; Vedamurthy et al., 2015). Implications of amblyopia are limited to a subset of individuals with strabismus, and thus will not be discussed in detail in this dissertation. An overview of amblyopia is provided by Hess and Daw (2010), while the binocular stereoacuity and stereopsis in amblyopia is discussed in a mini-review by Levi et al. (2015).

1.1.2.1. Diplopia

Lack of a single vision, which is double vision, also known as diplopia, usually is a symptom of acquired strabismus, which onsets after the age of eight due to direct damage of the extra-ocular eye muscles or neurological pathways (von Bartheld et al., 2010; Wright et al., 2006). In this case a visual system of a typically developed binocular individual is damaged and eyes become misaligned, thus receiving information from different points in space, however, the brain continues to process it as retrieved from the same direction and location in space (Motley, 2018). On the other hand, if strabismus is congenital or manifests in early childhood (before the age of nine), the human visual system finds ways of adapting and avoiding the ambiguity of diplopia. The visual system starts depending on the eye that seems to provide the most reliable information, i.e., that is able to focus on the intended point in space, or has higher visual acuity, which then becomes the dominant eye. Consequently, early childhood and congenital strabismus often results in the cortical suppression, when the information from the non-dominant eye is "suppressed" or "ignored" while both eyes are looking (binocular viewing conditions). This results in amblyopia, when overall visual acuity of the non-dominant eye decreases and provides a "poorer quality" image while both eyes are looking as well as while a person is looking only with the non-dominant eyes (binocular viewing conditions and monocular viewing conditions, respectively) (Motley, 2018; Wright et al., 2006). If infantile and early childhood strabismus is constant, in avoidance of diplopia, the visual system frequently develops anomalous retinal correspondence (ARC), when in binocular viewing conditions the fovea of the dominant eye is associated with an extrafoveal area of the non-dominant eye (Verhoeff, 1902; von Noorden & Campos, 2002). The development of the ARC has been observed as early as 1902, further noting that after strabismus alignment surgery individuals loose the single binocular vision and can only obtain it again by using prisms to reinstate the corrected misalignment (Verhoeff, 1902). In rarer cases, when the misaligned eye has severe amblyopia, an extrafoveal retinal area may be used as a "new" fovea for fixation in monocular viewing, which is known as development of eccentric fixation (Motley, 2018; von Noorden & Campos, 2002). To date majority of research on strabismus has been aimed at exploring these deficits and their possible medical treatments as well as therapies for preventing them, e.g. substituting therapy where the dominant eye is patched with therapies using modern visual technology that provides different property images to the two misaligned eyes (Cleary et al., 2009; Giaschi, Chapman, Meier, Narasimhan, & Regan, 2015; Li et al., 2015; Loudon & Simonsz, 2005; Rutstein et al., 2011; von Noorden & Campos, 2002; Wright et al., 2006).

1.1.2.2. Binocular depth perception

In order to understand more fully the second perceptual implication – lack of binocular depth perception – it is important to consider what viewing 3D space with two eyes provides us. Human eyes are separated laterally by an average of 6.5 cm, due to which the images falling on the two retinas are received from slightly different angles and thus there are slight differences between them (von Noorden & Campos, 2002; Wright et al., 2006). Therefore, when both eyes focus on a single point of an object, that point falls on the foveas of the two eyes, but other points and features of that object, which are either in front or behind the focus point, fall at slightly different distances from the respective foveas of the two eyes (Ponce & Born, 2008). The small difference between these distances for the corresponding features in the two retinal images are called binocular disparities, which are the information used to derive binocular depth (DeAngelis, 2000; Hubel & Wiesel, 1965; Ponce & Born, 2008; von Noorden & Campos, 2002). These binocular disparities are considered to provide the most precise information about depth, as well as give rise to a unique sensation of depth called stereopsis (Ogle, 1950; Ponce & Born, 2008; von Noorden & Campos, 2002). According to this standard binocular stereopsis theory individuals who have misaligned eyes and thus cannot obtain visual information from binocular disparities, do not only lack the precision of binocular depth perception, but also lack this unique sensation of stereopsis that can only emerge through vision with both eyes (Ogle, 1950; Wright et al., 2006). In fact, studies have shown that individuals' performance in such tasks as bead threading and peg placing is related to levels of binocular stereopsis, measured using ophthalmological stereoacuity tests (O'Connor, Birch, Anderson, &

Draper, 2010; O'Connor, Birch, Anderson, Draper, & Group, 2010; Piano & O'Connor, 2013). Moreover, critical period theory suggests that stereopsis can be developed or recovered only during a critical period of infancy and early childhood (up to about the age of 4 and a half years) and thus individuals with infantile strabismus, who were not treated in early childhood (up to that age), should not be able to experience stereopsis even if they recovered perfect eye alignment and binocular depth perception later on in life (Hubel & Wiesel, 1965; Sherry, Wang, & Birch, 2005; Wright et al., 2006). This view is widely acknowledge and development or restoration of motor fusion is seen as being the main goal of majority of research on strabismus (Read, 2015; Rutstein et al., 2011; von Noorden & Campos, 2002; Wright et al., 2006). However, research on the way individuals with strabismus or history of strabismus experience depth and space around them is limited.

1.1.3. Research on depth perception in strabismus

Up to the end of the XX century, research exploring depth perception in individuals with strabismus was aimed at quantifying the deficit of this disorder. For instance, a study by Henson and Williams (1980) measured monocular and binocular depth thresholds of control and strabismic individuals using a modified Howard-Dolman apparatus (Figure 1.3) and found that while monocular depth thresholds in strabismics and controls were the same, binocular depth thresholds were slightly higher among participants with small angle strabismus and high visual acuity in both eyes. A different aspect of vision was tackled by Sireteanu and Fronius (1989) who looked at retinal correspondence among individuals with strabismus and found that in the areas of peripheral vision there were larger corresponding areas allowing the visual system to overcome small angle misalignments, and thus suggesting possible binocular stereoscopic vision in the periphery.

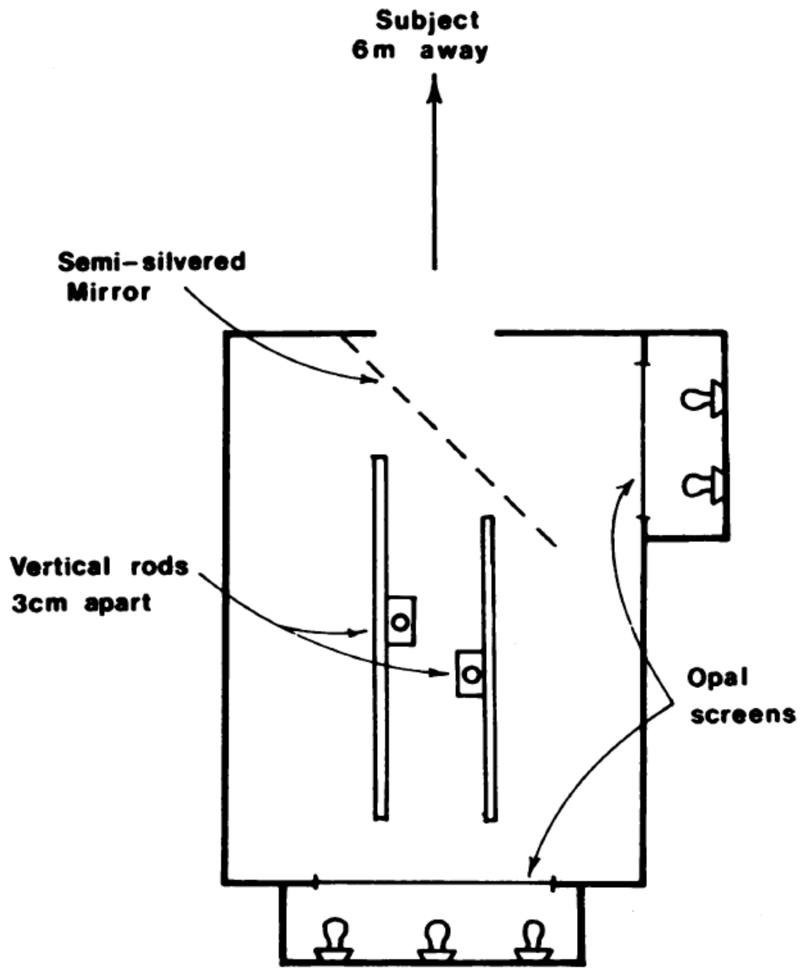


Figure 1.3. Diagram of the modified Howard-Dolman apparatus used by Henson and Williams (1980). A semi-silvered (half-silvered) mirror was placed between the viewing aperture and the rods (9.5mm in diameter). The half-silvered mirror reflected the light from the side opal screen and transmitted the light from the back opal screen. The lights behind the opal panels were switched on one at the time. The side panel with a fixation cross aligned with a centre of the right rod was used at the start of the trial, as a fixation point. Then the side panel lights would switch off and the lights behind the back opal panel would come on for a duration of 2 seconds, allowing the subject to see the two vertical black rods.

Interest in the topic has been regained after (anecdotal) reports at the beginning of the XXI century, the most famous of which is the case of Susan Barry, also known as Stereo-Sue, who had congenital esotropia but subsequently recovered eye alignment and binocular depth perception in her 40s (Barry, 2009). She describes the way she experienced things around her after recovering binocular depth perception in her book: “As I looked up to adjust the rear-view mirror, the mirror popped out at me, floating in front of the windshield”; “sink faucets popped out toward me…”; “I felt palpable volumes of empty space…I could see, not just infer, the volume of space between three limbs”; “ Objects seemed more solid, vibrant, and real” (Barry, 2009). These descriptions suggest that her depth perception considerably improved and that she was able to experience stereopsis. Currently, this and other anecdotal reports are the main source of knowledge about the ways individuals with strabismus experience depth and function in everyday life.

However, in recent years, researchers worldwide are regaining their interest in strabismus and have started investigating more qualitative aspects of strabismics’ depth perception, including the way it affects their motor performance. The research by Tidbury, Black, and O'Connor (2014) was prompted by anecdotal reports of individuals without stereovision (stereoblind) reporting compelling depth effects when watching 3D movies. They recruited participants who did not have clinically measurable stereovision (stereoblind) and asked them at the near distance to estimate the order of 4 highlighted objects in depth (handheld Nintendo 3DS computer game) and at the far distance rate the amount of depth they perceived in the displayed videos (3D TV). The seven stereoblind subjects, who took part in this study (five of which had strabismus), were found to report the correct order of the highlighted objects up to 55% of the time in the near distance task, and on average indicate that the 3D videos provided ‘a very obvious 3D effect that compels interaction’ in the far distance task, revealing a discrepancy between the clinical stereotests and 3D entertainment accessibility (Tidbury, Black, & O'Connor, 2014). A follow-up study by Tidbury, Black, and O'Connor (2015) tested 57 participants with measurable binocular stereovision using the same Nintendo 3DS game, 3DTV video and static tasks. The level of binocular stereoacuity was varied using lenses, which decreased visual acuity in the non-dominant eye from the normal viewing (no lens used to create blur) to visual acuity decreased by 3 lines, by 6 lines, or full suppression. Overall, the findings showed that decreasing visual acuity in the non-dominant eye (by introducing monocular blur) decreased perception of depth, while in the case of full suppression of the vision in the non-dominant eye subjects' performance was at chance (Tidbury et al., 2015).

The importance of binocular visual information and binocular stereoacuity has also been shown in motor skill tasks (O'Connor, Birch, Anderson, & Draper, 2010; O'Connor, Birch, Anderson, Draper, et al., 2010). Two studies tested motor skill performance of teenagers and young adults (12 to 28 years of age) with reduced or no clinically measurable binocular stereovision (O'Connor, Birch, Anderson, & Draper, 2010; O'Connor, Birch, Anderson, Draper, et al., 2010). Participants were asked to place pins in a vertical column of holes on a board in 30 seconds (Purdue Pegboard task), to place 30 large and 22 small beads on a needle (Bead task), and to pour water from a jug into 5 measuring cylinders set in fixed positions up to 90 millimetre line (Water pouring). In the first experiment the results were analysed in relation to the motor fusion (mechanism allowing fine-tuning of eye position to maintain eye alignment) (O'Connor, Birch, Anderson, & Draper, 2010), while in the second experiment the motor task performance was analysed in relation of clinically measurable binocular stereovision (O'Connor, Birch, Anderson, Draper, et al., 2010). In the Purdue Pegboard and Bead tasks, performance was significantly better in subjects with sensory and motor fusion than those without, while there was no significant difference in the water pouring task. However, the group with no clinically measurable binocular stereovision was faster under binocular viewing than group with normal binocular stereovision under monocular viewing of the Bead task (O'Connor, Birch, Anderson, Draper, et al., 2010). Overall, these studies found that motor skill performance was related to binocular stereovision and motor fusion, but varied between tasks, according to the task difficulty (e.g. small vs. large Bead threading task), and level of stereovision (O'Connor, Birch, Anderson, & Draper, 2010; O'Connor, Birch, Anderson, Draper, et al., 2010; Piano & O'Connor, 2013). Bloch, Uddin, Gannon, Rantell, and Jain (2015) explored strabismics' performance in a fine motor tasks under different viewing conditions. They (Bloch et al., 2015) recruited 45 participants, a third of whom were stereoblind individuals with strabismus, and asked them to perform a limited invasiveness surgical training task (placing plastic balls on different height columns using laparoscopic graspers; task performance was a number of balls placed in 50s) while viewing it in real space (3D) or on a monitor (2D), each condition repeated binocularly and monocularly. The study (Bloch et al., 2015) found that even though in 3D viewing condition, for both viewing the task binocularly and monocularly, the controls performed better than strabismic participants (mean difference 3.03 balls, $p<0.001$, and 1.43, $p=0.018$, respectively), in the monitor viewing condition for binocular and monocular conditions strabismics performed at a same level as controls (mean difference 0.29, $p=0.579$), which indicates that strabismic individuals in monitor viewing conditions are able to perform high spatial complexity tasks at the same level as typically developed binocular individuals. Niechwiej-Szwedo, Goltz, Chandrakumar, and Wong (2014) tested reaching to touch movements in 16 adults with strabismic amblyopia, 14 adults only with strabismus, and 16 visually normal adults. Participants were presented a white circle (0.5º visual angle) at one of the four locations (±5º or ±10º from fixation) on a black background, and were asked to reach to the target as fast and accurately as possible. The task was performed under three viewing conditions: binocular, amblyopic eye (non-dominant eye), and non-amblyopic eye (dominant eye for the control subjects). Even though, under amblyopic (non-dominant) eye viewing strabismic individuals performed significantly slower (by more than 30ms) and showed larger variability in reach precision than controls, performance of strabismics was comparable to typically developed binocular individuals under binocular and non-amblyopic (dominant) eye viewings (Niechwiej-Szwedo et al., 2014). Lastly, the study by

Ooi and He (2015) explored strabismics' visuo-motor performance using a blind walking task. The task required participants to stand at the end of a corridor, as steady as possible, and look at a target object (a sphere), placed either on the floor or suspended in the air at two different heights (30cm and 90cm above the floor), from various viewing distances (2.73-6.93m), then the experimenters covered participants' eyes and asked them to walk the distance they perceived the object was placed at and to gesture the height at which it was displayed (Ooi & He, 2015). Eight control stereonormal and eight strabismic individuals were tested under monocular (dominant eye) and binocular viewing conditions, and it was found that both groups in both viewing conditions accurately judged the distance to the target placed on the floor. However, when the sphere was suspended mid-air participants with strabismus in both binocular and monocular viewing conditions erroneously judged the target's location making larger localization error in monocular viewing condition, while the control participants made erroneous judgments only in monocular viewing condition and performed accurately under binocular viewing (Ooi & He, 2015). Using further analysis, this study (Ooi & He, 2015) found that the target localization error positively correlated with stereovision in binocular viewing but not in monocular viewing condition (r^2=0.479, $p<0.005$, and r^2=0.0002, p=0.963, respectively).

Overall, research up to this point shows that monocular depth perception in individuals with strabismus is comparable to that of typically developed binocular individuals. But more importantly, it also suggests that individuals with strabismus may experience depth in some cases better than in other, as there are many different mechanisms involved in depth perception. To understand the latter point we need to better understand depth perception itself.

1.2. Depth and distance perception

Depth perception can be defined as the ability to judge the distance of objects and the spatial relationship among objects at different distances, i.e., the ability to see how far away something is or how much space is between things (Sekuler & Blake, 1994). The initial part of these definitions refer to egocentric distance, which is the distance from an observer to an object, while the latter part of these definitions refer to depth, which is the distance between one object and another or between different parts of a single object (Loomis, da Silva, Philbeck, & Fukusima, 1996). A further distinction is between relative and absolute depth perception. While in the relative depth case, the viewer is able to perceive only the proportional differences and relative depth relations in a 3D scene he/she is looking at, absolute depth perception allows the viewer to know actual sizes and depth values in the 3D scene (Glennerster, Rogers, & Bradshaw, 1996; Vishwanath, 2014). This division is illustrated in Figure 1.4.

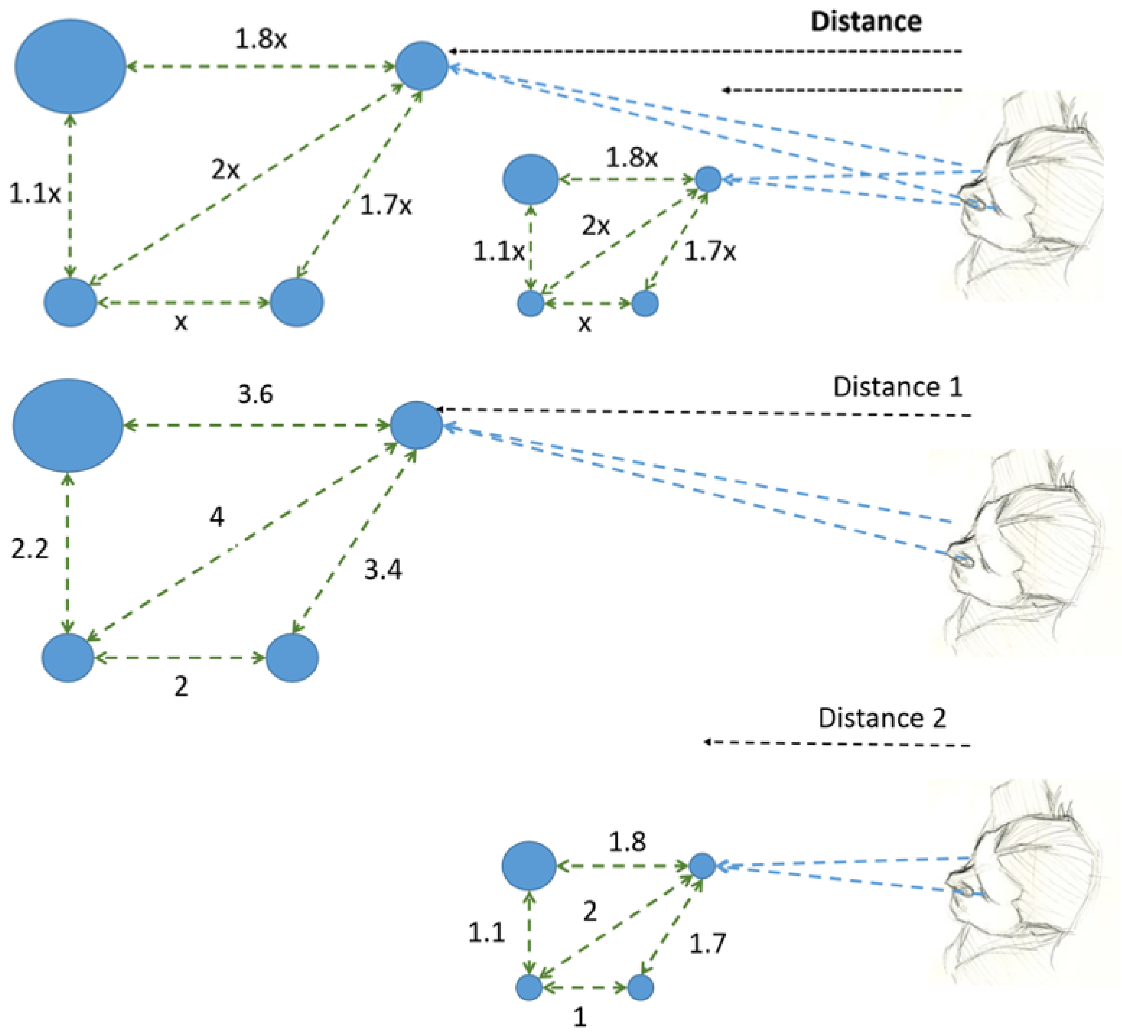


Figure 1.4. An observer looking at an arrangement of objects can perceive either relative (top panel) or absolute (lower two panels) depth, which depends if the observer can perceive the egocentric distance to the object he/she is focusing on (in the image marked as distance; line of sight marked with converging lines). Top panel: the egocentric distance to the object in focus is unknown, thus only relative depth is perceived. The observer can tell the magnitudes of depth between the objects (e.g. 2x is twice longer than x), but the exact values are unknown. In this case the observer could perceive same relative depth ratios from two different size arrangement of objects, i.e. the smaller one viewed from a closer distance, and the larger one viewed from further away, would elicit identical relative depth. Lower panels: the observer perceives egocentric distance to the object they are focusing on and thus is able to perceive absolute depth values. In this example distance 1 is twice of distance 2, thus the perceived absolute depth in the two arrangements differ, i.e. the depth values in the larger arrangement viewed from distance 1 are double of those in the smaller arrangement viewed from distance 2.

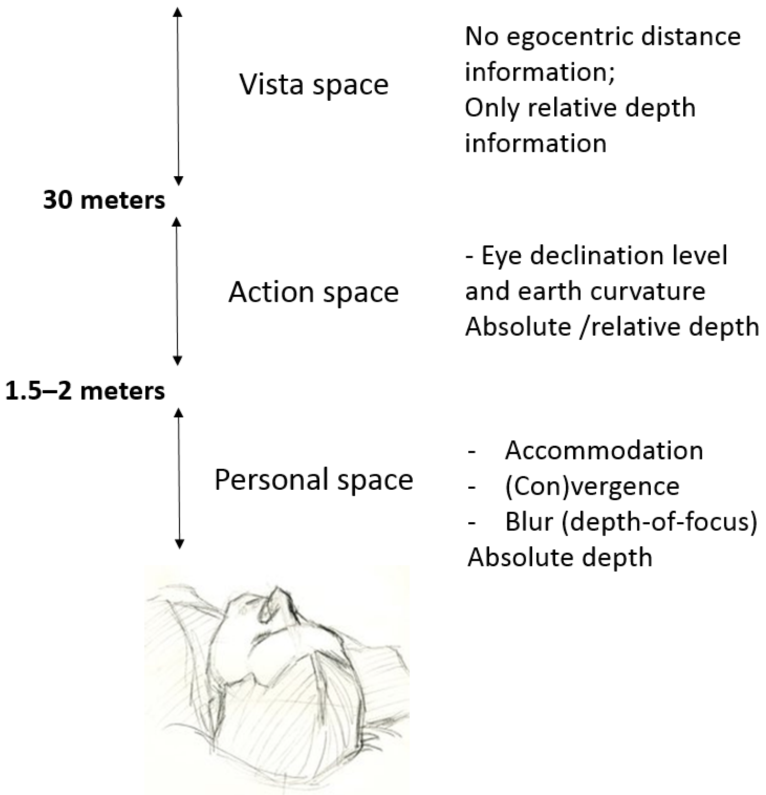


Figure 1.5. Separation of the 3-D space around a viewer according to Cutting (2003), and the available egocentric distance information for each of the three spaces. The Personal space – the closest to the viewer, extending a little beyond arm's reach; egocentric distance information available from accommodation, (con)vergence, and depth-of-focus blur, thus allowing absolute depth perception. The Action space – beyond direct reach, but space one can interact with by, for instance, throwing objects; egocentric distance information available from eye-declination level and earth curvature, which under full viewing conditions allow absolute depth perception. The Vista space – beyond possible interaction; does not have egocentric distance information, thus only relative depth perception is available.

1.2.1. Egocentric distance

A number of cues have been found to provide information about the distance from an observer to a point in space he/she is fixating on, a.k.a. egocentric distance (Loomis et al., 1996). However, the reliability and precision of these cues vary with the distance. Cutting (2003) has discussed the decrease of the available distance information by separating the 3-

dimensional space around us into a personal space (space a little beyond arm's reach), action space (space with can interact with by, e.g. throwing things), and vista space (beyond possible interaction; see Figure 1.5).

In personal space, when an object is approaching a viewer it triggers the near reflex (a.k.a. near triad), including accommodation, (con)vergence, and pupillary miosis (Wright et al., 2006). Accommodation and (con)vergence are the two oculomotor cues, which are derived from the sensation of muscular contraction and provide information about an object one is fixating on in a near space. Pupillary miosis is the constriction of a pupil, as an object in fixation approaches the viewer, thus increasing the depth of focus and reducing the retinal blur gradient (von Noorden & Campos, 2002; Wright et al., 2006). Accommodation is based on the information derived from the ciliary eye muscles, which adjust the shape of the lens to provide a focused and sharp retinal image of an object (von Noorden & Campos, 2002; Wright et al., 2006). Fisher and Ciuffreda (1988) investigated the effects changes in accommodative response have on monocular distance judgments, by using excellent, moderate and poor accommodative stimuli. They found that accommodative response (measured with an optometer) and apparent distance (indicated by participants adjusting a sliding hinge outside their visual field) decreased in range when the quality of the stimulus reduced. Even though there was a certain intersubject variability, this study (Fisher & Ciuffreda, 1988) provide evidence that accommodation can be used for reliable distance judgments up to 50cm. Viguier, Clement, and Trotter (2001) investigated vergence, which is cross-coupled with accommodation and is derived from the extra-ocular muscles rotating the eyes in order to keep an object in focus at different distances. In this study (Viguier et al., 2001) participants were presented with light diodes of a fixed visual angle (0.57º) and six different distances, and were asked to indicate the perceived distance of the target using a cursor diode adjustable by hand, while their eye positions were tracked in order to calculate vergence, and found a linear relationship between the perceived distances and the actual distances, when the distances were expressed in vergence angles. In agreement with prior studies using similar set-up, this study found that vergence information is a reliable indicator for the egocentric distance to at least 80cm (Viguier et al., 2001). Additionally, it has been suggested that blur gradient provides quantitative information about egocentric distance to an object in focus at a near distance (Vishwanath & Blaser, 2010). The effect of pupillary miosis on reducing the retinal blur gradient is counteracted at the nearer fixation by focus parameters, as the blur function is based on both: the distance of fixation for given lens and the pupil size (Vishwanath & Blaser, 2010; von Noorden & Campos, 2002). Thus, the pattern of blurring on the retina changes with a fixation distance, as nearer fixation produces larger gradients of blur outside the fovea (von Noorden & Campos, 2002). Applying blur mimicking the blur gradient of a human retina at a near fixation (Depth-of-focus gradient) to photographic images, has been found to have a robust effect on perceived distance and size (Vishwanath & Blaser, 2010). Consequently, if all these cues are available to an observer in a near space one should be able to judge egocentric distance with relatively high accuracy and precision up to about 80cm. While accommodation and (con)vergence and blur could theoretically still provide estimates of egocentric distance beyond this distance, their accuracy would decrease through the rest of the personal space (Cutting, 2003; Cutting & Vishton, 1995).

Considering action space, blind walking studies show that in both monocular and binocular viewing conditions on average participants are able to quite accurately perceive the target location ranging from 4 m to 15 m (mean error less than 30cm), implying that they also are able to accurately perceive egocentric distance to the target for that distance (Loomis et al., 1996). However, when asked to judge the frontal (perpendicular to the line of sight) and in-depth (sagittal) intervals from a standing point (indicate researchers to adjust one or another interval) participants tend to under-estimate the in-depth interval (sagittal), as they had to be made considerably larger (50% to 90% larger than the frontal interval) to be perceived as equal to the frontal intervals (Loomis, da Silva, Fujita, & Fukusima, 1992; Loomis et al., 1996). This suggests, that the knowledge used in blind walking is based on a different knowledge than that used to make visually correct interval judgments. In fact, Ooi, Wu, and He (2001) using prisms affecting angular declination in blind walking tasks in the natural terrain found that there is an adaptive mechanism calibrating information from eye declination level to the visual environment. Additional research revealed that in fact we are capable of accurately judging egocentric distance of an object up to 20m in the natural terrain, by integrating ground-surface information from a near distance up to the far, or the object we intend to locate (Wu, Ooi, & He, 2004). Therefore, these studies suggest that egocentric distance can be correctly judged for locomotion tasks in a natural terrain extensively into the action space.

Individuals with strabismus and no clinically measurable or limited binocular stereoacuity should be able to use eye declination and earth curvature information for egocentric distance, as in the work Loomis et al. (1996) judgments of perceived location of an object and distance to it did not differ between monocular and binocular viewings. Additionally, even if strabismics have an eye misalignment affecting their eye declination level, work by Ooi et al. (2001) shows adaptation to artificially induced declination misalignments (using prisms), suggesting possibility of similar adaptation in strabismus. The question of personal space egocentric cue availability to individuals with strabismus is complicated by the near reflex (near triad). The pupillary miosis has no clear link to accommodation or (con)vergence, thus the depth-of-focus blur is available for strabismic individuals, and amblyopic strabismics in their non-amblyopic eye (von Noorden & Campos, 2002). However, accommodation and vergence are linked by the synkinetic reflex, i.e. a specific amount of accommodation will result in a specific amount of vergence (Wright et al., 2006). The ratio between the accommodative (con)vergence (AC) and accommodation (A) is linked to different manifestations of strabismus. High ratio (AC/A) is linked to over-convergence, and individuals with the high ratio are more likely to develop esotropia at the near viewing distance (up to 1m). Low ratio (AC/A) indicates convergence insufficiency, and individuals with this type of ratio are predisposed to developing exotropia at the near viewing distance (von Noorden & Campos, 2002; Wright et al., 2006). Therefore, individuals with strabismus should be able to use the egocentric distance information from accommodation, but would have varying impairments in the (con)vergence information depending on the type of their strabismus. Missing a highly precise vergence cue (Viguier et al., 2001) at a near viewing distance is commonly expected to result in a large deficit at the near personal space (Schiffman, 2001; von Noorden & Campos, 2002; Wright et al., 2006).

1.2.2. Relative depth

Information about relative depth is derived from visual cues (i.e., genuinely visual in nature), which can be either monocular or binocular.

The majority of monocular depth cues are static, a.k.a. pictorial cues, and have been applied in art to create an impression of three-dimensional pictorial space in paintings for centuries (Kubovy, 1988). The traditionally identified pictorial cues are interposition (the occluded object appears to be further away), shading and shadow, relative size (if identical shapes are viewed simultaneously, the larger one appears closer), linear perspective (the projected image objects and space between them decrease with distance), aerial perspective (objects further away are less clear), elevation (relative height of objects in the visual field, with the higher ones appearing to be further away), and texture gradient (combination of relative size and linear perspective effects on the elements comprising a pattern) (Schiffman, 2001). These cues have been shown to provide reliable ordinal depth information about 3D layout as well as 3D shapes within pictorial spaces, using relative size, gauge figure, and size judgment tasks. In relative size tasks participants are presented with a scene and two spheres (van Doorn, Koenderink, Leyssen, & Wagemans, 2012; Wagemans, van Doorn, & Koenderink, 2011) or two figures within that scene (Wijntjes, 2013) and are asked to adjust them until they are perceived as equal, while the number of available visual cues can be adjusted depending on the research's aims. The gauge figure method is used for quantifying a pictorial relief, which could be viewed under different conditions, by asking observers to adjust a gauge figure (a circular patch with a line perpendicular of the surface at the centre, i.e. the centre surface normal) so that it appears to lie flat on a certain point of a displayed surface or shape (J. Koenderink & van Doorn, 2003; J. Koenderink, van Doorn, & Kappers, 1995; Wijntjes, 2012). Judgment tasks involve making judgments about a displayed shape or objects, for instance, Saunders and Backus (2006) found that perspective cue provides reliable information about depth by displaying slanted rectangles and asking participants to judge whether they appeared longer or wider than a square. A much more recently recognised static monocular visual cue is blur, which has been used in photography to suggest relative depth. It has been found that blur variation of different random texture regions and the border between them provides sufficient ordinal depth information within the pictorial space, without any additional cues (Mather, 1996; Mather & Smith, 2002).

A monocular kinetic cue, called motion parallax, derives information from differences in the two sequential images falling on a retina when an observer or an object in his/her visual field moves. Motion parallax can be induced in an experimental set-up by yoking the relative movement of displayed set of random dots to the movements of the head, and it has been shown to provide highly precise relative depth (DeAngelis, 2000; Ono, Rivest, & Ono, 1986). Binocular disparity is similar in geometric terms to motion parallax, but instead of using sequential information from a single eye, it derives information using differences between the images falling on the two retinas, which occur due to the lateral separation between the two eyes (Howard, 2012a; Howard & Rogers, 2012; von Noorden & Campos, 2002; Wright et al., 2006). However, while binocular disparity has been suggested to provide reliable depth information up to 650m (Ogle, 1950), the motion parallax range is much smaller, in fact, beyond 350cm depth perception has been found to partially shift into motion perception (Ono et al., 1986). Even though, both, motion parallax and binocular disparity, provide highly precise depth information, in contrast to other relative depth cues, in order to quantify the actual magnitude of depth they require distance information, as both of these cues derive information from angular disparities which vary as the inverse square of the viewing distance (Ogle, 1950; Ponce & Born, 2008). This has been proven empirically for both motion parallax (Ono et al., 1986) and binocular disparity (Glennerster et al., 1996; Glennerster, Rogers, & Bradshaw, 1998).

From all of the relative depth cues, only binocular disparity is known to require perfect eye coordination. It is considered that individuals without binocular depth perception would still be able to localize objects and perform visuo-motor tasks to some extent, but their performance would be impaired in tasks involving high precision depth judgments (Ogle, 1950; Wright et al., 2006). Considering other relative depth cues there are no known impairments beyond anecdotal reports (Barry, 2009; Sacks, 2006). On the one hand, if in typically developed binocular individuals the relative depth information is learned in conjunction with binocular disparity, then individuals with infantile or congenital strabismus during the critical period would not develop this link and thus may not be using bottom-up processing for relative depth information (Hubel & Wiesel, 1965; Wright et al., 2006). Instead, individuals with infantile strabismus may develop cognitive top-down strategies of using relative depth cues, which may lead to them having different relative depth perception to that of typically developed binocular individuals. On the other hand, monocular relative depth cues may be processed independently from binocular disparity, in which case deficits experienced by individuals with strabismus during critical period would not carry an effect and their relative depth perception should be similar to that of typically developed binocular individuals.

1.2.3. Absolute depth

When a person is looking at an arrangement of objects he/she perceives either relative or absolute depth (see Figure 1.4). Absolute depth can be perceived only when two types of cues are available: the ones that provide information about the egocentric distance to an object in focus, and the ones that provide information about the relative depth in the 3D scene around that object (Glennerster et al., 1996; Vishwanath, 2014). For instance, when the egocentric distance in unknown (top panel in Figure 1.4) observer will perceive only relative proportions of an arrangement of objects, their relative sizes, and relative distances between them (exocentric distances). Under these conditions a viewer could be looking at two different absolute size and exocentric distance arrangements at two different egocentric distances, but perceive them to be identical on account of their relative properties. Perceiving with such ambiguity would not allow the viewer to interact with the objects or to move through the space between them. Only when the egocentric distance to the object in fixation is known, the viewer can scale the retinal image of the object, and then scale the whole 3D layout around the object using the relative depth information (see middle and bottom panels in Figure 1.4). This allows the viewer to obtain absolute object sizes and exocentric distances between the objects in the arrangement he/she is looking at, thus perceiving absolute depth. This also means that the viewer knows egocentric distances to each point and objects in that 3D arrangements. Therefore, absolute depth perception is crucial for interaction with the 3D environment.

Because absolute depth is derived as a combination of both egocentric distance and relative depth, its perception as well as precision depends on the availability and precision of the prior described cues (Vishwanath, 2014). Consequently, as previously discussed that the usability of all egocentric distance cues diminishes with distance (Cutting, 2003; Cutting & Vishton, 1995), it is expected that the capacity to perceive absolute depth would diminish with the viewing distance as well. In the personal space absolute depth perception should be strong, though it might be affected by the reduced accuracy in accommodation and (con)vergence beyond approximately 1 meter (Cutting, 2003; Cutting & Vishton, 1995). Absolute depth perception would diminish through the action space, especially after 15-20 meters based on the blind-walking studies (Loomis et al., 1996; Wu et al., 2004), and would be absent for the vista space (Vishwanath, 2014).

Considering that individuals with strabismus, who, as previously discussed, are lacking distance and relative depth information provided by vergence and binocular disparity cues, respectively, we should, arguably, expect varying extent deficits in absolute depth perception (see Table 1.1).

Table 1.1. Summary of possible limitations experienced by individuals with strabismus in the three classes of space and predictions about strabismics absolute depth perception.

	Available visual information	Limitations	Predictions
Personal space	Accommodation	None known	Weak absolute depth perception
	Blur (depth-of-focus)	None known	If visual system adapted to strabismus, absolute depth perception could resemble typically developed binocular individuals
	(Con)vergence	Impaired or absent	
	Binocular disparity	Impaired or absent	
	Motion parallax	None known	
	Pictorial cues	None known	
Action space	Eye declination level and earth curvature	None known	Absolute depth perception similar to typically developed binocular individuals
	Binocular disparity	Impaired or absent	Possibly lower precision in exocentric depth judgments
	Motion parallax	None known	
	Pictorial cues	None known	
Vista space	No egocentric distance information	n.a.	Same as typically developed binocular individuals.
	Binocular disparity	Impaired or absent	Would perceive only relative depth, and not absolute depth
	Motion parallax	None known	Possibly lower precision in exocentric depth judgments
	Pictorial cues	None known	

In the personal space, (con)vergence cue provides highly reliable egocentric distance information, which allows to scale relative depth cues, to a high precision (Viguier et al., 2001). Individuals with strabismus are missing one of the most precise relative depth cues – binocular disparity (von Bartheld et al., 2010; von Noorden & Campos, 2002). In fact, if information from the relative depth cues is processed in conjunction, and if this process is affected in strabismics during the critical development period (Hubel & Wiesel, 1965; Wright et al., 2006), it is possible that not only binocular disparity but other cues, such as pictorial cues are also affected. This, to our knowledge, had not been explored and therefore it would be possible to conclude that individuals with strabismus should have weak absolute depth perception, which is traditionally assumed in the literature (Fielder & Moseley, 1996; Wright et al., 2006). However, accepting this assumption without considering whether vergence and binocular disparity information is completely ignored by strabismics' visual system would be erroneous. In fact, some research suggests that the visual system of individuals with esotropia incorporates information from extra-ocular eye muscles, as the pointing response to a target shifted consistently with the eye position information between the conditions when eyes were aligned using glasses and when they were misaligned (Weir, Cleary, Parks, & Dutton, 2000). This corresponds to an observation by Verhoeff (1902) that after visual system of a strabismic with a constant misalignment adjusts into perceiving a single image, corrective alignment surgery results in diplopia which can be corrected only via use of prisms. In the cases of constant small angle tropias, retinal correspondence can be formed and a point outside a fovea is processed by the brain as a fovea in the misaligned eye (Motley, 2018; von Noorden & Campos, 2002). Arguably, it could be possible that the brain similarly "adjusts" vergence information for the misaligned eyes, meaning that if the angle of misalignment is considerably small and constant, it could be processed as the "right" alignment, especially considering the fact that orthophoria is extremely rare (Motley, 2018; von Noorden & Campos, 2002). Additionally, research has suggested that binocular disparity processing is possible in the periphery in individuals with strabismus (Fronius & Sireteanu, 1989; Sireteanu & Fronius, 1989). Consequently, it is plausible that despite their disorder strabismics perceive absolute depth in a way that resembles that of typically developed binocular individuals in the personal space.

In the action space strabismics' absolute depth perception could, arguably, be the same as that of typically developed binocular individuals. Vergence does provide egocentric distance information up to six meters, but its accuracy in the action space is decreased (Cutting, 2003; Cutting & Vishton, 1995). Additionally, depending on the type of strabismus, individuals with impaired near distance (1/3m) vergence, could have sufficient far distance (6m) vergence (Wright et al., 2006). Thus, the only cue strabismics would be lacking is binocular disparity, which is expected to provide reliable depth information up to 650m (Ogle, 1950). In the near action space (up to 15m) strabismics should be expected to correctly perceive egocentric distance, but experience some limitations in the exocentric distance judgments, as it has been observed in blind-walking study (Ooi & He, 2015). Considering that in order to perceive magnitude of depth derived from disparities an observer needs distance information (Glennerster et al., 1996, 1998), and the distance information in the action space for all individuals would be derived from the eye declination level, it is plausible that after a distance of 15m (Loomis et al., 1992; Loomis et al., 1996), or 20m in the natural terrain (Ooi et al., 2001; Wu et al., 2004), strabismics and typically developed binocular individuals should perceive the same level of absolute depth. In the vista space there is no available egocentric distance information to scale the binocular disparity, thus no absolute depth can be perceived.

1.3. Qualitative perception of depth

As it has been already briefly mentioned in the prior section of this chapter, traditional binocular stereovision theory considers that stereopsis – a unique sensation of depth – emerges only as an outcome of binocular disparity processing and thus individuals with strabismus would not be able to experience it (Fielder & Moseley, 1996; Godber, 1981; Ogle, 1950; Wright et al., 2006). For instance according to DeAngelis (2000): "Depth perception based upon binocular disparities is known as stereopsis". Fielder and Moseley (1996) make a similar statement: "Stereopsis is the binocular perception of depth (retinal disparity)". Even when stereopsis is linked to monocular viewing, the key element in the quality of perceived depth is processing of disparities, as in monocular parallax (Rogers & Graham, 1982). In a way this is illustrated and supported by Susan Barry's anecdotal report (Barry, 2009), as her description of the qualitative depth perception after regaining eye alignment, and according to her account binocular stereovision, closely follows characteristics of stereopsis:

1. "Sense of "real" separation in depth between objects or points on a single object";

2. "Sense of tangibility and sense of spatial immersiveness";

3. "Sense of "reality" and "realness" of visual objects and scenes".

(Vishwanath, 2014).

The current thesis defines stereopsis via these key characteristics, emphasising object solidity, tangibility, an impression of negative space and its immersiveness. An alternative to the binocular stereopsis theory, which is based on the previously described distinction between the relative and absolute depth, suggests that stereopsis is present when a viewer is able, to some level of precision, perceive absolute depth, as until we are able to scale the objects and distances between them it is too ambiguous for an immersive and tangible experience (Vishwanath, 2014). Importantly, this theory implies that if individuals with strabismus can at some level of precision perceive absolute depth, they should be able, to some degree, perceive stereopsis without binocular vision.

1.4. Thesis outline

The remainder of this thesis is organised into three chapters that explore how individuals with strabismus with no or limited binocular stereovision perceive depth and distance in comparison to typically developed binocular individuals. The general methods used to test all participants vision and how it was used to further classify them into separate groups is discussed in detail in Chapter 2.

Chapter 3 contains two experiments investigating qualitative aspects of depth perception in strabismus, via monocular stereopsis. Typically developed binocular individuals have been found to experience stereopsis when looking at images of 3D objects via a monocular aperture (Vishwanath, 2014; Vishwanath & Hibbard, 2013). If the ability to experience stereopsis is in fact uniquely linked with binocular disparity (Fielder & Moseley, 1996; Ogle, 1950), then congenital strabismics with no clinically measurable binocular stereoacuity should not have developed binocular disparity neurons linked to stereopsis (Wright et al., 2006), and thus should not be able to experience monocular stereopsis. This has not been tested in strabismics and individuals with no or limited binocular stereovision. Additionally, experiments in Chapter 3 compared the depth experienced under monocular-aperture viewing to the depth strabismics experience on everyday basis viewing real 3D objects using both: non-blind (experiment 3.1) and blind (experiment 3.2) experimental set ups.

The following two aspects indirectly assess the previously discussed limitations in distance and depth cues strabismics experience. Limitations in vergence information would not only affect the egocentric distance information in the personal space, but could also disrupt the overall distance perception mechanism. Therefore, experiments in Chapter 4 explored egocentric distance perception derived from object size judgments. This experimental design was based on prior work on familiar object size and perceiving egocentric distance (W. C. Gogel, 1969a, 1969b, 1976) employing size-distance invariance hypothesis (Epstein, Park, & Casey, 1961; W. C. Gogel & da Silva, 1987). Additionally, the importance of binocular disparity information was explored in these experiments by including stereoscopic viewing conditions (3D TV), in addition to binocular and monocular viewing. The importance of relative depth cues was further explored in Chapter 5. If during the early stages of development the visual system processes all relative depth cues together, thus combining them for an ultimately accurate representation of surrounding world, it is possible that in individuals with infantile or congenital strabismus this process is disrupted by the lack of binocular disparity (Hubel & Wiesel, 1965; Wright et al., 2006). There are two possible ways in which strabismics' relative depth perception could be impaired. Firstly, it can be impaired in a bottom-up sense as its development and calibration depends on having depth from binocular vision (von Bartheld et al., 2010; Wright et al., 2006). Secondly, it may be impaired in a top-down sense, because cognitive inferences of depth from the relative monocular depth cues are developed from depth observed on everyday basis, and if it is impaired (e.g. more shallow) due to lack of binocular disparity relative depth would have equal cognitive inference impairments (e.g. more shallow depth derived from perspective information). Both of these possibilities were addressed in experiments 5.1 and 5.2. Chapter 5 experiments were carried out to test strabismics automatic susceptibility to pictorial depth information (perspective) via interval equidistance judgments on a 2D plane, in order to determine if relative depth cues operate in a bottom-up manner. Additionally, pictorial depth cues were used to investigate strabismics' capacity to perceive relative depth in comparison to typically developed binocular individuals (the amount of relative depth perspective information it allows them to perceive), thus exploring possible impairments in the top-down cognitive processing.

Therefore, the six experiments described in the following thesis chapters explored all key aspects of depth and distance perception in strabismus. The main findings in the thesis are summarised and discussed in Chapter 6.

Table 1.2. Outline of chapters and PhD thesis

	Chapter	Key research aims	Method
1.	Introduction		
2.	General methods		
3.	Qualia of depth perception in strabismus: monocular stereopsis	Explore if individuals with infantile strabismus and no measurable binocular stereoacuity can experience monocular stereopsis, and if they do, then how it compares to the depth they experience on everyday basis	Qualitative & Quantitative Original blind testing set-up
4.	Egocentric distance perception in strabismus: familiar object size	Explore egocentric distance perception by inferring it from the familiar object size judgments in individuals with strabismus and typically developed binocular individuals under monocular, binocular, and stereoscopic (3D TV) viewing.	Quantitative psychometric function
5.	Pictorial depth perception in strabismus: perspective	Explore if strabismics are susceptible to pictorial depth information (perspective) in 2D images, and thus investigate if individuals with no/limited binocular stereoacuity use bottom-up processing for pictorial cues. And by using pictorial cues explore how strabismics perceive relative depth in comparison to typically developed binocular individuals.	Quantitative
6.	General discussion and conclusion		

Chapter 2

General methods

The specific methods which were used vary between the experiments. Their detailed descriptions are provided in the method sections of each of the following experimental chapters. In the current chapter, the common aspects of testing will be described: the gathering of the information about participants' vision, including stereotests used, and the criteria for the classifications into groups.

Participants were primarily recruited at St Andrews and Dundee using self-selective sampling. Two types of advertisements were displayed at the St Andrews, Dundee and Abertay Universities in order to address two groups of participants: individuals with strabismus or impaired binocular stereovision, and stereonormal individuals with no known history of strabismus or any other visual disorders. These advertisements were additionally distributed to the local opticians. Further, they were adapted for University of St Andrews Wednesday memos and SONA participant recruitment system, and at the Abertay University via a press release. Collaborators at the School of Optometry, Nova Southeastern University in Florida, USA, recruited participants for the experiment 3.1 using similar methods. The corresponding ethical approvals were received for participant recruitment at all three sites. All recruited subjects were at least 18 years old at the time of testing. If participants indicated that they were willing to take part in more than one experiment, their contact details were kept by the author of this thesis separately from the gathered data. The document with the codes linking subjects' data to their personal details was kept in a separate document on a password protected computer.

2.1. Gathering visual information

2.1.1. Clinical history of strabismus

The current research was carried out without a collaboration with the NHS, and thus there were no available medical records about visual history of participants with strabismus. Instead, self-reports about participants' clinical history were gathered, specifically focusing on the onset of strabismus, whether it was constant or intermittent, the history of surgeries and other treatments, and any other notes or deficits reflecting a participant's current visual experiences (see Appendix 2.1). In order to identify any current deviations the Cover and Cover-Uncover tests (see Figure 1.2) were performed at a near distance by the experimenter. The experimenter sat in front of the participant and held a pen so its tip was just in front of her nose. Then she asked a participant to fixate on the tip of the pen, while the experimenter covered one of the participant's eye, then the other, observing any occurring deviations. The tests were performed at a near viewing distance. If participants were wearing corrective glasses, the testing to define the type of deviation was performed both with and without the corrective glasses. Ophthalmologists use prisms for measuring the amount of misalignments in strabismus. In the US and UK misalignment is measured in prism diopter (i.e. measure for prism's ability to bend light), while occasionally it can be measured in degrees. One prism diopter will shift light one centimetre at a one meter viewing distance, which is equal to an approximate half a degree displacement (Wright et al., 2006). A small number of participants in experiment 3.1 had their misalignment measured in such manner by a collaborator in the School of Optometry in Nova Southeastern University, US. However, the primary experimenter and the author of this thesis had no ophthalmological training, and thus was unable to use prisms for measuring the misalignment. Instead, if the experimenter was able to clearly observe the misalignment without the Cover or the Cover-Uncover test, it was noted to be severe, or of large angle. If the misalignment was noticeable only during the testing, it was noted to be a mild angle deviation.

The limitations in the clinical assessment of strabismus due to experimenter's lack of ophthalmological training are discussed in detail in the General Discussion 6.4 Section.

2.1.2. Visual acuity

The visual acuity was measured at distance using the Snellen chart. Due to the limited space in the laboratory, the original viewing distance of 20 feet was halved to 10 feet. Consequently, in order to obtain an equivalent of the 20/20 vision participants had to be able to see the 10/20 vision line. Western Ophthalmics near distance visual acuity test was used at approximately 40 cm to measure near distance visual acuity (should see line 15 J1), and at 60 cm to measure visual acuity at the monitor viewing distance (should see line 20-25 J2-J3; see Figure 2.1). Participants wore their corresponding habitual corrections during the testing, for instance, reading glasses for the near distance visual acuity test. The aim of these tests was to ensure that participants are able to see the provided visual stimuli at least with their dominant eye.

2.1.3. Colour vision

The stimuli used in experiments described in Chapter 3 were colour photographs or real 3D objects, thus colour deficiency was an exclusion criteria in experiments 3.1 and 3.2. Colour deficiency was measured using the concise edition of the Ishihara's test for colour deficiency (Ishihara, 2014).

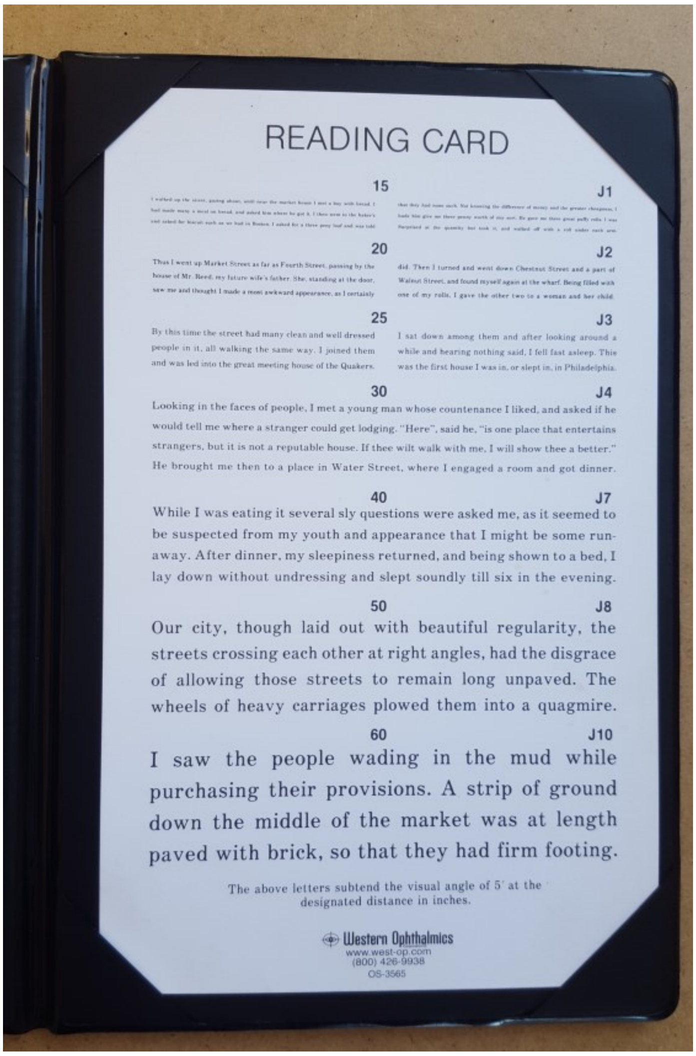


Figure 2.1. Image of the near distance visual acuity test.

Figure 2.2. Example of the Miles test for defining eye dominance. A subject makes a small triangular opening with their hands and views an object (focus point) with both eyes through it. In this example the subject then brings the hands towards their face whilst keeping the focus point in the middle of the opening. The hands naturally moved towards the dominant eye, in this example the subject's left eye.

2.1.4. Eye dominance

Eye dominance was identified using the Miles test. Participants were asked to extend both arms, bring their hands together and make a small triangular opening (example in Figure 2.2.). Then they were shown a water bottle and were asked to look at it with both eyes through the opening. Further, they were asked without moving their hands to alternate closing the eyes, and to say in which case the water bottle stayed in the centre or moved less, thus defining the dominant eye. If participants experienced difficulty making the decision, they were asked to look through the opening with both eyes and slowly bring the hands towards their face in such way that the bottle stayed in the middle. The dominant eye was the eye towards which the hands moved, as it is shown in Figure 2.2.

2.1.5. Stereoscopic rendering parameters

Experiments described in Chapter 4 used 3D TV set ups with active display. In order to ensure accurate 3D rendering of the images, participants' interpupillary distance (IPD) was measured. The experimenter sat in front of the participant and whilst looking into the subjects' right eye asked them to look into her left eye. Then the experimenter held a ruler in front of the subject's face in such way that the start of its indices was at the centre of the right eye's pupil. Holding the ruler still the experimenter asked the participant to look into her right eye. The number on the ruler matching the centre of the subject's left eye pupil was thus the measured IPD.

2.1.6. Binocular stereovision tests

Three stereotests were used to clinically measure binocular stereovision: Titmus (Fly), TNO, and RanDot (Figure 2.3). These tests are widely used and measure both types of binocular stereovision: global and local (Fricke & Siderov, 1997; Lee & McIntyre, 1996). Local stereovision entails feature matching, while global stereovision requires global integration of images without a recognisable pattern. Global stereovision requires sensory fusion as the corresponding retinal dots between the two eyes are processed. Random-dot stereograms are used to measure it, as under monocular viewing they contain only random noise, but under binocular viewing a "hidden" shape can be perceived. While the majority of dots in the two images are identical, the dots defining any recognisable shape (e.g. circle) are displaced nasally, thus producing the perception that the shape is coming up off the page (von Noorden & Campos, 2002; Wright et al., 2006). This is the testing principle in the TNO test which uses red/green random dots and matching glasses, and in RanDot which instead uses the polarised glasses. The Titmus test contains horizontally displaced stereoscopic figures with a continuous contoured edge. It measures local stereovision as it requires comparisons of the local features, rather than dot-by-dot processing in order to perceive a shape (von Noorden & Campos, 2002).

Figure 2.3. Three binocular stereovision tests used in the experiments. Left to right: Titmus (Fly) test; TNO test; RanDot test

2.2. Classification into groups

Individuals with strabismus can be classified into different groups either based on the history of strabismus and the angle of deviation, or according to the level of clinically measurable binocular stereovision. Due to the high variability among participants' visual history and lack of medical records, the classification for the analyses described in the following chapters was based on the level of participants' binocular stereovision.

2.2.1. Classification according to the level of binocular stereovision

Literature discussing clinical binocular stereovision tests highlights their limitations and the fact that, currently, there is no single perfect test for measuring binocular stereovision (Fricke & Siderov, 1997; Lee & McIntyre, 1996; O'Connor & Tidbury, 2018). This is also evident in studies showing that individuals with no clinically measurable binocular stereovision are able, to some extent, to perceive depth in 3D stereoscopic displays (Tidbury, Black, & O'Connor, 2014; Tidbury et al., 2015).

The Titmus test is considered to be clinically useful, as the stereoscopic effect is obvious and thus it is easy to use (von Noorden & Campos, 2002). However, it contains monocular information that may be the basis for correct performance rather than the subject's ability to process binocular disparity information. This may lead to false over-performance and thus false classification according to the level of binocular stereovision. For instance, stereoblind subjects could identify the stereoscopic circle, because it would be slightly displaced nasally, or it would slightly shift if they alternated their view between the two eyes (Wright et al., 2006). Therefore, first two correct responses in the Titmus test are not considered to be indicative of the presence of binocular stereoacuity (von Noorden & Campos, 2002; Wright et al., 2006). On the contrary, TNO test has almost no monocular cues and very few false positive responses. However, the random-dot images used in TNO have been found too difficult by many typically binocularly developed children and adults to use and to perceive depth in (von Noorden & Campos, 2002). Tests using polarised filters, such as RanDot, have been suggested to be more accurate (Fricke & Siderov, 1997). Based on these concerns, scores of all three binocular stereoacuity tests were considered, while creating a set of guidelines for classifying participants into four groups (see Table 2.1).

Table. 2.1. Guidelines for participant classification according to their binocular stereoacuity measured using TNO, RanDot and Titmus (Fly) tests.

	Titmus	**TNO**	**RanDot**
range in arc’	800’ to 40’	480’ to 15’	400’ to 20’
No stereovision	≥ 400’	none	none
Local stereovision	≤ 200’	≥ 480’	≥ 200’
Stereo-normal	≤ 50’	≤ 240’	≤ 30’
Anomalous stereovision	Better performance at TNO and RanDot than Titmus test		

2.2.2.1. No binocular stereovision group

The first two stereoscopic circles in the Titmus test (800’ and 400’ arc’) have clear monocular feature changes and thus are not considered to be indicative of the presence of binocular stereoacuity (von Noorden & Campos, 2002; Wright et al., 2006). Therefore, participants were classified into the no stereovision group if they had no measurable stereovision in RanDot and TNO tests, and could correctly identify none or only the first two stereoscopic circles in the Titmus test (800’ and 400’ arc’). This classification allowed no exceptions, as no clinically measurable binocular stereovision was one of the key descriptives of the population of interest in the experiments presented in Chapter 3.

2.2.2.2. Local binocular stereovision group

Correct responses to the first pairs of stimuli in TNO and RanDot tests (480' and 200' arc', respectively) , might suggest presence of residual global disparity processing, but does not indicate sufficient global binocular stereovision level. Therefore, participants who correctly identified three or more stereoscopic circles in the Titmus test (200' arc'), but gave accurate responses to none or only to the first pair of TNO and RanDot circles (480' and 200' arc', respectively), were classified as having local stereovision (i.e. their local binocular stereovision was better than their global binocular stereovision). This group also included participants who responded correctly to the first three TNO Plates (used to establish presence of stereoscopic vision), but were not able to see the stimuli in the following quantitative TNO Plates (used for the exact determination of stereoscopic sensitivity).

2.2.2.3. Stereonormal group

In the majority of cases, participants classified as stereonormal, provided all correct responses to Titmus and RanDot tests (40' and 20' arc', respectively) and to the first four pairs of TNO stimuli (60' arc'). However, variability in binocular stereovision levels was observed in participants with no history of strabismus or present deviations in their eye alignments. While it is possible that these participants had some unknown visual conditions (e.g. anisometropia), in order to have a stereonormal subject sample representative of the general population, some of the variability observed in the binocular stereovision tests was allowed. Taking into account the reported underperformance in the TNO test, as well as its robustness and low number of false positives (von Noorden & Campos, 2002), correct responses to the first 2 pairs of TNO stimuli (240' arc') were considered to be indicative of sufficient global binocular stereovision. However, if subjects responded correctly only to the first 2 pairs of TNO stimuli, they were expected to provide correct responses to the majority of Titmus and

RanDot stimuli in order to be classified as stereonormal participants (see Table 2.1). In some rare cases more careful considerations of the binocular stereovision test scores were required, the outcome of which largely depended on the TNO scores. For instance, in case of the typically developed participant P3 in experiment 4.1 RanDot score was 70' and Titmus score was 60', which are relatively low scores. However, the TNO score was 60' (correct responses to the 4 pairs of stimuli). Therefore, overall the participant was considered to have sufficient binocular stereovision.

2.2.2.4. Anomalous binocular stereovision group

The last classification group was created taking into account the prior discussed differences between the binocular stereovision tests, specifically under-performance in TNO test and over-performance in Titmus test (Fielder & Moseley, 1996; von Noorden & Campos, 2002). Despite these prior findings (von Noorden & Campos, 2002) a certain number of participants performed better at the TNO test than the Titmus test. For instance, subject (CS5) correctly identified only the first two stereoscopic circles in the Titmus test (400' arc), but gave correct responses to the four pairs of TNO stimuli (60'). This group would have also included participants if they had correctly answered to the first pair of TNO stimuli (480' arc'), but to none or only the first couple of the Titmus stimuli (≥ 400' arc'), as the latter in contrast to the TNO stimuli contain clear monocular feature changes.

The majority of participant classification according to these fourfold guidelines has been performed based only on the Titmus and TNO binocular stereoacuity scores, as the RanDot test was acquired later than the prior two tests and some participants were missing this measurement. For the population tested in the experiments presented in this thesis such classification was sufficient. However, inclusion of the RanDot test score raises additional possibilities unaccounted in the Table 2.1, specifically the RanDot range between the 200' and

30' arc'. As previously discussed it is considered that TNO test and its images are more difficult than the RanDot test and its stimuli, which would suggest that participants are expected to perform better at RanDot than TNO test. Therefore, it was considered that, if participants were to answer correctly to less than half of RanDot circles (>70' arc'), but could provide correct responses to more than first two stimuli pairs in TNO (<240' arc'), they would be classified as having anomalous binocular stereovision. Similarly, considering the previously discussed difference between the global and local binocular stereovision, if participants were to perform better by more than a 20' arc' difference under RanDot than Titmus test, their binocular stereovision would be considered anomalous. As the TNO test is expected to provide fewer false positives than RanDot or Titmus (Fricke & Siderov, 1997; von Noorden & Campos, 2002), it was considered to be a crucial test in determining classification between the groups. For instance, if participants were to answer correctly to more than two Titmus circles (<400' arc'), but could provide no correct responses for the TNO stimuli, they would be considered to have local binocular stereovision even if they answered correctly up to a half of RanDot stimuli (>70' arc'). If in this situation participants were to answer correctly to more than half of RanDot stimuli (≤ 70' arc'), and the RanDot measured stereoacuity were to differ by less than 20' arc' from the level of stereoacuity measured with the Titmus test, retesting TNO should be considered or further information about participants' vision should be gathered. Lastly, considering that the TNO test is considered to be the most robust and difficult out of the three binocular stereoacuity tests, if participants were to perform better at TNO than Titmus test, but not the RanDot test, their binocular stereovision would still be classified as anomalous.

All visual information about participants is summarised in the appendices. TNO and RanDot test values, as measures of global binocular stereovision, are presented within the same column.

Chapter 3

Qualia of depth perception in strabismus: monocular stereopsis

3.1. Introduction

Strabismus, otherwise known as a strabismus, refers to a misalignment of the eyes which results in the eyes receiving information from two non-corresponding areas of space.

This misalignment of the eyes in strabismics results in the lack of binocular depth perception which is derived from binocular disparities (which are the differences between the corresponding features in the two images falling on the right and left eye retinas (DeAngelis, 2000; Ponce & Born, 2008). According to the standard binocular stereopsis theory, binocular depth perception gives rise to a unique sensation of depth called stereopsis (Ogle, 1950). This suggests that individuals, who are not able to perceive depth on the basis of binocular disparities, such as those with uncorrected strabismus, will be lacking the ability to experience stereopsis (Ponce & Born, 2008; Wright et al., 2006). Further, it is thought that age of onset of strabismus also plays an important role in individual's ability to experience stereopsis. The critical period theory suggests that strabismus in early infancy and childhood irreversibly affects the development of visual disparity neurons (Hubel & Wiesel, 1965; von Noorden & Campos, 2002; Wright et al., 2006).Thus, individuals with infantile strabismus who are not treated in early childhood (up to about the age of 4 and a half), in contrast to individuals with later onset strabismus (after the age of 5), will not be able to experience stereopsis even though they regain perfect eye alignment later on in life (Sherry et al., 2005).

However, this view has been challenged by the famous case of Susan Barry, a.k.a. Stereo Sue, a woman with infantile esotropia and no measurable binocular stereoacuity, who in her

40s gained binocular stereovision and stereopsis through ophthalmological exercises aimed at improving vergence (the coordinated inward and outward movements of the eyes). Here are some examples Barry gave about the change in her perception of (Barry, 2009):

"This sense of objects projecting straight toward me was novel. Objects had always appeared a little to one side, depending upon whether I was paying attention to the input from my right or left eye. Now that I was developing stereovision, I saw the horse's head projecting straight toward me in the direction of a virtual "cyclopean eye". The same was true for my view of car bumpers, open doors, light fixtures, tree limbs, and outside corners of large buildings." (p. 95)

"While gazing up at the trees, I was startled to see the branches in layers of depth. I saw how the outer branches captured and enclosed a palpable volume of space into which the inner branches permeated. I could make sense of the whole intricate network." (p. 126)

After discussing her case in a number of interviews, Susan Barry received a number of letters from people describing similar changes in the qualia of their depth perception (Barry, 2009). These and other anecdotal reports have made researchers start questioning the reliability of binocular stereovision assessment tools, and how accurately they represent quality of depth experienced on daily basis (O'Connor & Tidbury, 2018). In fact, studies have shown that individuals with no clinically measurable binocular stereoacuity are able to identify depth in 3D movies (Tidbury et al., 2015; Tidbury, Black, & O'Connor, 2014). This suggests that current understanding of depth perception and the quality of it on everyday basis is still poorly understood in individuals with strabismus with no or limited binocular stereovision.

Recent research has found a monocular stereopsis effect, which occurs when an individual views a static pictorial image of a 3D scene through a monocular aperture. Vishwanath and Hibbard (2013) found that the majority of typically developed binocular participants (20 out of 23) perceived a better impression of depth under monocular-aperture viewing of static 2D images of 3D scenes than under binocular viewing. More importantly, participants were found to attribute the same visual characteristics perceived in binocular stereopsis to the depth they perceived viewing images through a monocular aperture (Vishwanath & Hibbard, 2013). A later study by Volcic, Vishwanath, and Domini (2014) asked typically developed binocular individuals to perform motor movements (reaching) when viewing pictorial images under both binocular- and monocular-aperture viewing conditions. Participants viewed a static 2D image of natural 3D objects with dots marking three different pictorial depths. Images were displayed using a half-silvered mirror setup such that the pictorial image appeared virtually in front of them and allowed participants' to make manual responses while their hand motion was tracked. Unknown to the participants, the display monitor was moved randomly from trial to trial to present the images at different distances (Volcic et al., 2014). This study found that under monocular-aperture viewing conditions, participants' pointing responses correlated with the three levels of pictorial depth, while in binocular-aperture viewing pointing responses were mostly based on physical monitor distance (Volcic et al., 2014). These studies show that it is possible to experience depth in a vivid and immersive way, which according to the participants' descriptions, closely resembles binocular stereopsis, even though they viewed images only with one eye and thus there was no usage of binocular disparities information.

The alternative to the binocular stereopsis theory (Vishwanath, 2014) provides an explanation of the monocular-aperture effect. According to the alternative theory the experience of stereopsis depends upon the ability to scale the 3D scene and objects within it, which generates an immersive and tangible experience of depth (Vishwanath, 2014). Thus, when an observer views a static 2D image on a monitor binocularly, he/she can perceive absolute depth and experience stereopsis for the monitor on which the image is displayed and the space around it, but not for the 3D scene depicted within the image, as there are no distance cues available for the pictorial space and only relative depth can be perceived. However, when the same image is viewed through a monocular-aperture the awareness of the display surface is removed, as the monitor frame is covered, and any available egocentric distance information, in this case accommodation, is assigned to the pictorial content, thus allowing it to be scaled (Vishwanath, 2014). Importantly, this theory implies that it may be possible for individuals with strabismus to experience stereopsis without the use of binocular depth perception.

This chapter will explore the monocular stereopsis effect in the context of the strabismic population. The main population of interest are strabismics with congenital or infantile strabismus, who did not have a corrective surgery in an early age. This is because according to the critical period theory (Hubel & Wiesel, 1965; Sherry et al., 2005) these individuals should not be able to experience stereopsis. Any contradictory findings would suggest a different underlying cause for stereopsis than only the fusion of binocular disparities. Firstly, this experiment aims to explore if strabismics with congenital uncorrected strabismus or individuals with no clinically measurable stereovision are able to experience monocular stereopsis. Secondly, this study will aim to compare the qualitative depth experienced under monocular-aperture viewing with the depth stereoblind individuals experience under typical everyday viewing conditions. It is plausible that for strabismics with a small-angle constant misalignment, whose visual system is incorporating information from both eyes, monocular-aperture viewing would eliminate the erroneous information from the misaligned eye and improve their depth perception considerably. On the other hand, for individuals with a large angle misalignment and/or extremely low visual acuity in one of the eyes, it is plausible that their everyday depth perception is largely based on the dominant eye and thus the monocular-aperture would carry a lesser effect. Lastly, it is important to consider how widely the traditional binocular stereopsis theory (Fielder & Moseley, 1996; Ogle, 1950) is naively expected by strabismics and whether the idea of binocular vision being "better" than monocular vision could create a personal bias in the participants' comparative depth judgments. Therefore, the experiment will comprise both non-blind and blind comparisons of quality of depth perceived when viewing 2D static images and real 3D objects under various viewing conditions (binocular, monocular, monocular-aperture).

Experiment 3.1

In this experiment we investigated if individuals with congenital constant strabismus can experience stereopsis when viewing images through a monocular-aperture. We aimed to test the replicability of monocular stereopsis perception (Vishwanath & Hibbard, 2013) for both participants with normal stereovision and those with no/limited binocular stereovision. Furthermore, we planned to compare the experiences between the groups in order to explore the importance of the binocular stereovision level for obtaining monocular stereopsis. Lastly, we aimed to gain a better understanding of the extent of monocular stereopsis depth, by exploring how the depth effect created by monocular stereopsis compares to strabismics' depth perception in real everyday situations.

3.2. Methods

3.2.1. Stimuli

The stimuli and their presentation were based on the images used by Vishwanath and Hibbard (2013). Images of plants had been selected as highly familiar objects, which have complex depth structure, and which allow an easy explanation of the concepts of relative depth, absolute depth, and particularly descriptive aspects of depth impression, e.g., between the leaves, as it had been described in great detail by Susan Barry after she gained binocular stereopsis (Barry, 2009; Sacks, 2006). Colour photographs of plants (1600px-1200px) were displayed on an LCD monitor viewed from 60 centimetre distance. Participants' heads were stabilized using a chin rest. The whole monitor, including its frame, was visible during the binocular viewing condition. During the monocular-aperture viewing condition, participants looked only with their dominant eye through an oval aperture (1.3cm x 0.95cm) held at such a distance from their eyes that only the image displayed on the monitor, but not the monitor's frame was visible (approximately distance of 1.5cm-2cm) (see Figure 3.1).

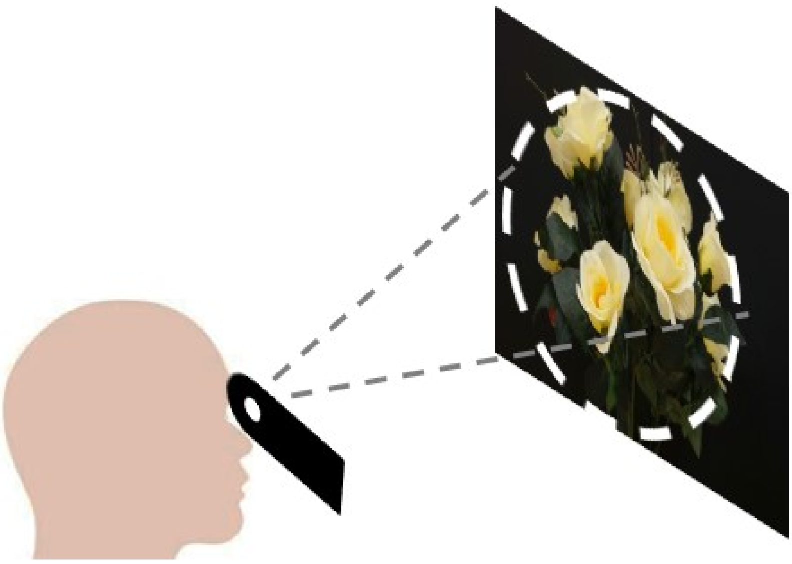


Figure 3.1. Viewing set up for inducing monocular stereopsis. A pictorial image viewed only with the dominant eye through an oval aperture (1.3 x 0.95 cm). The aperture is held in a way that the boundary of the image is occluded.

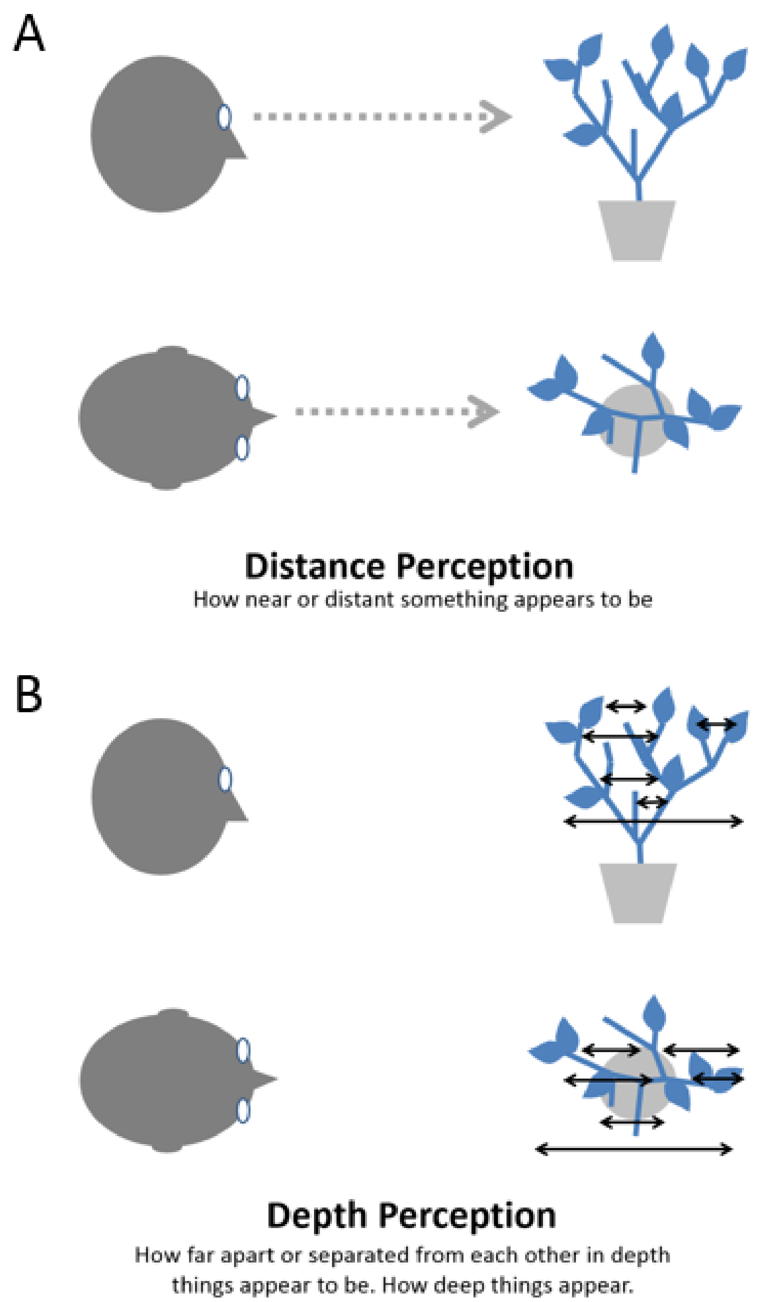


Figure 3.2. Slides from the PowerPoint presentation explaining differentiation between distance perception (panel A), and depth perception (panel B).

3.2.2. Procedure

Participants were given explanations for the concepts of distance and depth clarifying the distinction between the two using PowerPoint presentation (Figure 3.2).

Participants were asked to view the displayed image binocularly and then through a monocular-aperture, and compare the way they perceived depth in each of these viewing conditions. Participants were instructed to view each case at least for 5-7 seconds, and repeat the comparison at least 3 times, before answering if there was a difference in their perception of depth in the two viewing conditions (Yes/No response). The same steps were repeated for the second stimulus image. Participants who indicated that they did not perceive any difference between binocular and monocular-aperture viewings for either of the stimuli, did not continue with the study as all the following questions asked subjects to describe the perceived difference between the two viewing conditions.

In Part 1 participants were asked to indicate in which viewing condition their depth perception was better, as well as to describe in their own words the differences they perceived. Further participants were asked to compare the way they perceived depth viewing real 3D objects on an everyday basis to the quality of depth they experienced in the experiment viewing displayed images binocularly or through a monocular-aperture. This was followed by an open-ended question allowing them to further describe the comparison.

Part 2 of the experiment was a questionnaire comprised of 10 Likert-scale items (Appendix 3.1): five of which were target items related to the characteristics associated with stereopsis according to prior research (Vishwanath & Hibbard, 2013); the other five were distractor items, functioning as controls for suggestibility and task compliance. The 10 items were presented in one out of five quasi-randomised sequences. Participants could view the images again and compare their depth perception in both viewing conditions at any point throughout the Part 1 and Part 2 of the experiment.

3.2.3 Participants

Information about participants' vision was gathered using a number of ophthalmological tests as well as self-reports about participants' clinical history (Appendix 2.1.). Participants' visual acuity was measured with the Snellen chart and the near visual acuity optometry test. Presence of tropias or phorias and their type was identified using the Cover and Cover-Uncover tests, while further information about strabismus or other disorders was based on self-reports. Stereovision was tested using the Fly test (a.k.a., the Titmus stereo-test) and the TNO test. The two tests had been chosen as they test two different types of stimuli of different complexity, with the contour stimuli being easier, thus indicating the different extents of stereovision deficits (Fricke & Siderov, 1997; Lee & McIntyre, 1996). Additionally, the Miles test was used to determine eye dominance and Ishihara Colour Vision test was used to test presence of any colour deficiencies (see Chapter 2 for more details).

3.3. Results

3.3.1 Participants

A total of 54 participants took part in the study, 37 of which were recruited at the University of St Andrews, 8 at the University of Abertay in Dundee, and 9 at The School of Optometry, Nova Southeastern University in Florida, USA. Ten participants (18.5%) experienced no difference between viewing images through a monocular aperture and binocularly (3 participants had no stereovision, 2 had only local stereovision, 4 were stereonormal subjects, and 1 had anomalous stereovision). Six (16.2%) were tested at St Andrews, three (37.5%) at Abertay (Dundee), and one (11%) at Nova Southeastern (Florida).

Thus, 44 participants took part in the following testing, one of whom was a collaborator of this study and was therefore excluded from the analysis as she was not naïve to the purposes of the study. More information about the participants used in the analysis (N=43) is provided in Table 3.1 and in Appendix 3.2.

Table 3.1. Participants classification based on their clinically measurable binocular stereovision and descriptives of these groups.

Classification group	N (43)	Average age	Physiology
1. No stereovision	13	45.5	1 mild & 3 severe uncorrected strabismus, 9 corrected strabismus
2. Local stereovision	10	28.4	1 corrected strabismus, 4 severe strabismus, 5 other
3. Stereo-normal	16	22.0	2 corrected strabismus, 3 possible intermittent strabismus, 11 none
4. Anomalous stereovision	4	22.5	2 corrected strabismus, 2 none

3.3.2. Perceived depth of a 2D pictorial image of a 3D scene: monocular aperture vs. binocular viewing

In each of the four groups around 80% of participants perceived a difference in depth between the monocular-aperture and binocular viewing conditions. A binomial test for all subjects indicated that the proportion of participants choosing monocular-aperture viewing as providing better depth perception (0.91 proportion) than binocular viewing was significantly higher than choices made at chance (0.5 proportion; $p<0.001$, one-tailed). The four participants, who identified depth perception being better whilst viewing 2D images binocularly were of varying age and level of stereovision, but did not include any control participants (for more details see Appendix 3.2).

Overall, participants' written responses describing differences between perceived depth under binocular and monocular-aperture viewing replicated prior findings (Vishwanath & Hibbard, 2013), and closely resembled the ratings obtained in the Likert-style questionnaire

(Part 2). There were clear repetitions in wording and characteristics attributed to perceived depth when viewing a 2D image through a monocular-aperture, which can be seen in participants with varying visual characteristics (Table 3.2). In contrast, participants who previously indicated depth to be better under binocular viewing, provided responses that were hard to interpret and used terms, e.g. 3D effect, in an unclear manner (examples in Table 3.3).

Table 3.2. Verbatim written descriptions of the differences perceived between viewing colour photographs binocularly and through a monocular-aperture (examples from participants who indicated depth perception under monocular-aperture viewing to be better).

Participant (participant code)	Description
Control (C10)	When viewed with both eyes the pictures appear to be a singular flat image, when viewed with one eye, the layers of leaves feel more distant and layered. These effects are especially significant when looking at the parts of the plants where it angles towards the eye.
Corrected strabismus (CS3)	- Picture 2 – the stick seems to be near enough to touch. - Picture 1 – the water droplets become more real.
Uncorrected strabismus (SS1)	- With one eye the leaves at the foreground seemed to pop out more. - With both the entire picture seemed to “flatten out”
Other, e.g. amblyopia (O6)	- Viewing through the hole, images seem more ‘real’, i.e. as they would be seen in life, as opposed to in image. - Parts of the image which are closer to the camera appear to be facing forwards, more than downwards (as with both eyes), giving greater degree of separation from their surrounding than with both eyes. - Objects appear to be less directly stacked upon others.

Table 3.3. Verbatim written descriptions of the differences perceived between viewing colour photographs binocularly and through a monocular-aperture (examples from participants who indicated depth perception under binocular viewing to be better).

Participant (participant number)	Description
Corrected strabismus (CS2)	3D effect more visible when viewing with both eyes. In some instances marginal, but difference is there.
Uncorrected strabismus (SS2)	- With 2 eyes I feel the picture more real, in the sense that I perceive a difference in depth between the leaves. With one eye this difference is a bit flattened out. - I think that also with 2 eyes is possible to look at the entire picture and perceive more depth, while with one eye the view is more limited.

Figure 3.3 summarises the results of the Part 2 of the experiment. The A panel of the Figure 3.3 shows the ranking of all participants for each of the 10 Likert-scale statements describing depth perception in monocular-aperture viewing condition in comparison to binocular viewing condition. The responses range from ‘strongly disagree’, which numerically is equal to 1, to ‘strongly agree’ numeric equivalent of which is 7. Overall, on average participants agreed with all five target statements, as the median answer for all five statements was 6, followed by the mean of 5.9 for “objects appear more three-dimensional” (Figure 3.3 Panel A). On the contrary, participants on average disagreed with the four distractor statements, as the median answer was equal to 2 for “objects appear more blurry”, “object shapes are different”, and “colours are more washed out”, and for “objects appear more transparent” the median response was equal to 3 (‘somewhat disagree’). The statement “objects appear to move” was on average rated as neutral (mean and median = 4; for further discussion on its rating see frequency bar graphs in Appendix 3.3). This distinctive difference between the trends

for the target and control items is clear when the data is summarised for all statements for all of the participants (Panel B, Figure 3.3). All participants on average responded significantly different to control and target statements (paired-samples t-test: $t(24)=8.43$, $p<0.001$), with the average for the control statements being 3.1 (3 = 'somewhat disagree') and the average for the target statements being 5.8 (5 = 'somewhat agree'; 6 = 'agree'). The other graphs in the Panel B (Figure 3.3) present the summarised target and distractor statement data for each of the four participant classification groups. The distinction between answers to target and distractor statements remains true for all four groups. The groups with the largest number of participants (stereo-normal group, n=16; and no stereovision group, n=13) have smaller standard errors of the means and less difference between the means and medians, than the two groups with fewer subjects (local stereovision group, n=10; and anomalous stereovision group, n=4).

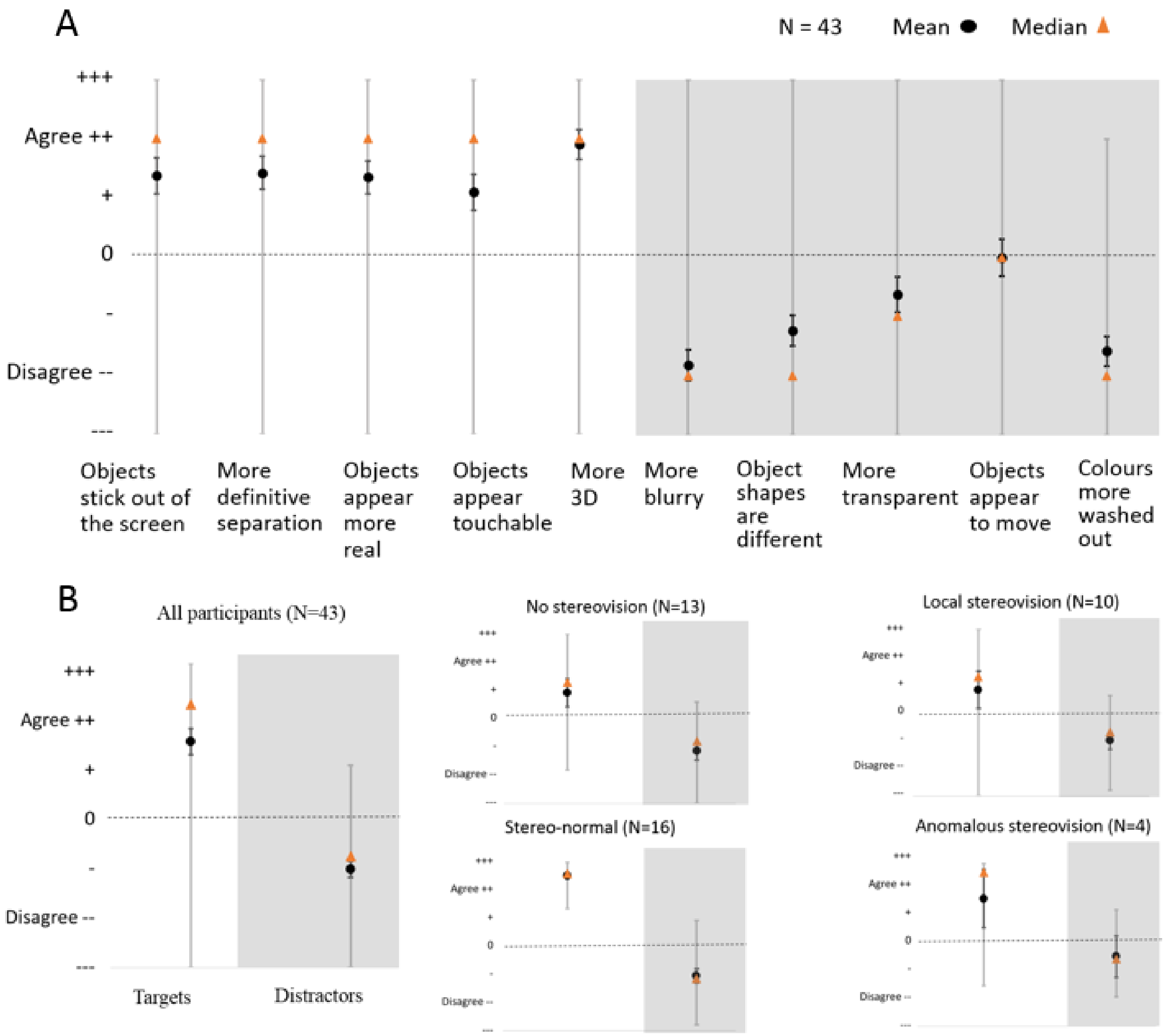


Figure 3.3. Results of Part 2. A) Summary of all participants' responses to each of the five target statements (white area of the graph) and five distractor statements (grey area of the graph). B) Summary of data on target statements (white areas of the graph) and distractor statements (grey areas of the graph) overall, for all participants and for each of the four classification groups. Black circles indicate mean responses, the orange triangles indicate median responses, black error bars represent standard errors of the mean, and light-grey error bars represent the range of responses.

3.3.3. Comparison of monocular aperture and binocular experimental viewings to depth perceived on an everyday basis viewing real 3D objects

The Figure 3.4 summarises the data of Part 1 of the experiment comparing the quality of depth participants experienced during the experimental viewing conditions to the quality of depth they experience on everyday basis. Almost an equal number of participants indicated that the quality of depth they experienced when viewing pictures binocularly was about the same or worse than the depth they experienced on everyday basis, and none of the participants indicated that it was better (Panel A, Figure 3.4). On the contrary, the majority of participants (53.5%) indicated that the depth they experienced when viewing images through a monocular-aperture was better than the depth they experienced on everyday basis, 32.6% indicated that it was about the same, and only 14% indicated that it was worse (Panel A, Figure 3.4). The other graphs in the Panel A of the Figure 3.4 summarise data in the same manner for each of the four participant classification groups, which reveals that the trends slightly vary among the groups. In all groups, the majority of participants stated that their depth perception in monocular-aperture viewing was better or about the same as the depth they experienced on every day basis (Panel A, Figure 3.4). No participants reported it to be worse in the anomalous stereovision group, while in the other groups it varied with the lowest proportion being in stereonormal group (6.3%) and the highest in the local stereovision group (30%). The local stereovision group had the highest proportion of subjects stating monocular aperture viewing condition was better than everyday viewing (70%), whilst no participants in this group stated it to be about the same. In comparison to the local stereovision group, participants' responses in the stereo-normal group (better 56.3%, about the same 37.5%), and no stereovision group (better 38.5%, about the same 46.2%) were more consistent and less spread out. No participants in any of the groups indicated depth in the binocular viewing of the picture was better than on an everyday basis. The majority of the participants in the local stereovision group indicated it as being about the same (80%), followed by no stereovision group (61.5%), and anomalous stereovision group (50%). The majority of stereo-normal participants indicated binocular viewing of the picture under the experimental conditions to be worse than everyday viewing (68.8%).

Once asked to make a forced choice if the depth they experienced on everyday basis was more similar to viewing pictures binocularly or through a monocular-aperture, overall the same proportion of participants chose either of the options (Panel B, Figure 3.4). However, there are notable differences in trends within the classification groups, as more participants in no stereovision and local stereovision groups reported the depth experienced on everyday basis being more similar to viewing images binocularly (53.8% and 60%, respectively). The anomalous stereovision group, the group with the smallest sample size, split evenly between the two responses. While the normal stereovision group showed a reverse trend and had slightly more (56.3%) who reported their depth perception on everyday basis being more similar to monocular aperture viewing of a 2D image. It is important to note, that four out of the nine stereo-normal participants completed the slightly differently arranged questionnaire, which did not emphasise that in order to answer the latter questions participants had to imagine or remember the way they experience depth viewing real 3D objects on daily basis, rather than try to base their answers on what they saw in the laboratory where the experiment took place.

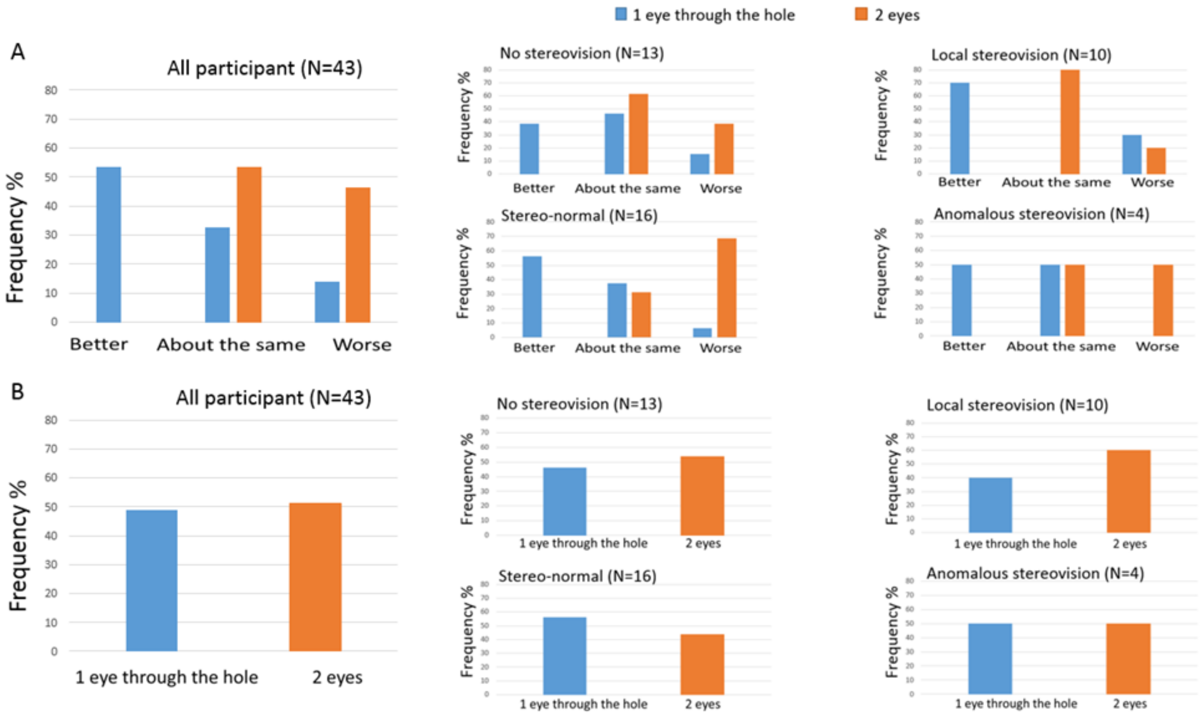


Figure 3.4. Summary of responses comparing depth perceived on everyday basis viewing real 3D objects to depth perceived under experimental 2D picture viewing. A) Summary of all participant responses and responses of participants within each of the four classification groups on the quality of depth they experienced viewing pictures with two eyes or a monocular-aperture being better, about the same, or worse that the depth they experience on everyday basis when looking at real 3D objects. B) Summary of all participant responses and responses of all participants within each of the four classification groups on whether the depth they experience on everyday basis when looking at real 3D objects is more similar to viewing pictures through a monocular aperture or binocularly. The blue bar is the monocular aperture viewing condition and orange bar is the binocular viewing condition.

The difficulty in making the comparison between the experimental environment and everyday viewing of 3D objects had also been mentioned by majority of participants in the open ended question. An example verbatim answer of a subject with an uncorrected strabismus (participant nr. 9): “Not sure as don’t have similar seating right now for comparison”. Difficulty in the judgment resulted in mixed explanations about the perceived depth, in many cases involving more cognitive processes than just memory and perception (examples in Table 3.4).

Table 3.4. Verbatim written descriptions of the differences between experience of depth perception viewing real 3D objects in everyday life and experience of depth viewing the picture through a monocular-aperture.

Participant (participant number)	Description
Control (C8)	- Through hole the eye is drawn to and focuses on the central part of the plant; - Through one eye the depth between the leaves of the plants can be seen in greater detail than in real life.
Corrected strabismus (CS15)	When I consciously try to focus on an object and be observant I probably get close to the one eye through hole effect
Uncorrected strabismus (SS2)	- When I look with one eye I can really tell it is a picture and not reality.
Other, e.g. amblyopia (O7)	- With one eye through the hole, the things in the picture seems to be within my touch. Their depths are clearer. - No obvious depth-difference is observed in everyday life.
Other, e.g. amblyopia (O6)	I feel that sometimes, when viewing objects in everyday life, especially if close, I know their depth by assumption, as opposed to actually seeing it as in the eye hole. But this is not frequently the case.

3.4. Discussion and limitations

Overall, the current experiment replicated the prior findings regarding monocular stereopsis for stereonormal typically developed subjects (Vishwanath & Hibbard, 2013), and further extended them to all groups of participants with varying levels of binocular stereovision and manifestations of strabismus. Consistent proportions of participants experienced monocular stereopsis in all groups, including congenital strabismic subjects with no measurable binocular stereovision.

A large majority of participants reported better depth perception when viewing 2D image through a monocular aperture than with two eyes. Their descriptions of the enhanced percept of depth closely followed characteristics of enhanced tangible depth perception – stereopsis – commonly associated with binocular stereovision (Barry, 2009). However, these target descriptive terms were used by all participants with varying levels of stereovision and strabismus manifestations, which has been further shown in their responses to the Likert scale target statements. The responses for the Likert scale distractor items indicate that monocular-aperture viewing was not associated with other aspects of vision than quality of depth perception. An exception could, arguably, be seen for the "objects appear to move" statement, which had an average score of 4 which corresponded to 'Neutral'. On the other hand, it may be that instead of describing the quality of the depth experienced when viewing the 2D image, participants experienced readjustment of focus (retinal focus), as they hadn't closed their eyes while placing the aperture in front of their eye. This seems plausible considering that participant responses show a large split between Agree and Disagree (see Appendix 3.3). This has been addressed in the experiment 3.2 (Part 3), as participants were asked to close their eyes before viewing again through the aperture, which had been slid in place by the experimenter.

The comparison of depth experienced under monocular-aperture and binocular viewing of experimental 2D image to everyday 3D object viewing has revealed mixed findings with some notable trends for different participant classification groups. However, a majority of participants identified that monocular-aperture viewing provided depth percept either better or the same as the depth perceived on everyday basis. The findings suggest that monocular stereopsis was evoked, but participants had difficulty comparing it to everyday experiences and were driven more towards cognitive derivations rather than remembering experience of depth perception with real 3D objects (e.g. plants, trees). Thus, in experiment 3.2 (Part 3) participants were provided a real object as well as its image for non-blind comparison.

The results of the current experiment suggests that participants with no or local stereovision, experience depth on an everyday basis that is more similar to binocular viewing of a 2D image than a monocular-aperture viewing. This pattern was reversed for stereonormal subjects, suggesting that monocular stereopsis may fall somewhere between binocular stereopsis of a typically developed binocular individual and binocular viewing of an individual with no/limited binocular stereovision. However, it is hard to make such conclusions from a non-blind comparison, as personal and cognitive biases may have affected the results. For instance, no typically developed individuals, who experienced depth differently between monocular aperture and binocular 2D image viewing, claimed that the depth they perceived under binocular viewing was better than under monocular aperture viewing. This, arguably, may indicate personal bias formed due to a history with strabismus and the standard representation to them by opticians or ophthalmologists that depth perception with two eyes is better than with one. Also there may have been an associated misunderstanding of terms and definitions of different visual perceptions. Support for this can be found in the written responses describing difference in depth perception of a 2D image under binocular and monocular-aperture viewing, and also when both experimental viewings are compared to depth experienced on daily basis. Some of the verbatim responses: “When looking with one eye only (the left eye) I see the image as if I am looking through a prism. The image seems to be more “spheric”” (subject code O3); “looking through the hole seems to cut out ‘clutter’ which renders flat images flat, i.e. enhances depth perception – but I am not aware of any issue in normal life with depth perception” (subject code CS8); “I think that also with 2 eyes is possible to look at the entire picture and perceive more depth, while with one eye the view is more limited” (subject code SS2). Taking this into account, in experiment 3.2 a specially designed presentation box was used, which allowed blind comparisons between the 2D pictures of 3D objects, and the actual 3D objects.

Experiment 3.2

In this experiment we explored further monocular stereopsis evoked when viewing 2D images through an aperture, and how it compares to depth experienced viewing real 3D objects. In the prior experiment participants made this comparison based on their memory rather than perception, which, arguably, could have been biased by their personal beliefs, as well as lack of direct comparison. Therefore, in this experiment a specially designed box was used to ensure blind comparison between the real object and its image for both individuals with strabismus, with no or limited stereovision, and typically developed binocular individuals with normal stereovision.

3.5 Methods

3.5.1. Stimuli

There were two stimuli used in this experiment: roses (Part A: non-blind introductory comparison), and lilies (Part A & Part B: blind comparison). The plastic flowers were composed into two arrangements (diameter ~21cm), securing their positions using plasticine. Photographic images were taken of these arrangements from the set eye position (set using chinrest) with a 10 megapixel camera focusing at the centre of the flower arrangement. The images were cropped and adjusted for being displayed on a LCD monitor (Figure 3.5 introductory and testing stimuli). To ensure that participant judgments were not based on differences in brightness alone, there were two images created differing by 5 lux in brightness (Figure 3.5 testing stimuli I and II; see Stimuli tested). Additional stimulus was created (see Figure 3.5) to be displayed during set up of the chinrest and the viewing apertures.

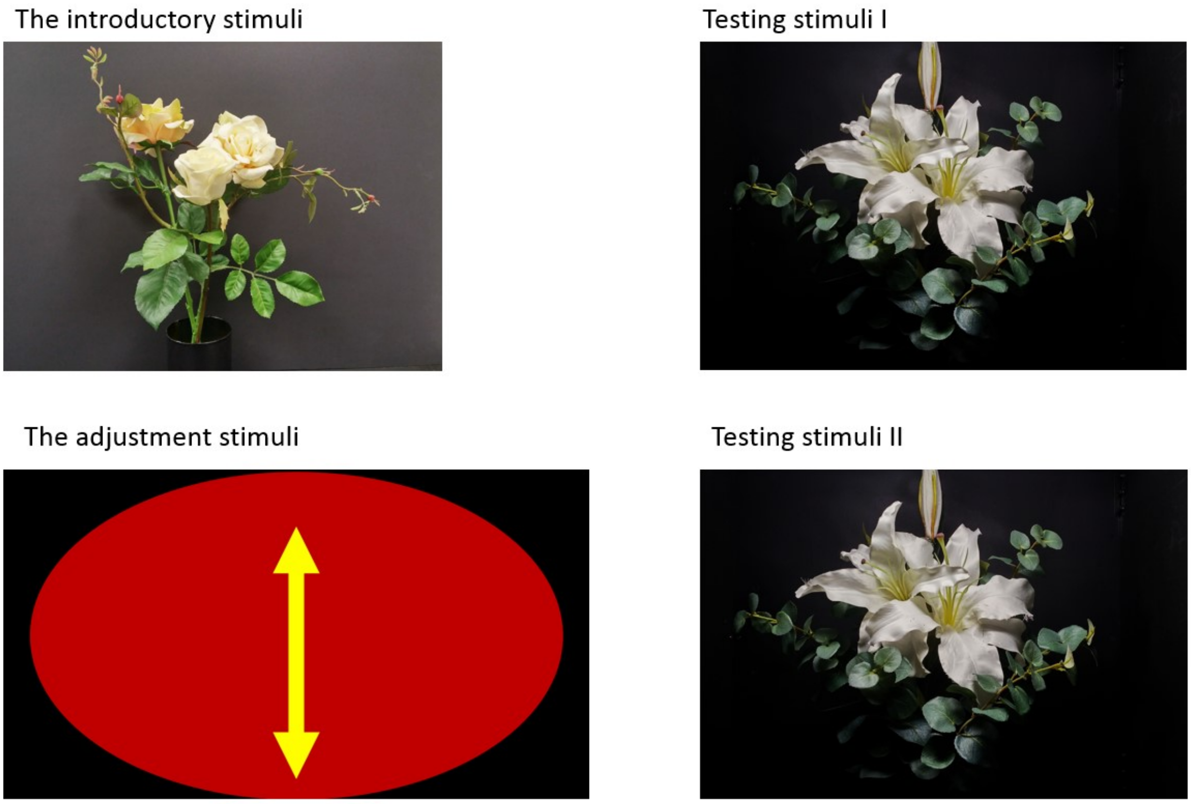


Figure 3.5. Stimuli used in the experiment. The introductory stimuli: arrangement of roses and its photographic image used for the introductory comparison (Part A). Testing stimuli: arrangement of lilies and its photographic image used for blind comparisons in a specially designed display box (Part A & Part B). Testing stimuli I is 5 lux brighter than Testing stimuli II (the main image to be used in Part A, and for reference comparison in Part B). The adjustment stimuli: image displayed whilst adjusting chinrest and viewing aperture positions; participants are seeing the correct part of the screen when both arrowheads are visible.

3.5.2. Stimuli presentation

The introductory comparison was set up in a different room from the testing stimuli. The 4160x3120 px original image of roses was displayed using PowerPoint presentation slides on a 1920x1080 px resolution LCD monitor. The arrangement of plastic roses was set opposite the monitor, with a black foam board placed behind to cover distractions in the background. Participants were instructed to turn the chair around and view either of the stimuli only when sitting directly in front of it. For participants tested in Abertay University, the arrangement of roses was set next to the monitor with a black foam board behind it. In this case participants were instructed to slide the chair and view the stimuli only when sitting directly in front of it. Participants viewed the real stimuli and its image under normal lighting conditions from approximately 60cm viewing distance.

The testing stimuli was presented using a specially designed display box such that both the digital image as well as the real object were viewed from approximately 60cm (Figure 3.6). The participant's head was fixed using a chinrest attached to the box. On top of the chinrest there were adjustable apertures that slid into place (see Figure 3.6 Panel B). The rest of the front of the box was fully covered, so participants were seeing only the stimuli (see Figure 3.6 Panel C vs. Panel D). A half-silvered mirror was set at the front end of the box such that the participants either saw the real object through the mirror (when the object was lit) or saw the reflection of the digital image on the LCD monitor suspended above the mirror. The real object (flower arrangement) was lit by a strip of remote controlled halogen lights. There were two lighting options used for the real objects: 25% and 50% of the full brightness of the halogen light (see Stimuli tested). The LCD monitor was mounted on top of the box directly above the half-silvered mirror (see Figure 3.6). The top of the box had a sliding lid, which allowed to experimenter to cover the monitor ensuring that only the real object was seen. A black image was displayed on the monitor when participants were looking at the real object so that no part of the image was seen when the viewing conditions (sliding of apertures) took place. This way the luminance of the monitor's backlight was present in all viewing conditions, ensuring higher uniformity among them. The 3971x2680 px original images of lilies were displayed using a PowerPoint presentation slide on a 2560x1440 px resolution LCD monitor. This PowerPoint presentation also contained the adjustment image (see Figure 3.5 and Procedure section), and the black background image. Participants viewed the stimuli in a dark or dimly lit room, with no direct light above the display box. The frame holding the monitor in place was covered with black tissue paper to ensure that the viewing box design was hidden to participants. This was revealed to them after the testing.

There were no attempts to match the levels of blur between the pictorial and the real presentations of the stimuli. However, the levels of blur under the described stimuli presentation conditions were expected to be minimal.

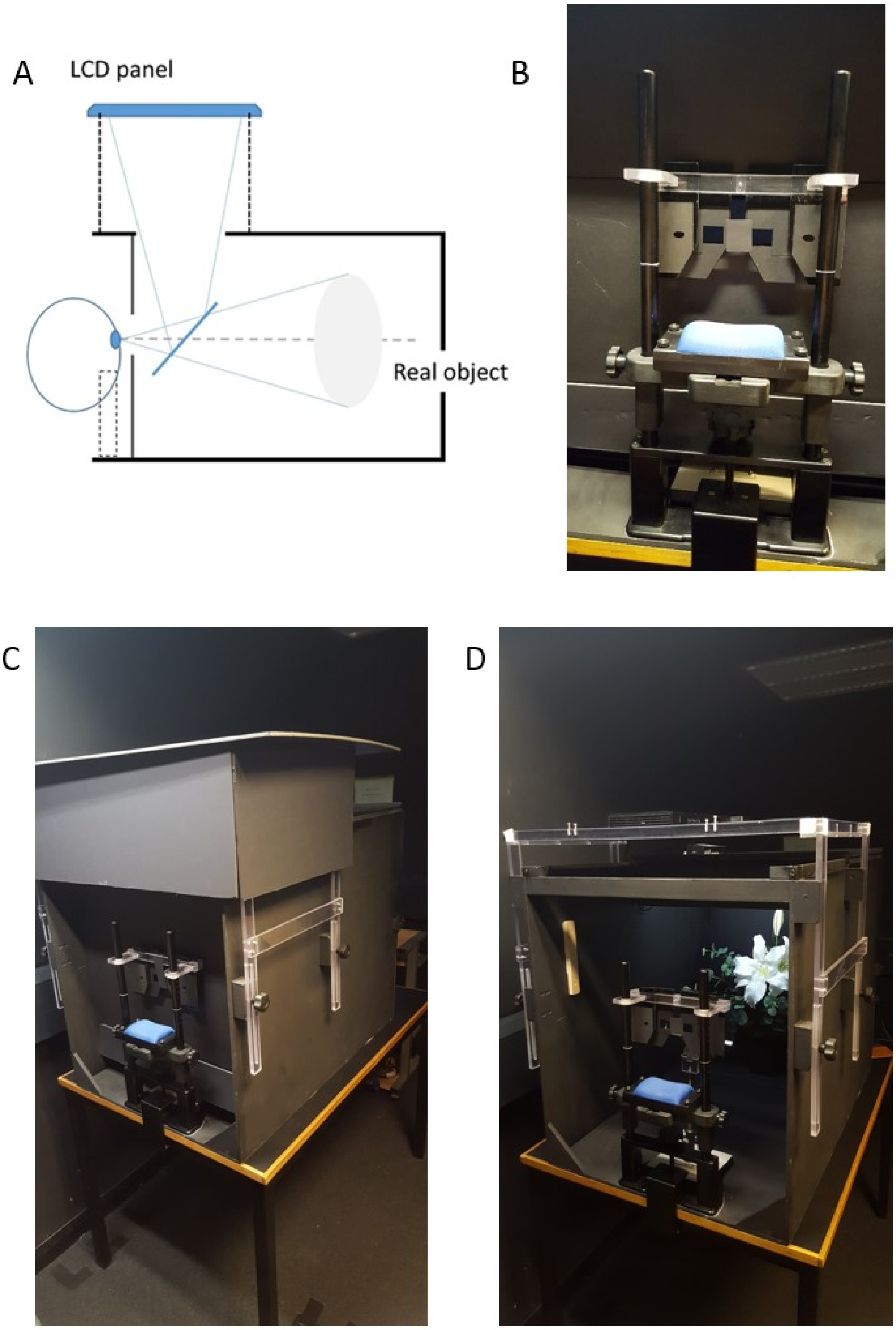


Figure 3.6. The display box designed for blind real object vs picture comparisons. Panel A: schematic presentation of the display box. TV monitor is mounted on top of the box, above the half-silvered mirror. When the monitor is off and the viewer is looking straight through the half-silvered mirror, he/she sees the real object hidden in the box. When the light (halogen strip) above the real object is switched off and the monitor is on, the viewer sees the reflected image of the monitor via the half-silvered mirror. Panel B: adjustable apertures mounted on the chinrest. Panel C: covered box set up for testing. Panel D: uncovered box.

3.5.3. Procedure

The same PowerPoint presentation from experiment 3.1 was used to explain the concept of distance and depth clarifying the distinction between the two (Figure 3.2).

Part A started by participants reading printed instructions, which explained that they will be asked to make judgments about depth they experience in presentations of a 3D objects, and if it appears more like the depth they experience when viewing a real object, or when viewing a picture of the object (Part 3A, top sheet in Appendix 3.4). In order for participants to have a clear understanding of the difference in depth between the two conditions (real 3D object vs. 2D picture of the 3D object), and effectively set the two extremes for an internal depth perception scale, they were asked to view the introductory comparison. Participants viewed the real arrangement of roses and then its image on the monitor at least 3 times. Next they read the second part of the instruction sheet, which emphasised that the judgments should be made about the depth actually perceived, rather than cognitively derived, when rating the experienced "realness" of the 8 experimental presentations (Part 3A, back sheet in Appendix 3.4). The rating was performed on a Likert-type scale ranging from "Picture" to "Real object", which was explained to participants before taking them to the testing room.

Before the testing of the actual experiment, participants were seated in front of the box, and their chair and chinrest were adjusted to a comfortable position. The adjustment image was displayed to ensure that the chinrest and apertures were in the correct location, allowing participants to view the intended part of the monitor (see Figure 3.5). Participants were asked to keep their eyes closed until instructed by the experimenter to open one eye (dominant eye) in monocular and monocular-aperture viewing conditions, or two eyes in binocular and binocular-aperture viewing conditions. Additionally before opening their eyes they were asked to adjust the apertures either for one eye or both eyes. In a couple of cases, with older participants, the experimenter had to slide the aperture into an approximately correct location and then ask participants to adjust it more finely. After viewing the object for at least 10 seconds, participants closed their eyes again and responded with one of the following options: exactly like a picture, like a picture, somewhat like a picture, neutral, somewhat like a real object, like a real object, and exactly like a real object. This was repeated for 8 presentations of a 3D object (summarised in Figure 3.7.). The testing order (Figure 3.7) could not be random, as different viewing conditions could interfere and evoke different qualities of perceived depth, making participants less sensitive to subtle changes in the quality of depth, as well as promoting residual hysteresis effects. For instance, since the aperture viewing condition will likely invoke pupil constriction/dilation and accommodative responses, it is plausible that, if it is followed by a viewing condition that does not involve the aperture, the latter viewing condition may still carry to some extent the aperture effect purely because the pupil has not been forced yet to refocus. The sequence of conditions was therefore designed to minimise such effects.

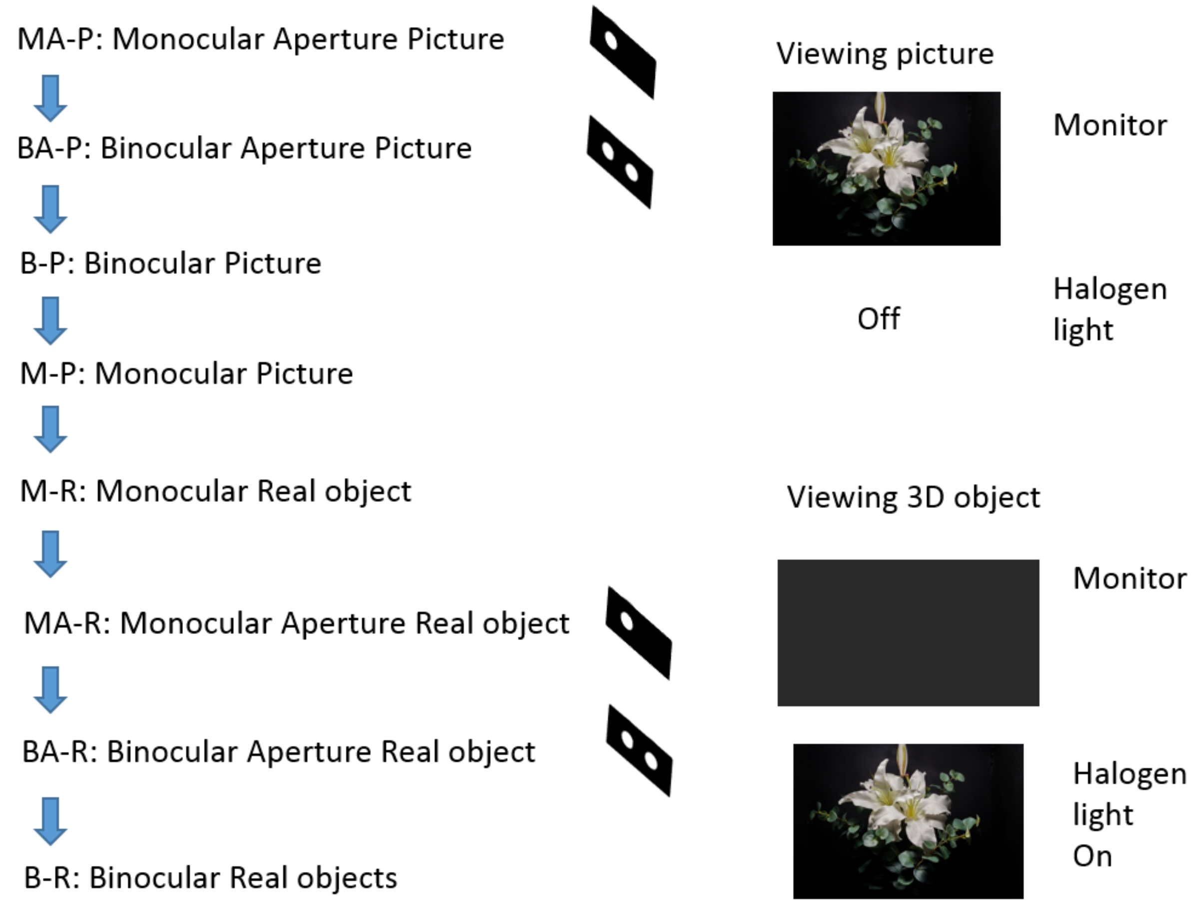


Figure 3.7. Testing order for Part A: evaluation of the perceived quality of depth on a Likert-type scale where the two extremes are the quality of depth experienced when viewing 2D images of a real object binocularly, and the quality of depth experienced when viewing the real 3D object binocularly.

Similar to Part A, Part B started with a printed instruction sheet, which once more emphasised participants to make their following judgments based only on the perceived quality of depth (Part 3B in Appendix 3.5). Participants were asked to perform a comparison task judging perceived quality of depth in two sequential presentations of a 3D object. There were 11 comparison pairs, which had been chosen to test a number of assumptions about the way depth experienced viewing images through a monocular-aperture compares to depth experienced viewing 2D images, and real 3D objects (see Figure 3.8 and Stimuli tested).

The viewing procedure was identical to Part A, as participants followed the experimenter's instructions and kept their eyes closed between the comparison stimuli. At the end of the comparison, participants indicated which of the sequential presentations they perceived to have better quality of depth and the magnitude of the difference they perceived. A scale was created for perceived difference using a reference comparison pair MA-P (monocular-aperture picture) vs. B-P (binocular picture). This comparison was chosen as a reference, because all participants had already indicated to perceive difference between the two viewing conditions in Experiment 3.1. The magnitude of the difference between MA-P and B-P was assigned a value of 5, while 0 expressed no perceivable difference among the two sequential presentations (Vishwanath & Hibbard, 2013). Thus, if participants did not perceive difference among the two sequential presentations, they could mark 0 on the scale and were not forced to choose one of the 3D object presentations. This ensured that participants were not starting to focus on aspects other than their depth perception, e.g. lighting, which had been observed in written responses in Experiment 3.1. Additionally, the random changes in lightness level ensured that participants could not make judgments based on differences in brightness between the real and digital image (see Stimuli tested). If participants perceived any differences they wrote down a number between 0 and 5, or any number above 5, which indicated that the magnitude of difference in the comparison was less than, or larger than in the reference comparison, respectively. The reference comparison was included between the testing comparisons in a systematic manner (see Stimuli tested) to remind the viewers of their internal scale, and participants could request to view it at any point during the testing.

1. B-R vs BA-R ← aperture effect
2. B-R vs M-R ← different in strabismics?
3. B-R vs B-P ← different in strabismics?
4. B-R vs MA-P ← monocular stereopsis
5. MA-R vs M-R ← aperture effect
6. M-R vs MA-P ← monocular stereopsis
7. MA-R vs MA-P ← same?
8. M-P vs B-P ← possible binocularity bias?
9. BA-P vs B-P ← aperture effect
10. MA-P vs M-P ← monocular stereopsis
11. MA-P vs BA-P ← monocular stereopsis

Figure 3.8. The 11 comparisons chosen to be tested in Part B of Experiment 2, order from real vs. real to picture vs. picture. *Outlined in red* – comparing the quality of depth perceived in monocular stereopsis to binocular picture, monocular picture, monocular real object, and binocular real object viewing (which should provide increasingly stereoscopic quality of depth, respectively). *Marked in green* – testing for possible aperture effects, by adding apertures to binocular picture, monocular real object, and binocular real object viewings. In all these comparisons apertures are not expected to elicit monocular stereopsis, and thus should not have an effect on the quality of perceived depth. *Marked in blue* – the two comparisons which highlight the importance of binocular stereovision, and thus strabismics with no/limited binocular stereoacuity would be expected to perceive less difference in the quality of depth in these comparisons than stereo-normal subjects. *Unmarked* – two comparisons were included to check for potential biases and unaccounted visual effects: theoretically there should not have any perceivable difference in the quality of depth unless design is non-blind (comparison 7); if there is difference binocularity bias or cue-coherence theory has an effect (comparison 8).

3.5.4. Stimuli tested

In Part B there were 11 comparisons chosen from the total possible 28 comparisons, due to limited testing time. The chosen comparisons were aimed to test 3 main aspects (summarised in Figure 3.8): quality of depth in monocular stereopsis (comparisons 4, 6, 10, and 11); testing for possible aperture effects (comparisons 1, 5, and 9); and if strabismics with no binocular stereovision perceive depth differently (comparisons 2 and 3 in Figure 3.8). Additional two comparisons were included to check for potential biases and unaccounted visual effects. The first of these comparisons was to check if the real object and picture viewed through a monocular aperture provided the same quality of depth, as theoretically the two presentations should provide identical quality of depth unless the stimulus/viewing design has flaws or participants can clearly tell that they are looking at different things based on other cues such as defocus blur (comparison 7 in Figure 3.8). The second comparison was to check for possible binocularity bias, as mentioned in experiment 3.1 limitations, and effect of cue-coherence theory (Ames, 1925) according to which eliminating conflicting information of binocular disparity would mean that monocular picture viewing provides a much better quality of depth (comparison 8 in Figure 3.8).

Each of the 11 comparisons was repeated 4 times: twice with one viewing condition presented first and twice with the other viewing conditions presented first. The brightness in the tested pictorial stimuli was varied in the same manner when comparisons were made between two images. Similarly there were two lighting levels for the real objects (25% and 50% of the halogen total brightness), when comparisons were made between two real object viewing conditions. For all picture vs. real object comparisons Testing stimuli II and 25% brightness option for the real object were used.

A total of 44 comparisons were presented in 2 blocks (22 in each). Each block started with a reference comparison (MA-P vs. B-P), which was displayed again after 3, then after 6, and once more after 6 testing comparisons. Two computer generated randomised sequences were created for the testing comparison presentation order. The randomisation order was slightly adjusted based on our prior knowledge about the perception of depth and how it is experienced under different viewing conditions. M-P was always presented first when in a comparison pair with MA-P (comparison 10, Figure 3.8), because using an aperture affects pupil and focus, and if the M-P would be viewed afterwards there still would be a residual effect as the pupil would not necessarily have enough time to readjust. Due to similar reasoning and in order to allow the visual system to "reset" - so visual comparisons participants were making would not just be based on just former trials and that participants' visual systems would be "reminded" of the whole spectrum of depth they perceive in different viewing conditions - M-P (comparisons 8 and 10, Figure 3.8) was presented after comparison pairs that involved B-P or BA-P (Comparisons 3 and 9, Figure 3.8). Therefore, the random sequences were created for 9 comparison pairs in total, excluding comparison pairs 8 and 10 (Figure 3.8). Once the order for all other comparisons was set, the comparisons 8 and 10 were placed after comparisons 3 and 9 (Figure 3.8). The two final testing sequences with all additional randomisation, e.g. lighting, are provided in the Appendix 3.6.

3.5.5. Participants

All participants were those who had taken part in experiment 3.1 and had indicated that they perceived differences between monocular-aperture and binocular picture viewing conditions. All typically developed binocular individuals were new recruits after the display box set-up was finished, who could take part in experiment 3.1 and experiment 3.2. Thirteen participants with no/limited binocular stereovision were able to take part in the current experiment.

3.6. Results

3.6.1. Participants

A total of 20 participants took part in the study, 16 of which were tested at the University of St Andrews, and 4 at the University of Abertay in Dundee. More information about the participants is provided in Table 3.5 and in Appendix 3.7.

Table 3.5. Participants classification based on their clinically measurable binocular stereovision and descriptives of these groups.

Classification group	N (20)	Average age	Physiology
1. No stereovision	6	53.5	6 corrected strabismus (4 with tropias)
2. Local stereovision	5	29.8	1 severe uncorrected strabismus (with tropia), 4 other (3 amblyopia)
3. Stereo-normal	7	21.1	7 none
4. Anomalous stereovision	2	25.0	1 corrected strabismus (with tropia), 1 none

3.6.2. Realness rating task

Figure 3.9 summarises the results of the Part A of the experiment 3.2. The A panel of the Figure 3.9 shows all participants' judgments of the quality of depth on a Likert-type scale for each of the 8 visual presentations (Figure 3.7). The Liker-type scale ranged from the quality of depth experienced when viewing 2D picture binocularly (attributed a value of 1) to the quality of depth experienced when viewing real 3D object binocularly (attributed a value of 7), with a neutral option in a middle (attributed a value of 4). Overall, on average participants rated presentations of real objects as having a depth similar to that of real 3D objects they view on an everyday basis, with the highest rating attributed to binocular-real viewing (B-R mean 6.2, SE of the mean 0.236; BA-R mean 5.9, SE 0.339; MA-R mean 5.4, SE 0.294; M-R mean 5.5, SE 0.294). Monocular-aperture picture viewing (MA-P mean 5.15, SE of the mean 0.335) was the only one of the pictorial viewing conditions rated as providing quality of depth similar to that of real 3D objects, with its median matching the medians of monocular, monocular-aperture, and binocular-aperture real object viewings (for all median 6 = "Like a real object"). Binocular-aperture and monocular picture viewings were rated as neutral (BA-P mean 3.65, SE of the mean 0.386; M-P mean 4.1, SE of the mean 0.416), while binocular picture viewing was rated as having depth most similar to that of viewing picture binocularly (B-P mean 2.85, SE of the mean 0.379).

The graphs in the Panel B (Figure 3.9) present the average data for each of the four participant classification groups, with the blue dashed line marking the average values for all participants (summarised in panel A). The same pattern is notable for all participant groups, however, there is variation in the amplitude of perceived differences in the quality of depth across the 8 visual presentations. Stereo-normal and anomalous stereovision groups show higher rating for the real object presentations (all averages above 6), as well as monocular-aperture picture viewing (MA-P: Stereo-normal mean 5.6, SE 0.428; Anomalous mean 6, SE 0). Other picture viewings in these groups are rated lower than the overall participant average, with the stereo-normal group having a median of "exactly like a picture" for binocular picture viewing (B-P median 1, mean 2.3, SE 0.747). On the contrary, no stereovision and local stereovision groups rated binocular, binocular-aperture, and monocular picture viewings closer to "Neutral". No stereovision group overall shows a pattern of all average responses being closer to neutral values, with monocular-aperture picture viewing being rated as providing depth of exactly the same quality as monocular-aperture real object viewing (MA-P and MA-R mean 4.5, median 5), which falls in the middle of real object viewing scores (M-R mean 3.8, median 4.5; BA-R mean 4.5, median 4.5; B-R mean 5.5, median 5.5). In the local stereovision group the monocular-aperture picture viewing is also rated to have the same quality of depth as monocular-aperture real object viewing (MA-P mean 5, median 5; MA-R mean 5.2 median 5), with the other real object viewings rated slightly higher as providing quality of depth more similar to that of real 3-D objects viewed on everyday basis (M-R mean, 6 median 6; BA-R and B-R mean 6.2, median 6).

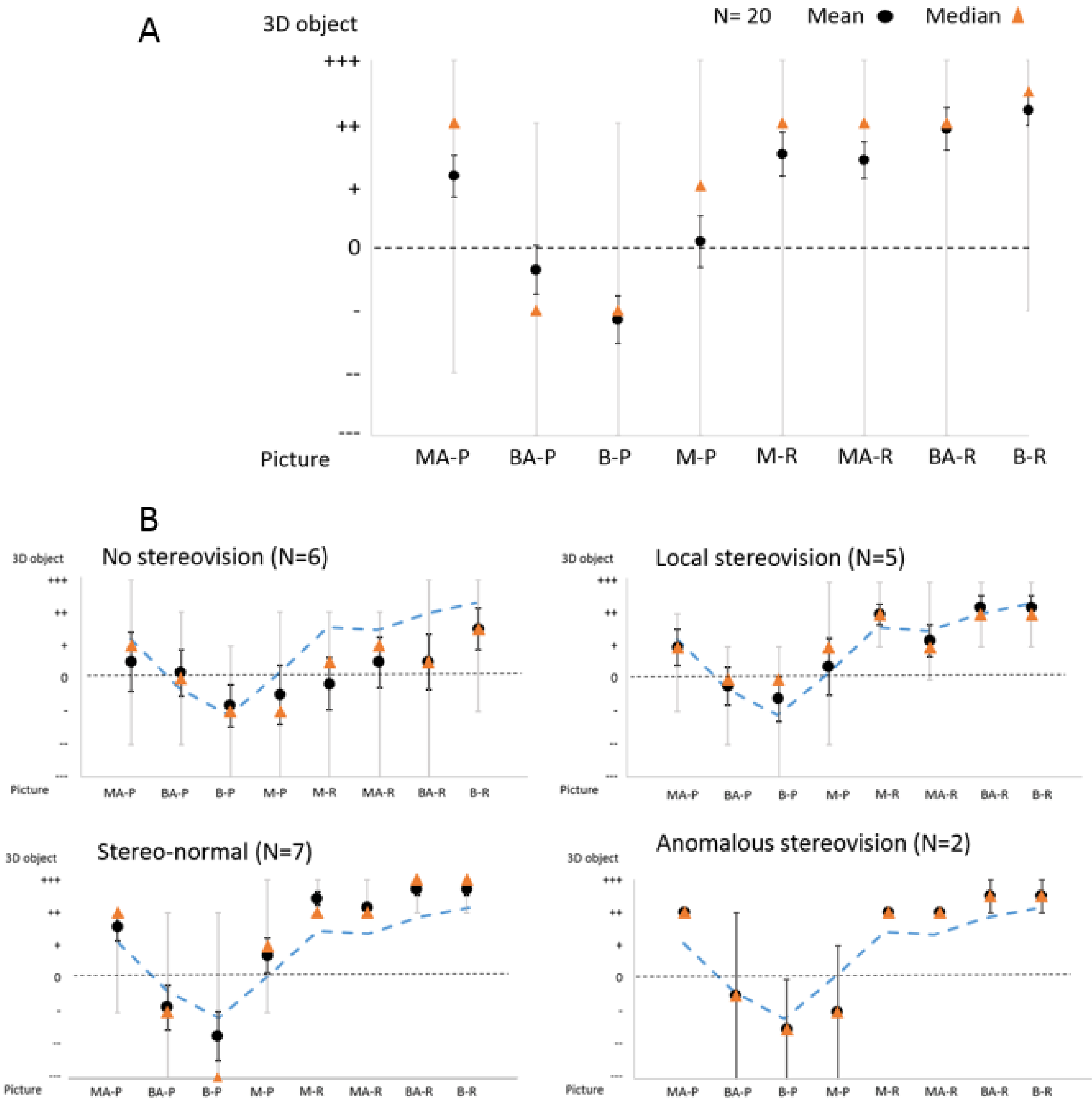


Figure 3.9. Results of Part A: quality of depth ratings on a Likert-type scale for 8 visual presentations A) Summary of all participants' ratings. B) Summary of ratings for each of the four participant classification groups, with the blue dashed line marking the average values for all participants (shown in panel A). Black circles indicate mean responses, orange triangles indicate median responses, black error bars represent standard error of the mean, and light-grey error bars represent the range of responses.

3.6.3. Quality of depth comparison tasks

Part B of experiment 3.2 provided two types of different data. Firstly, participants indicated which of the two sequential presentations of a 3D object provided better quality of depth. The choices were calculated for all participants and in each of the 11 comparisons the visual presentation which overall had been chosen more times was marked as positive ('+1'), while presentation rated as poorer depth quality marked as negative ('-1'), see Table 3.6. The proportions of choices were plotted for all participants (Figure 3.10), and for each of the four participant classification groups (Figure 3.11). As the participants had a third option of choosing that there was no perceivable difference between the two sequential presentations, the proportions were calculated including only the trials when the decision had been made. The frequencies of choices made vs. no choice made did not raise any strong concerns, though in some cases it suggests that making decisions was more difficult in some comparisons than others (see Appendix 3.8).

The second type of data was the magnitude of the perceived difference identified by the participants in every trial they made a choice stating that one of the two sequential presentations had better a quality of depth. All the perceived difference magnitudes attributed to the positive presentations (see Table 3.6) had a positive sign, whilst the difference magnitudes attributed to the negative presentations (Table 3.6) had a negative sign. Thus, when the average magnitude score was calculated the total sum of the difference was the scores given to the visual presentation chosen by a majority minus the scores given to the presentation chosen by a minority. For instance, let us say for the four presentations of B-R and BA-R comparison (comparison 1, Table 3.6) every time a participant indicated the difference magnitude to be equal to 2, but only once out of 4 times chose B-R as providing better quality of depth perception. In this case, as the BA-R was chosen by minority, the magnitude difference score assigned to it will be negative, and thus the total sum of difference will be +4 (-2 +2 +2 +2), and the average magnitude score will be 1 (4/4). This allows to account for any non-corresponding choices made by participants. The averages of the perceived magnitude difference scores are summarised for all participants in Panel A (Figure 3.12), and for each of the four participant classification groups in Panel B (Figure 3.12).

Table 3.6. The 11 comparisons tested in Part B, marked as either positive '+' (if chosen by majority) or negative '-' (if chosen by minority). The colour coding of the comparisons corresponds to the four different aspects they were aimed to explore (see Figure 3.8).

	1	2	3	4	5	6	7	8	9	10	11
+	B-R	B-R	B-R	B-R	MA-R	M-R	MA-R	M-P	BA-P	MA-P	MA-P
-	BA-R	M-R	B-P	MA-P	M-R	MA-P	MA-P	B-P	B-P	M-P	BA-P

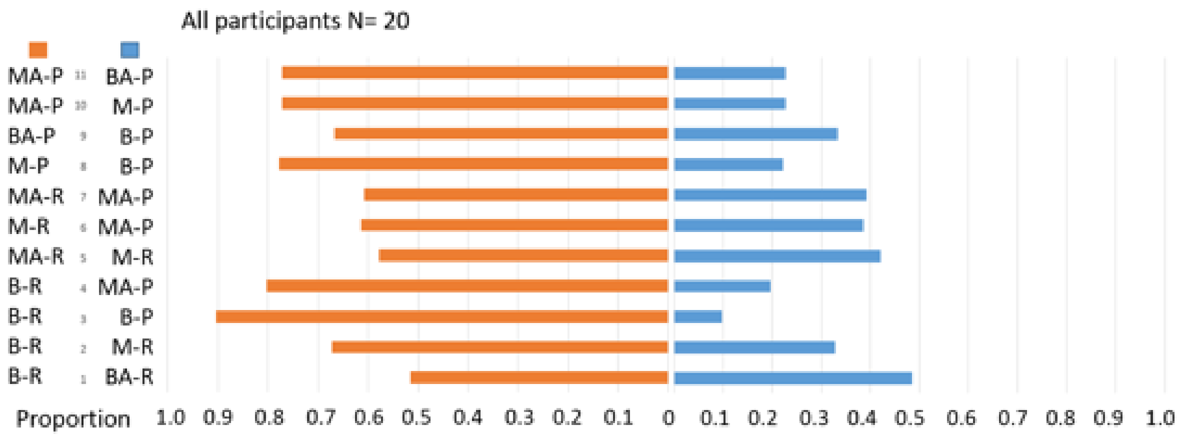


Figure 3.10. Results of Part B experiment 3.2. The proportions of choices identifying one of the two sequential presentations as having a better quality of depth plotted for all participants and each of the 11 comparisons. The viewing presentations in the orange column were chosen by the majority of participants (marked as positive). The viewing presentations in the blue column were chosen by minority of participants (marked as negative).

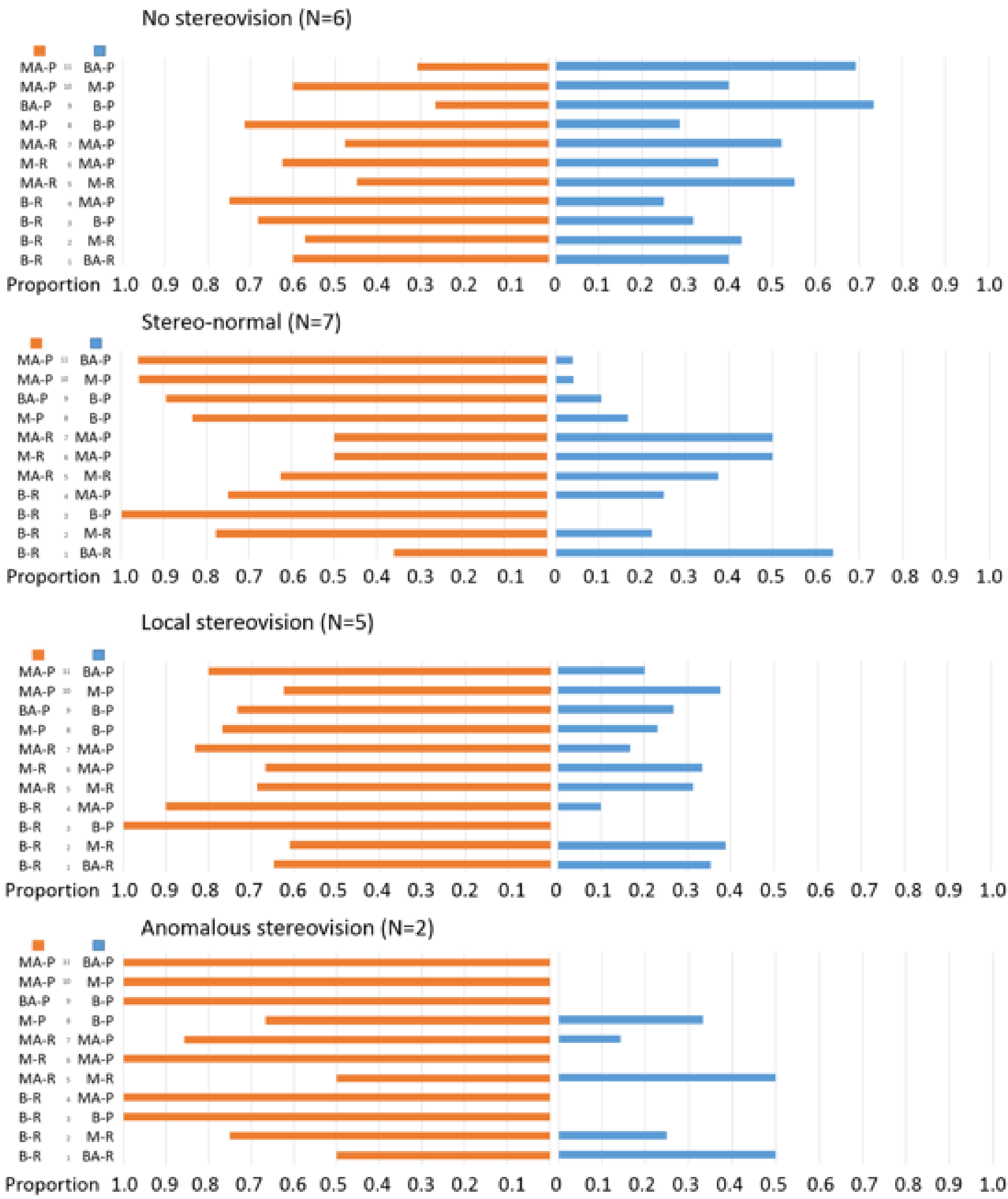
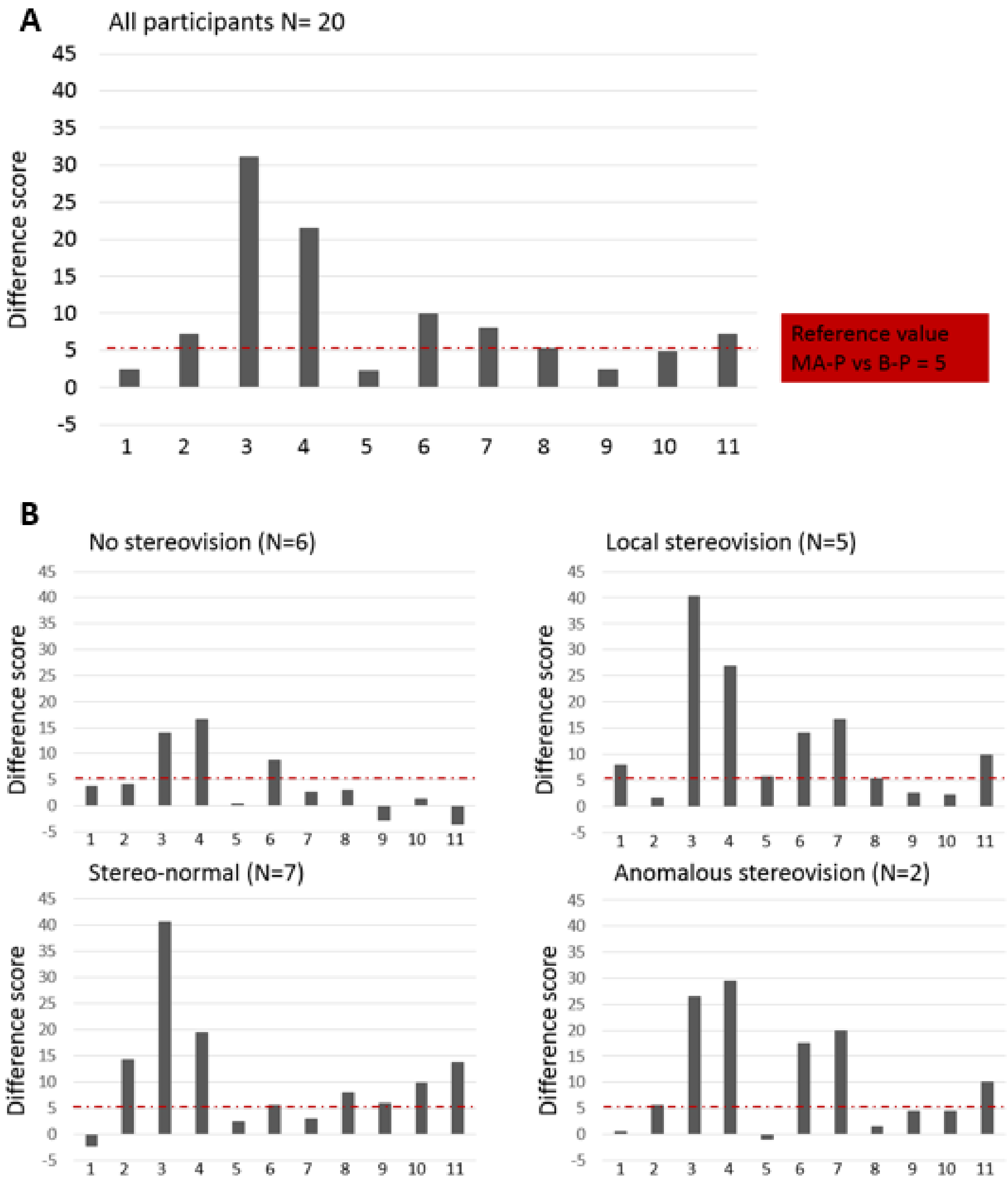


Figure 3.11. Results of Part B experiment 3.2. The proportions of choices identifying one of the two sequential presentations as having a better quality of depth plotted for each of the four participant classification groups and each of the 11 comparisons. The viewing presentations in the orange column were chosen by the majority of all participants (marked as positive). The viewing presentations in the blue column were chosen by minority of all participants (marked as negative).



C

	1	2	3	4	5	6	7	8	9	10	11
+	B-R	B-R	B-R	B-R	MA-R	M-R	MA-R	M-P	BA-P	MA-P	MA-P
-	BA-R	M-R	B-P	MA-P	M-R	MA-P	MA-P	B-P	B-P	M-P	BA-P

Figure 3.12. Results of Part B Experiment 2. The averages of the perceived magnitude difference scores. A) Summarised for all participants. B) Summarised for each of the four participant classification groups. C) Table with the corresponding comparisons maintaining the colour coding of the four different aspects they were aimed to explore.

3.6.3.1. Quality of depth in monocular stereopsis

According to all participant data (Figure 3.10, and Figure 3.12 Panel B), the minority of people chose the monocular-aperture picture as providing better quality of depth than binocular or monocular real object viewing (MA-P better 0.19 and 0.39, respectively). On the other hand, the majority of participants chose MA-P to provide better quality of depth than monocular viewing or binocular-aperture viewing of pictures (MA-P better 0.77 for both). Moreover, whilst the magnitude of the difference for B-R vs. MA-P was 4 times larger than the reference value (21.5), the amount by which M-R was better than MA-P was similar to the amount by which MA-P was better than BA-P (9.9 and 7.2, respectively).

Variations in these trends are notable between the four participant classification groups (Figure 3.11, and Figure 3.12 Panel B). For comparison 4, all groups of participants chose B-R to provide better quality of depth than MA-P, but only in the smallest – anomalous stereovision - group it was a unanimous choice, closely followed by the local stereo group (0.90), whilst proportions were identical in no stereovision and stereo-normal groups (0.75). The difference magnitudes for no stereovision and stereo-normal groups were again similar (16.7 and 19.4, respectively), and smaller than local and anomalous stereovision groups (27 and 29.5, respectively). In comparison 6, monocular real object viewing was chosen over MA-P viewing at chance by stereo-normal subjects (0.5), and almost at chance by local and no stereo groups (0.67 and 0.63, respectively), whilst once more only in the anonymous stereovision group was the choice unanimous.

All groups reported MA-P to provide better quality of depth than M-P in Comparison 10, with the highest proportions being in stereo-normal and anomalous groups (0.96 and 1.0, respectively). The reported magnitude difference for this comparison overall was quite small and similar to the reference value 5. High proportions of participants in stereo-normal, local, and anomalous stereovision groups chose MA-P over BA-P (0.96, 0.8, 1.0, respectively). However, the trend was reversed in the no stereovision group, as majority of the participants chose BA-P to provide better quality of depth than MA-P (BA-P better 0.69). The difference magnitude therefore for this comparison in no stereovision group was negative (-3.5), but notably smaller than the “inverted” reference value (Figure 3.12 Panel B).

3.6.3.2. Possible aperture effects

According to all participant data (Figure 3.10 and Figure 3.12 Panel A) the addition of aperture had some effect, but the proportions are much more evenly split than in the prior discussed comparisons, and there are a number of reversed patterns within the participant groups (Figure 3.11 and Figure 3.12 B).

Overall, the majority of participants chose BA-P viewing as providing better quality of depth than B-P in comparison 9 (0.67), whilst the magnitude difference was minimal (2.3). This pattern was replicated unanimously in the anomalous stereovision group (difference: 4.5), followed by the stereo-normal group (proportion 0.89, difference 5.86), and the local stereo group (proportion 0.73, difference 2.6). However, this pattern was reversed in the no stereovision group with the majority of subjects choosing B-P viewing to be better (0.73), which thus resulted in a negative magnitude difference (-2.83) which was still smaller than the “inverted” reference value.

The choice in comparison 5 between M-R and MA-R viewings were roughly at chance, with the highest proportion in favour of MA-R being in the local and the stereo-normal groups (0.69 and 0.63, respectively), followed by the anomalous and no stereovision groups (0.5 and 0.45, respectively). A similar reversed pattern appeared in comparison 1, with the highest proportion being in the local and the no stereovision groups in favour of B-R (0.65 and 0.6, respectively), followed by an at chance choice in the anomalous group, and a reversed pattern in the stereo-normal group (0.36 for B-R). For both of these comparisons the difference magnitudes were small, with the highest ones being close to the reference value in the local stereovision group (comparison 5 difference 5.8, comparison 1 difference 8).

3.6.3.3. Strabismics with no stereovision

The two comparisons which were included to explore the importance of binocular stereoacuity and the effects of its limitations have showed clear differences between the groups (Figure 3.11 and Figure 3.12 Panel B).

In contrast to all other groups, the no stereovision subjects in comparison 3 were split between B-R and B-P viewings (B-R better 0.68), whilst all other groups unanimously chose B-R as providing better quality of depth. Additionally, this comparison had one of the highest difference magnitudes, the highest being in the stereo-normal and the local stereovision groups (40.57 and 40.2, respectively), followed by the anomalous stereovision group (26.5), and with the no stereovision group having the smallest difference magnitude (14.0). In comparison 2 the division was less apparent but the same pattern was maintained in the data. The majority of people chose B-R over M-R with the highest proportions being in the normal and anomalous stereovision groups (0.78 and 0.75, respectively), followed by proportions close to chance in the local and no stereovision groups (0.61 and 0.57, respectively). The perceived magnitude differences were close to or lower than the reference value for all groups with exception of the stereonormal group (difference 14.14).

3.6.3.4. Other Conditions – biases and unaccounted visual effects

The two comparisons which were included for the further exploration of possible biases and unaccounted visual effects had notable patterns in the group responses (Figure 3.11 and Figure 3.12 Panel B).

In all groups, in comparison 8, the majority of participants chose M-P viewing to provide better quality of depth than B-P viewing (proportions: stereo-normal 0.83, local stereo 0.77, no stereo 0.71, and anomalous stereo 0.67). However, the magnitude differences were relatively low, lower or close to the reference value (difference: stereo-normal 8, local stereo 5.4, no stereo 3.0, and anomalous stereo 1.5).

In comparison 7, participants' responses had two patterns. No stereo and stereo-normal subject groups responded at chance (MA-R better than MA-P: 0.48 and 0.5, respectively). The magnitude differences reported by these groups were small (difference: no stereo 2.67, stereonormal 2.86). In contrast, in the local and anomalous stereovision groups the majority of participants indicated MA-R to have better quality of depth than MA-P (0.83 and 0.86, respectively). In these groups the difference magnitude was one of the largest from all 11 comparisons (difference: local 16.8, anomalous 20.0), and almost 10 times bigger than the magnitudes reported by the stereo-normal and no stereovision groups.

3.7. Discussion and limitations

3.7.1. Realness rating task

In relation to the experiment 3.1 findings, in all groups monocular-aperture picture viewing was rated to provide similar quality of depth as real 3D object viewings, whilst all other picture viewings were rated to have quality of depth similar to 2D picture viewing binocularly. Even though in the no and local stereovision groups, responses were closer to neutral, monocular-aperture picture viewing ratings corresponded to those of the real object viewings. In fact, monocular-aperture picture and real object viewings were rated to provide a similar quality of depth, with this rating being identical in all participant groups with the exception of stereo-normal group. Therefore, under blind conditions, monocular stereopsis evoked in the monocular-aperture picture viewing conditions seem to have allowed participants with varying levels of stereovision to perceive depth of quality analogous to real 3D object viewing. This quality of depth seems to be the closest to monocular-aperture real object viewing, but not as good as viewing real 3D object binocularly. It is possible that less similarity between the rating of the monocular-aperture picture and monocular real object viewing is due to the fact that participants still subconsciously rate conditions with similarly sized visual fields as providing more similar qualitative characteristics.

In comparison to other groups, individuals with no and limited binocular stereovision on average reported to perceive a smaller quality of depth between picture and real object viewings. In fact, the averages were far from the extreme end options of the Likert-type scale (exactly like a picture and exactly like real 3D object). This could suggest that in everyday life, depth perception is based on other sources of information, such as monocular parallax, skeleton-muscular information, and cognitive processing, as well as the fact that in everyday life one would usually know if they are looking at the real 3D object or a 2D picture.

3.7.2. Quality of depth comparisons

Quality of depth in monocular stereopsis comparisons suggest that monocular-aperture picture viewing provided better quality of depth than viewing pictures (monocular, binocular and binocular-aperture viewings). In some trials participants chose monocular-aperture picture viewing to even have better quality of depth than binocular real object viewing. Overall, the findings resemble those of the realness rating task, as monocular-aperture viewing was rated the closest to monocular real object viewing. This comparison in all participant groups yielded roughly at chance outcome, with the exception of the anomalous stereovision group. However, this group had only two participants and cannot be considered to be representative of individuals with anomalous stereovision. Another consideration raised by the data was that no stereovision subjects, in contrast to all other groups, chose binocular-aperture over monocular-aperture picture viewing. It is not clear if this is due to possible binocular viewing bias, or a generally older sample of subjects who have weaker pupil muscles and thus less information is received from accommodation which may adversely affect induction of monocular stereopsis (Vishwanath, 2014). Therefore, a larger sample of participants should be tested with more age-matched cohorts.

Comparisons looking at the possible effect of the aperture independent of depth perception showed some differences, but the proportions were more evenly split, and closer to chance. The fact that there were three inverse patterns and no clear trends between the groups, and that difference magnitudes were very small, indicate that these comparisons were highly difficult to judge. This is supported by response frequency data, as one of these comparisons (binocular picture vs. binocular-aperture picture) had the lowest percentage of answered trials out of all 11 comparisons (see Appendix 3.8) indicating that these two conditions were seen as highly similar. It is plausible that high difficulty judgments, requiring high sensitivity and identifying minor difference magnitudes, yielded unreliable results as participants might have attempted to find a difference where they perceived none. Thus, either the binocular-aperture does not have an effect or more data needs to be gathered to expose any systematic patterns.

The presence of stereovision has been found to be important in comparisons aimed to explore the significance of binocular stereovision in perceiving difference in the quality of depth under the specific experimental testing conditions. The no stereovision group was the only one to not unanimously choose binocular real object viewing as providing better quality of depth than binocular picture viewing. That being said, their responses in this comparison were not at chance, as their performance in clinical binocular stereovision tests would have predicted. In the binocular and monocular real object comparisons both no and local stereovision groups had the closest to chance proportions, whilst anomalous stereovision group performed as stereo-normal group, thus suggesting that perceived global stereopsis, as measured by TNO and RanDot tests, played an important role in this comparison.

The last two comparisons exploring biases and unaccounted visual effects, did not appear to reveal any design flaws. As predicted, the no stereovision and stereo-normal groups performed at chance and indicated a low difference magnitude when having to choose between the monocular-aperture real object and picture. On the other hand, the monocular-aperture real object condition was chosen over the monocular-aperture picture in the anomalous and local stereo groups, and with a large magnitude difference. Whilst this interesting split between the groups does not suggest that the design was non-blind, it may point to differences in visual processing in individuals with limited stereovision. It is plausible that subjects in the latter two groups have learnt to focus on monocular depth cues, such as blur, contrast, and lighting/shading. Additionally, a number of subjects in the local stereovision group were amblyopes or strabismic amblyopes, which have been known to have reduced contrast sensitivity in their amblyopic eye (Levi et al., 2015) and may have, arguably, learned to associate it with better quality of depth perception. The second comparison provided evidence against the possibility of a binocularity bias (i.e., subjects choosing binocular viewing as providing better quality of depth than monocular viewing purely due to their belief than two eyes are better than one), as in all groups monocular picture viewing was indicated as providing better quality of depth than binocular picture viewing. This outcome is expected according to cue-coherence theory (Ames, 1925), as the conflicting binocular disparity cue had been eliminated under monocular viewing and thus the depth would be perceived as less "flattened" (J. Koenderink, van Doorn, & Kappers, 1994). However, participants had difficulty making a decision in this comparison, as it had one of the lowest percentages of choice made (see Appendix 3.8) and low magnitude differences. Therefore cue-coherence effect even if present is small and hard to detect for a large number of subjects.

3.8. General discussion

The current study not only replicated the prior findings on monocular stereopsis in stereonormal typically developed binocular individuals (Vishwanath & Hibbard, 2013), but also showed that monocular stereopsis can be experienced by individuals with varying levels of binocular stereovision and manifestations of strabismus, including subjects with infantile uncorrected strabismus.

Written responses in experiment 3.1 closely resemble characteristics of binocular stereopsis so beautifully described by Susan Barry (Barry, 2009), and show that a monocular-aperture allows the majority of subjects to experience immersive and tangible space – monocular stereopsis. Further, blind comparisons in experiment 3.2 indicated that for all participants, the quality of depth experienced viewing 2D pictures through a monocular-aperture was better than viewing 2D pictures under any other conditions, and overall seemed to most closely resemble a quality of depth experienced when viewing real objects monocularly. These findings are aligned to an alternative view of stereopsis (Vishwanath, 2014). For the sample of individuals tested there appears to be a continuum of conditions with different levels of stereopsis (quality of depth spectrum), with binocular viewing of a real object on one extreme and binocular viewing of a 2D picture on the other. Monocular stereopsis evoked under monocular-aperture viewing of a picture, was rated by participants to provide the same quality of depth as monocular real object viewing (same absolute depth precision). Therefore, even though the magnitude of the difference in the quality of depth between binocular picture viewing and monocular-aperture picture viewing is relatively small (e.g. in comparison to magnitude of the difference between binocular picture and binocular real object viewing), monocular stereopsis seems to tend towards the middle of the quality of depth spectrum for all levels of binocular stereovision tested.

Binocular stereoacuity levels seems to have had a couple of effects on the quality of depth perceived under different viewing conditions. The previously described spectrum of the perceived quality of depth, on average, had a smaller amplitude among participants with no and local binocular stereovision (see Figure 3.9). This, though, may not mean that they have a smaller depth spectrum on an everyday basis, where they arguably use other sources of information. In fact, anomalous and local stereovision subjects indicated monocular-aperture real object viewing to have better quality of depth than monocular-aperture picture viewing, thus suggesting that their choices largely depended on the defocus blur – the only available cue for absolute depth scaling in that real object viewing condition. It is possible that participants in these groups have tendency to focus on monocular cues, such as blur, contrast and lighting, which had not been perfectly matched between the 2D picture and real 3D object, and thus for instance chose object presentation with higher contrast or differences in blur as having better quality of depth. This corresponds to previous research on amblyopia (Levi et al., 2015), and the fact that the local stereovision group included a number of amblyopes or strabismic amblyopes. The second effect notable in the current study was, as predicted, in comparisons requiring binocular disparity processing for perceiving difference in sequential presentation of objects. While only participants with no clinically measurable binocular stereovision were unsure about difference between binocular real object vs. picture viewing, the choices were closest to chance when comparing binocular and monocular real object viewing in both no and limited stereovision groups. However, the responses were only close to chance, which suggests there was some level of binocular disparity processing among some of the participants, which is plausible considering research on the presence of peripheral disparities in strabismic amblyopes (Fronius & Sireteanu, 1989) and anomalous retinal correspondence (von Noorden & Campos, 2002; Wright et al., 2006). On the other hand we cannot dismiss more cognitive use of monocular cues in the local stereovision group, which was highlighted in some of the written responses, e.g. "I feel that sometimes, when viewing objects in everyday life, especially if close, I know their depth by assumption, as opposed to actually seeing it as in the eye hole".

These observations of the findings are complicated due to limited participant numbers in each group. Ideally the testing should be carried out to gather more substantial amounts of data allowing to perform statistical analysis between the groups. Additional limitations discussed in respect to each of the two experiments indicate the high complexity of the task as well as possible misunderstandings of terminology and personal and learned biases. Semi-structured interviews could be employed for better understanding of the beliefs and biases individuals with strabismus may hold. Overall addressing these limitations would allow to improve the testing procedure and stimuli presentation, but none of them indicate any essential flaws in the unique testing design developed in the current study allowing to perform blind comparisons between real 3-D objects and their 2-D images.

Chapter 4

Egocentric distance perception in strabismus: familiar object size

4.1. Introduction

The accurate perception of viewing distance is necessary for interacting with space (e.g., for correctly reaching and grasping or throwing objects) and making correct estimates of objects within it (e.g. estimating size) (Glennerster et al., 1996). As discussed in the General introduction chapter egocentric distance is the distance from an observer to a point in space he/she is focusing on (Loomis et al., 1996). In the near personal space the two oculomotor cues – accommodation and vergence – provide accurate egocentric distance information up to approximately one meter (Fisher & Ciuffreda, 1988; Viguier et al., 2001). Additional egocentric distance information at the near personal space is derived from the retinal blur and can be induced artificially by applying the depth-of-focus gradient to photographic images (Vishwanath & Blaser, 2010). Egocentric distance information can be accurately perceived not only in the personal space, but also throughout most of the action space (up to 15m according to Loomis et al. (1996), and 20m in the natural terrain according to Wu et al. (2004)). Therefore, if individuals with strabismus have impairments in their ability to estimate egocentric distance, it will affect their ability to interact with objects and space around them, including difficulties not only in reaching and grasping of objects, but also in throwing or kicking objects into the action space, estimating walking time, or driving.

4.1.1. Egocentric distance perception in individuals with strabismus

Individuals with strabismus are expected to have impaired or absent egocentric distance information from the vergence. Though as discussed in the General introduction chapter (Section 1.2.1.) deficits in vergence information would be expected to vary among strabismics depending on the type of their strabismus (Rutstein et al., 2011; von Noorden & Campos, 2002; Wright et al., 2006). All of the other egocentric distance information sources - accommodation, depth-of-focus blur, eye declination level, and earth curvature - should be available to individuals with strabismus. Lack of direct predictions are due to the fact that there are a limited number of studies exploring distance perception in strabismics. Simon Grant's and colleagues work on amblyopes and stereo-deficient adults show the importance of binocular stereovision in everyday visuomotor tasks (Simon Grant & Conway, 2015; S. Grant & Moseley, 2011; Melmoth, Finlay, Morgan, & Grant, 2009). Research on reaching and grasping in strabismics and strabismic amblyopes showed their performance to be comparable to controls under binocular and monocular dominant eye viewings, while deficits in reach precision and latency were found only for monocular amblyopic eye viewing in strabismic amblyopes (Niechwiej-Szwedo et al., 2014). During the reaching task both strabismics and strabismic amblyopes were found under all viewing conditions to have lower peak acceleration and a longer duration of acceleration phase than controls (Niechwiej-Szwedo et al., 2014). The authors (Niechwiej-Szwedo et al., 2014) suggest that due to the binocular visual impairments affecting strabismics' depth judgments, the observed differences in acceleration are part of the adapted motor strategy allowing correction of the movement plan according to visual feedback. In the action space, egocentric distance available from eye declination level is explored using the blind walking paradigm, where an observer views an object from a stationary position then is blindfolded and asked to walk the perceived distance (Loomis et al., 1992; Loomis et al., 1996; Ooi & He, 2015; Ooi et al., 2001; Wu et al., 2004). A blind walking study by Ooi and He (2015) explored egocentric distance perception in strabismic individuals in comparison to typically developed binocular individuals. In this study (Ooi & He, 2015) participants were asked to view a target object (a sphere) either on the ground or suspended in the air, and when blind-folded to walk the perceived distance to the object's location and to gesture the height at which it was displayed. Strabismics performed similarly to control subjects under binocular and monocular (dominant eye) viewing when an object was placed on the floor up to seven meters in distance. However, when the object was suspended in midair, strabismics misjudged the location of the objects with lower accuracy under binocular viewing, while controls made erroneous judgments only under monocular viewing (Ooi & He, 2015).The authors (Ooi & He, 2015) suggest that strabismics performance, when the object was placed on the floor, was similar to performance of the controls, due to the monocular depth cues, such as floor texture gradient, providing information about the target's location. However, when the target object was suspended in the air, its location information had to be derived from binocular disparity, which in strabismic participants was impaired (Ooi & He, 2015).

According to this limited amount of research exploring egocentric distance perception in individuals with strabismus, the exact extent of the impairment of limitations strabismics experience is still unclear. Anecdotal reports make it clear that individuals with no binocular vision and even diplopia are capable of functioning in the everyday world, including such high complexity tasks as driving (Barry, 2009). Susan Barry reports suggest that infantile strabismics with no measurable binocular stereoacuity seem to be able to interact with objects better than stereo normal people with monocular viewing: "I took some tennis lessons with an accomplished pro. One day, I asked him to wear an eye patch so that he had to hit the ball using only one eye. I hit a ball to him high in the air and watched this superb athlete miss the ball entirely" (Sacks, 2006). Of course in this situation (described in the quote) there are motion cues (motion parallax), as well as a number of other monocular cues (e.g. relative size, perspective), which strabismics may learn to depend on. In fact, Sacks (2006) in his New Yorker article about Susan Barry mentions an account of a filmmaker Errol Morris, who was born with strabismus and lost almost all vision in one eye: "I see things in 3-D. I move my head when I need to – parallax is enough". The design of the previously discussed experiments (Niechwiej-Szwedo et al., 2014; Ooi & He, 2015) also contained monocular relative depth information that affected the outcome of their findings. Therefore, there is a need to explore how well strabismics can perceive egocentric distance in the environments with limited visual information, for instance, without ground plane, eye declination level, or motion parallax information.

4.1.2. The link between the object size and egocentric distance perception

One of the possible ways of investigating egocentric distance perception is by measuring perceived object size, because perceived size depends on perceived distance. The example provided in the Figure 4.1 illustrates this relationship. A person viewing two identical coke cans placed at two different distances, would receive two retinal size images that would differ in size. In this case (Figure 4.1.) the coke can viewed by the right eye is twice as far as the coke can viewed by the left eye, and thus the right eye retinal size will be half the size of the left eye retinal image. Therefore, only the perception of egocentric distance to the two coke cans would allow the viewer to accurately perceive them as being identical in size. This is known as size constancy – the tendency of objects to appear relatively constant in size despite changes in the size of the retinal image due to being viewed from difference distances (Schiffman, 2001). Holway and Boring (1941) found size constancy of an abstract disk object under normal visual cue binocular and monocular viewing, but the size constancy dropped with the elimination of visual information by viewing the disk through a small hole (artificial pupil), or by covering the floor, walls, and ceiling with black cloth (tunnel of black cloth). In their experiment Holway and Boring (1941) asked participants to adjust the comparison disk to match the size of the standard disk (the varying stimuli) displayed from 3 to 36 meters. Research on eye-declination and earth curvature providing egocentric distance would explain lack of size constancy due to limited visual information up to 15 meters (Loomis et al., 1996). The principle of adjacency described by W. C. Gogel (1963) suggests that perceptions of relative size and distance are locally determined, i.e. judgments of two object sizes do not involve egocentric perception but rather the judgments of the two retinal images of those objects ("perceptually organising the relative retinal stimuli"). Therefore, seeing a target object in an environment, with other information sources, such as tile patterns or doors, would allow to make local judgments and thus size judgments without perception of egocentric distance to the object. Similar suggestions were made by Ooi and He (2015) in relation to their strabismic subjects being able to accurately judge an object located on a floor. This raises questions about how accurately individuals with strabismus would be able to make size judgments under limited visual conditions, for instance in a dark room, and how comparable their performance would be to that of typically developed binocular individuals.

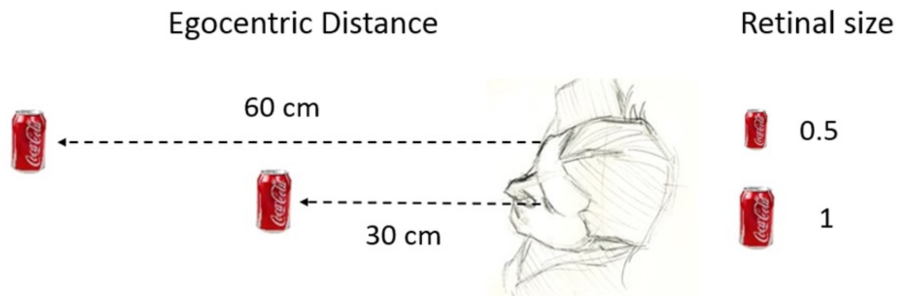


Figure 4.1. Example of relationship between perceived egocentric distance and object size. A viewer sees two cans of coke and two different distances (30 cm and 60 cm). The retinal images received by the two eyes are inversely proportional to viewing distance. This means if the coke can viewed at 30 cm (left eye) produces a retinal image of size 1, the coke can viewed at 60 cm (right eye) will produce a retinal image of half that size (0.5). Accurate perception of the egocentric distance allows the visual system to scale the retinal object sizes, and provide veridical perception, i.e. both coke cans are perceived to be the same size.

In order to explore this, we must consider the relationship between the perceived object size and distance in more detail. The size-distance invariance hypothesis (SDIH) states that the perceived absolute size (S') of an object producing a constant retinal size (ϴ) is specified by the perceived absolute distance (D') (W. C. Gogel, 1963) . According to a specific case of SDIH, Emmert's Law: when the retinal size of an object is constant the perceived object size is proportional to the perceived distance (Epstein et al., 1961). This can be mathematically expressed by the formula 1, where S' is the perceived object size, D' is the perceived distance, and ϴ is the visual angle (W. C. Gogel, 1963; W. C. Gogel & da Silva, 1987).

$$S'/D' = \tan \Theta \tag{1}$$

In personal space, typically developed binocular individuals can accurately perceive egocentric distance (D') using accommodation, vergence, and depth-of-focus blur information, and thus should perceive accurate object size (S'). As discussed in the General introduction chapter, the extent of vergence impairment in individuals with strabismus varies according to the type and cause of the misalignment, thus we can assume that there is an impairment but its exact extent is unclear. Therefore, it is hard to make exact predictions about the way strabismics would perceive object size, though they should perform most accurately under near distance viewing (~1m) where accommodation and depth-of-focus blur information is available. In action space, when the visual information is limited, and thus there is no available earth curvature or adjacent object retinal comparison information, a "specific distance" tendency was found to take place in object size judgments of typically developed binocular individuals (W. C. Gogel, 1963; W. C. Gogel & da Silva, 1987). Specific distance tendency is a tendency to perceive an object at about 2-3 meters from the observer, when visual information cues to distance are reduced or eliminated (W. C. Gogel, 1969b, 1976). Most research on this tendency has been carried out using familiar objects (W. C. Gogel, 1969b, 1976; W. C. Gogel & da Silva, 1987), which allow to explore the importance of monocular cue – familiar size – for perceived size and thus perceived distance judgments. Using familiar size as a cue to distance is considered to be a cognitive process, as it is based on a memory of the object size rather purely on the perception of it (Schiffman, 2001). W. C. Gogel and da Silva (1987) suggest that size and distance perception of SDIH is affected by this cognitive familiar size processing, which can be expressed as formula 2.

$$D_c = D' (S_c/S') \tag{2}$$

In this equation S' is perceived object size, and D' is perceived distance, while S_c is a cognitive familiar object size, and the D_c is the cognitively perceived distance according to that size (W. C. Gogel & da Silva, 1987). For instance, a human figure has a relatively familiar size, thus even when seen in a dark room by him/herself, viewers would cognitively assume the distance to that human figure based on their experience of seeing such figures prior in their life. According to the formula 2, if a viewer perceives the familiar object being smaller than normal ($S_c/S' > 1$) they think that it must be at a greater distance ($D_c > D'$), but if they perceive it being bigger than normal ($S_c/S' < 1$) it must be at a shorter distance than it is perceived to be at ($D_c < D'$). This relationship is important when explaining familiar object size judgments in situations where specific distance tendency takes place. W. C. Gogel (1976) showed typically developed binocular individuals familiar objects at over 3 meter viewing distances under limited visual information conditions, and found that specific distance tendency took place, as the participants perceived objects being off-sized, for instance a guitar was reported to be smaller than normal. Due to the specific distance tendency participants perceived all objects to be displayed at 2-3 meter viewing distance, while in fact they were displayed at a distance further away. The perceived distance was smaller than the cognitive distance based on the familiarity of the guitar size ($D_c > D'$), and thus the familiar object was perceived as being smaller than normal ($S_c/S' > 1$). It is unclear how comparable strabismics' performance would be, as, to our knowledge, there is no research exploring familiar size and egocentric distance perception in strabismic individuals with none or limited binocular stereoacuity. Further research in this would help us understand if the reliance on familiar size and specific distance tendency is different for strabismics.

The current study used familiar object size judgments as a mean to inferring perceived egocentric distance in order to explore the extent of limitations individuals with no/limited binocular stereovision experience in comparison to individuals with normal binocular stereovision. The experiments included binocular-stereoscopic, binocular-pictorial, and monocular-pictorial viewing, and were carried out in a dark room at the personal and action spaces in order to observe changes in perceived size with visual information diminishment. The idea of this “range” can be revealed considering the two extremes: binocular-stereoscopic or binocular-pictorial viewing at the near personal space, and monocular-pictorial viewing at the action space. These can be considered to be extremes in the capacity to judge distance and size based on typically developed binocular individuals. In the former these participants would have egocentric distance information from accommodation and vergence, and highly precise depth information from binocular disparity (Ogle, 1950), and thus should be able to perceive object size most accurately. In the latter, these participants would have no binocular disparity or egocentric distance information, and thus there will be a tendency to judge the distance of an object to be at a default distance (specific distance tendency), resulting in the stereo typical subjects having the least accurate judgments. As discussed above, we can only speculate about the strabismics performance under these conditions. Therefore, exploring how these different viewing conditions affect strabismic individuals’ ability to judge egocentric distance, would allow us to better understand limitations people with no or limited stereovision experience on daily basis, and the sorts of visual signals they rely on to make such judgements.

Experiment 4.1

In this experiment we investigated how individuals with strabismus perceive egocentric distance in comparison to typically developed binocular individuals. Familiar object size judgments were used as the proxy for perceived distance. This allowed to explore the accuracy and precision of perceiving absolute size of familiar objects, for both participant groups: strabismics with no/limited binocular stereovision, and control subjects with normal binocular stereovision.

4.2. Methods

4.2.1. Stimuli

The stimuli were images of real objects varying in levels of familiarity and size: basketball, coke can, and golf ball (Figure 4.2 Panel A). These objects were chosen as substantially varying in size, but still being of a size that subjects could comfortably hold in their hand. The real objects were present in the laboratory as reference objects and were shown only during specific timings. 3D images of these objects were developed and displayed using openGL routines and implemented in C++ code (this programming was conducted by a research assistant with a background in computer science; the author of the current study was able to make changes to the code affecting parameters of the stimuli presentation during the testing). When the images of the objects were projected in stereoscopic mode (viewing with 3D glasses), the centre of the 3D object matched the plane of the monitor, i.e. the 3D image was intended to create a 3D projection where the centre of the object is at the distance of the monitor plane. In order to account for individuals with strabismus and potentially limit visual discomfort linked with 3D viewing condition, the participants' own inter-pupillary distance was used in the run-time stereoscopic rendering. It was measured and then inputted by the experimenter before the testing started.

The calibration image (Figure 4.2. Panel B) was used before the testing to ensure that the active shutter 3D glasses were operating correctly, and to confirm absence of crosstalk. This image contains overlapping R and L letters, with should be seen only with the right and left eyes, respectively, when viewed with 3D glasses.

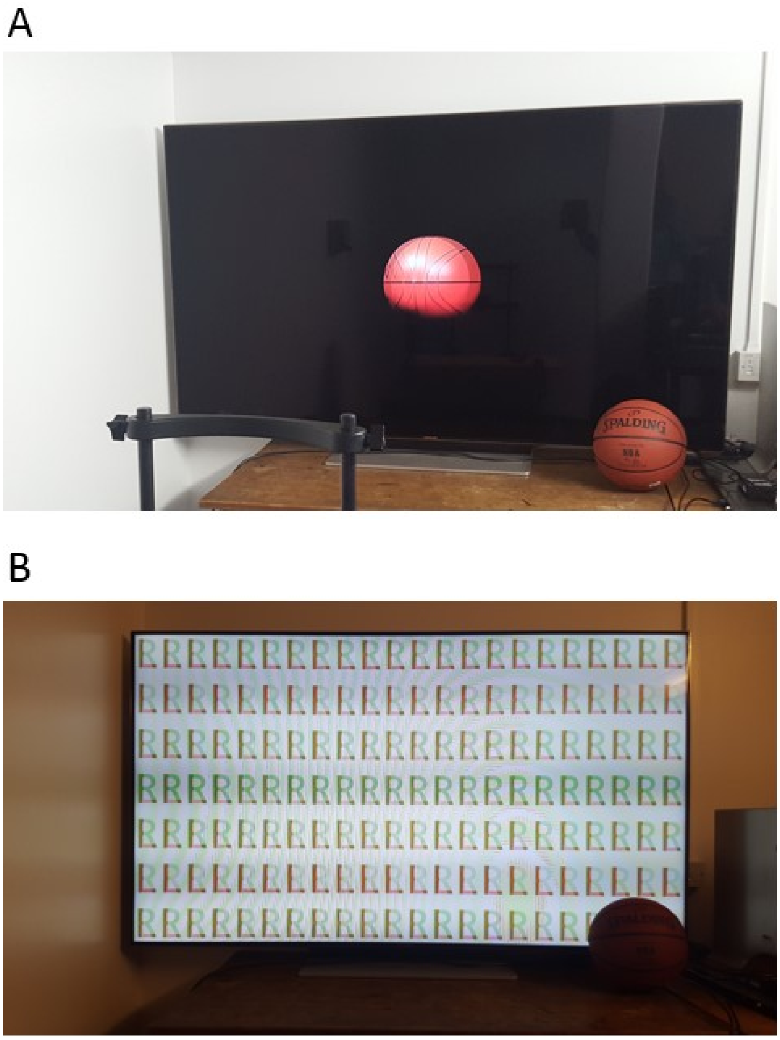


Figure 4.2. Stimuli examples used in Experiment 1. Panel A: example of one of the objects (basketball) and its 3D image viewing binocularly (without 3D glasses). Panel B: calibration image viewed without glasses. With glasses this image allows to tests that the 3D active shutter glasses are operating correctly, which is when the Rs are seen with the right eye and the Ls with the left eye.

4.2.2. Stimuli presentation

The colour images of the three objects were viewed on an active 3D LCD monitor (1920x1080px operating at a refresh rate of 120Hz) from two viewing distances: 1.75 metres (near viewing distance), and 3.5 meters (far viewing distance). These distances were limited by the experimental space, as the furthest distance possible to test in the laboratory was 3.5 meters. Then, the second distance was chosen as half of the first distance. The participants' heads were stabilized using a chin rest, whilst they viewed the stimuli with 3D active shutter glasses (stereoscopic), with two eyes (binocularly), or with one eye (monocularly). 3D glasses were worn only in the binocular-stereoscopic viewing condition, whilst in the monocular viewing condition participants wore a patch on their non-dominant eye. Participants wore their prescribed corrections suitable for the viewing distance, i.e. reading glasses were not necessary under these testing conditions. Lighting was turned on during the gathering of the participants' visual information and explanation of the task, which took place in the same room as the testing. The lighting was turned off during the testing, thus limiting visibility of the monitor frame and other objects in the laboratory, which could have allowed relative depth perception. However, as the participants were able to freely look around the room under the lit conditions prior the experimental testing, they might have obtained some level of cognitive percept of egocentric distance.

4.2.3. Procedure

Participants were given a demonstration about how object sizes (retinal) change with viewing distance even though we continue to perceive the object size as being correct. This was done by placing a water bottle at different distances from the participants all the way to the far end of the laboratory space. Afterwards, they were instructed that they would be making judgments about the displayed object size in relation to the actual size of that familiar object.

Participants were given the three objects and were asked to hold each of them whilst committing to memory their size. Then participants were seated at a table with a chinrest and a keyboard and the lights were turned off. Participants were asked to report any visual discomfort during the binocular-stereoscopic viewing condition, and were informed that they could stop at any point during the testing.

Using the two-alternative forced choice staircase method task participants judged the displayed object as being bigger or smaller than the actual size of their memory of the familiar object (i.e. their internal standard). Participants initiated the trial via a keyboard press ('Space bar'), at which time the stimulus was displayed for a total of 2 seconds. When the stimulus disappeared participants responded using keyboard keys: '4' for smaller and '6' for larger. After their response, a new stimulus would appear, until the end of the trial. The task was identical under all viewing conditions and distances. Before starting another block of trials under different viewing condition or distance, participants were asked to hold the three objects.

This testing procedure was carried out in two identical sessions, each lasting no longer than one hour. The datasets from these sessions were combined during the analysis.

Table 4.1. Hypothetical predictions for each of the chosen viewing distances and viewing conditions and for the two participant groups: controls with normal stereovision, and strabismics with no stereovision. Individuals with normal binocular stereovision at a near distance viewing in binocular-stereoscopic and -pictorial viewing conditions should provide accurate estimates of familiar object size, as they have accommodation and vergence information providing precise egocentric distance estimate. They might perform better in binocular-stereoscopic viewing as additional binocular disparity information will be available. Under monocular-pictorial viewing, their size estimates at the near distance should be less precise, as only the accommodation cue is available, and it loses precision after approximately 0.7m distance (Fisher & Ciuffreda, 1988). This should resemble predictions made by strabismics with no binocular stereovision for all viewing conditions at the near distance, as they have only accommodation (and accommodative vergence) cue available (von Noorden & Campos, 2002). Accuracy of accommodation and vergence egocentric distance decreases information with distance (Cutting, 2003), and thus at the far distance specific distance tendency should be notable (W. C. Gogel, 1969b; W. C. Gogel & da Silva, 1987): participants underestimate the distance to 2-3m and thus underestimate the object size, i.e. they perceive the object as closer and smaller and thus will chose a larger sized match to their internal standard than they should for 3.5m distance. This should be seen in all 3 viewing conditions for control subjects, and possibly for strabismics (to our knowledge, specific distance tendency had not been tested for individuals with strabismus and no/limited binocular stereovision). Additionally it is not clear how many individuals would be able to perform binocular-stereoscopic viewing task without experiencing visual discomfort.

	Stereoscopic viewing	**Binocular picture viewing**	**Monocular picture viewing**
Controls stereonormal	Near distance (1.75m): Accommodation & vergence → Precise distance → Size correct Far distance (3.5m) Poor cues; specific distance tendency → Perceived distance 2-3m → Size underestimated	Similar to 3D viewing	Near distance (1.75m): Accommodation → Less precise distance → Size under/over estimated Far distance (3.5m): Poor cues; specific distance tendency → Perceived distance 2-3m → Size underestimated
Strabismics No stereovision	Able to perform task without visual discomfort?	Near distance (1.75m): Accommodation → Less precise distance → Size under/over estimated Far distance (3.5m): Specific distance tendency?	Same as binocular viewing

4.2.4. Stimuli tested

Each testing session consisted of 6 blocks of trials: three viewing conditions tested at a near and far viewing distances. The choice of these viewing conditions and the hypothetical predictions linked to them are discussed in Table 4.1. The order of the 6 blocks were pseudo randomised between participants, by testing either far or near distance first and reversing the viewing condition order (Table 4.2). Viewing conditions were tested in the way that allowed gradual change in the available visual information cues, e.g. monocular, binocular, and stereoscopic viewing, and in order to reduce possible discomfort during the stereoscopic viewing condition. This randomisation was repeated every four participants.

Table 4.2. Block randomisation in experiment 4.1 repeated every four participants, resulting in 6 block per participant in each session.

Participant	Viewing distance					
1	Far (3.5m)			Near (1.75m)		
	Monocular	Binocular	Stereo	Monocular	Binocular	Stereo
2	Far (3.5m)			Near (1.75m)		
	Stereo	Binocular	Monocular	Stereo	Binocular	Monocular
3	Near (1.75m)			Far (3.5m)		
	Monocular	Binocular	Stereo	Monocular	Binocular	Stereo
4	Near (1.75m)			Far (3.5m)		
	Stereo	Binocular	Monocular	Stereo	Binocular	Monocular
Block	1	2	3	4	5	6

Each block contained three trials: one per familiar object. The object presentation order was randomised within participants. If during the participant's first testing session object order was: basketball, coke can, golf ball (1st testing order); during the same participant's second session the object order was reversed to: golf ball, coke can, basketball (2nd testing order). This was implemented to avoid possible testing order biases, as participants might always pay less attention to the last out of the three trials in the block due to tiredness. The coke can was kept in the middle of the testing order, because the golf ball and the basketball are same round shapes, which were presented on a screen only for a short period of time and thus could be mixed up. Half of participants were presented 1st testing order in the first session, whilst the other half were presented 2nd testing order in the first session, in order to avoid session bias, i.e. a participant might always pay more attention to the task while doing it for the first time, thus paying more attention to the task during the first session than the second session, and producing different results which may be erroneously linked to the testing order.

In each trial of the two-alternative forced choice staircase method task, there were 5 interleaved adaptive staircases per each unique stimulus, terminating at the maximum count of 6 reversals. The veridical object size of the familiar object on the monitor plane was attributed a value of 1 (basketball 22cm, coke can 11.5, golf ball 3.9cm). The minimum end of the display object size range was 0.5, and the maximum was 2.0. During testing this range had to be lowered to start from the minimum value of 0.2 (after participant 22 finished the 1st session). Staircase step size before the first reversal was 0.25, then before the second reversal it was 0.125, and after the second reversal the step size was set to be 0.0625. The initial scale factor (shows how much of either minimum/maximum end of the object size range the initially displayed object's size will be) was chosen from the converted scale where minimum was 0 and maximum was 1, and was set from 0.2 to 0.5.

4.2.5. Participants

Information about participants' vision was gathered using a number of ophthalmological tests as well as self-reports about participants' clinical history (see Chapter 2). All participants had their stereoacuity tested using three stereotests: Fly (a.k.a. Titmus), TNO, and RanDot, thus assessing the full extent of stereovision deficits (Lee & McIntyre, 1996). The type of strabismus was determined using Cover and Cover-Uncover tests and self-reported history of the disorder. The inter-pupillary distance (IPD) was measured by the experimenter using a ruler. If the participant was wearing corrective glasses during the testing, the IPD was measured with glasses.

4.2.6. Statistical analysis

Matlab was used to process the raw data and fit psychometric functions (maximum likelihood sigmoidal curve), thus obtaining alpha (point of subjective equality) and beta (slope) values, as well as plotting the best fit psychometric functions for each subject and each object (see Appendix 4.1 for the Matlab code and all psychometric functions). The theoretical example of the sigmoidal psychometric curve is presented in Figure 4.3. The probability of participant saying that the displayed object is larger (y axis) was plotted against the familiar objects true size (x axis), where the value 1 represents the veridical object size being displayed at the monitor. The point of subjective equality of the perceived size of the viewed object with the internal standard of the familiar-sized object is at the 0.5 probability on the y axis, as it marks the point at which a participant is no longer sure if the perceived object appears larger or smaller that his/hers internal standard, and chooses one of these responses at chance level. If at the near distance under binocular-stereoscopic viewing participants are able to correctly judge the familiar object size their responses should yield S-curve resembling the blue curve in Figure 4.3, with alpha being equal to one. If participants at the far viewing distance perceptually underestimate the size (i.e. adjust the displayed object to be larger than it should be, as they perceive it to be closer and smaller than it really is due to specific distance tendency; see Table 4.1), they will choose a larger object size as being correct, which is represented by the red S-curve. The red curve alpha is equal to 1.1 and thus the perceived correct object size is 10% larger than the veridical object size (Figure 4.3). Individual differences and variabilities are unavoidable, but, overall, the psychometric function obtained for the far distance viewing is expected to be on the right of the near distance viewing function.

The obtained points of subjective equality (alphas), were further processed in Excel, where data corrections were made and further figures were created. Finally, SPSS was used for statistical analysis of the data.

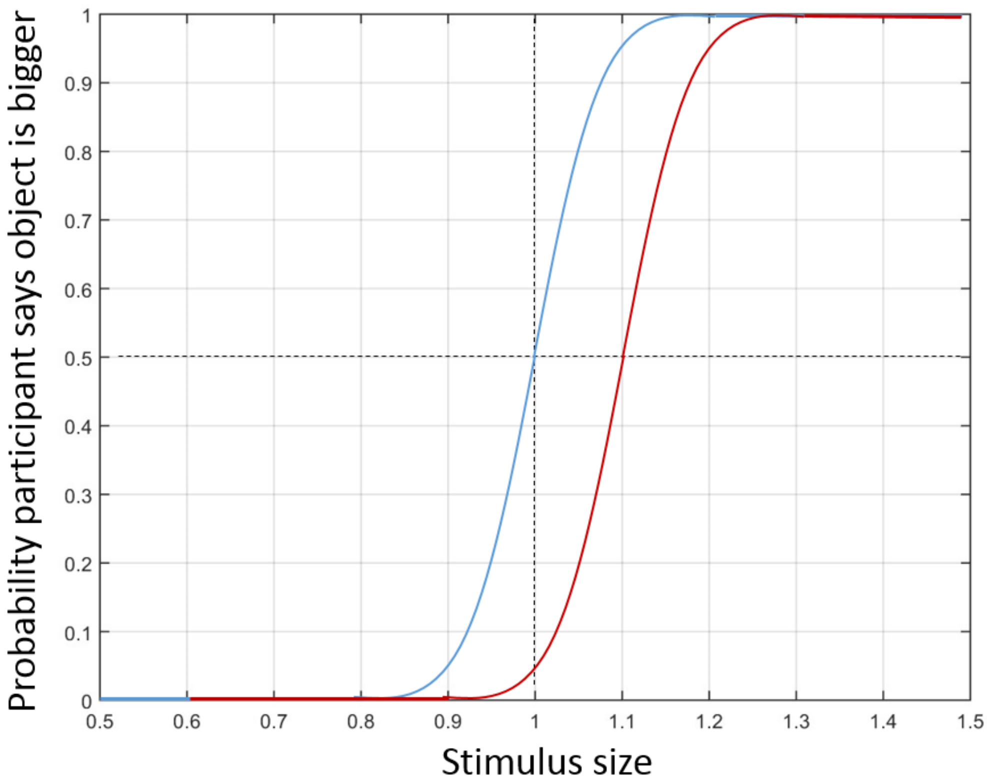


Figure 4.3. The theoretical example of a sigmoidal psychometric curve showing how with increasing object size changes the participants' likelihood of perceiving an object as being larger than their internal standard for the size of the familiar object. Stimulus size is plotted on the x axis – range from 0.5 to 1.5, where 1 is the true size of the real object. The probability of participant saying that the object is larger is plotted on the y axis. The 0.5 probability level indicates the stimulus size at which the perceived object size matches the subject's internal size standard. *The blue curve*: a subject who has a veridical perception of the object size, i.e., their internal standard matches the true size of the object (no underestimation or overestimation of the distance and therefore the size of the displayed stimulus). The point of subjective equality (alpha) is equal to 1. This would be expected assuming that the subject's internal standard is veridical and distance estimates are accurate (e.g., viewing at near distance under the binocular-stereoscopic viewing condition). *The red curve*: a larger stimulus size is selected as matching the internal standard, i.e., the stimulus is perceived as being smaller than it actually is (size underestimation).This might occur because the subject's internal standard is too large, or because the subject is underestimating the distance to the stimulus. For any given subject, we assume their internal standard is stable, so any relative shifts in the curve indicate an under- or over-estimation in the perceived size of the stimulus of a given object and therefore imply an under- or over-estimation of the perceived egocentric distance.

4.3. Results

4.3.1. Data Corrections

Participants were asked to make judgments using their internal standard for the size of the familiar object, which may vary among individuals and lead to inter-subject differences. To eliminate variation in the data due to these factors, corrections were applied according to the binocular-pictorial near distance viewing condition (which was assumed to represent the closest correct match to the subject internal standard). According to the theoretical predictions (Table 4.1) all subjects should have the most precise egocentric distance information under the binocular-pictorial viewing of the stimuli at the near distance (1.75m). In contrast, binocular-stereoscopic viewing conditions would not be inclusive of individuals with no/limited binocular stereovision, as some of these individuals may not be able to fuse a single image or finish the trials due to visual discomfort. Thus, for each participant and each object the original alpha values were standardized by normalising to the binocular-pictorial near distance viewing condition, which has an attributed a value of 1 (representing veridical object size, see section 4.2.6 Statistical analysis). The difference between the original value for this viewing condition and the value of 1, was used to adjust all alphas at other viewing conditions and distances for each object separately, to estimate variation in perceived distance with perceived size as the proxy.

Using ratios between the original value for the binocular-pictorial near distance viewing and the value of 1 was considered. Ratios would allow to capture the way perceived object size changes with distance by maintaining the ratio between near and far distance viewing original and corrected values. However, using ratios for rescaling familiar object size judgments for all viewing distances and conditions, would increase the difference magnitudes between the viewing conditions and in turn possibly lead to erroneous significant results. On the other hand, applying correction based on difference (as described prior), allows to maintain true differences between the viewing conditions, as well as the trends in subjects' responses with increasing viewing distance, and thus it allows to perform meaningful statistical analysis. The possible limitations linked to the use of corrections are discussed in the 4.4. Section: Discussion and limitations.

The amount of corrections made for each subject and object are summarised in Figure 4.4. It is notable that there are no clear trends or patterns among the participants, which highlights that the required corrections are highly individual. A few subjects required similar corrections for all three objects (e.g. participant number 8, 15, and 21). However, the majority of subjects required corrections that were not consistent between the three objects (e.g. participant number 4, 14, and 20), which suggests different levels of familiarity for the specific objects within the participants. There were a few outlier corrections (e.g. participant number 1 and 10) that are discussed further.

4.3.2. Participants

In total 24 subjects took part in this experiment. One of the subjects did not finish the trial, as the staircase for the golf ball did not receive a sufficient amount of reversals and the same stimuli was repeated until participant asked to terminate the testing. This issue was due to the fact that the point of subjective equality for this participant was below the minimum stimulus display size set in the programme to be 0.5. As mentioned in the Methods (section 4.2.4. Stimuli tested), this issue was resolved after the experimenter realized the cause, and the new minimum stimulus display size was set to 0.2 for further testing. Out of the 23 subjects, 15 were controls with normal binocular stereovision, 2 had only local stereovision, and 6 had no measurable binocular stereovision.

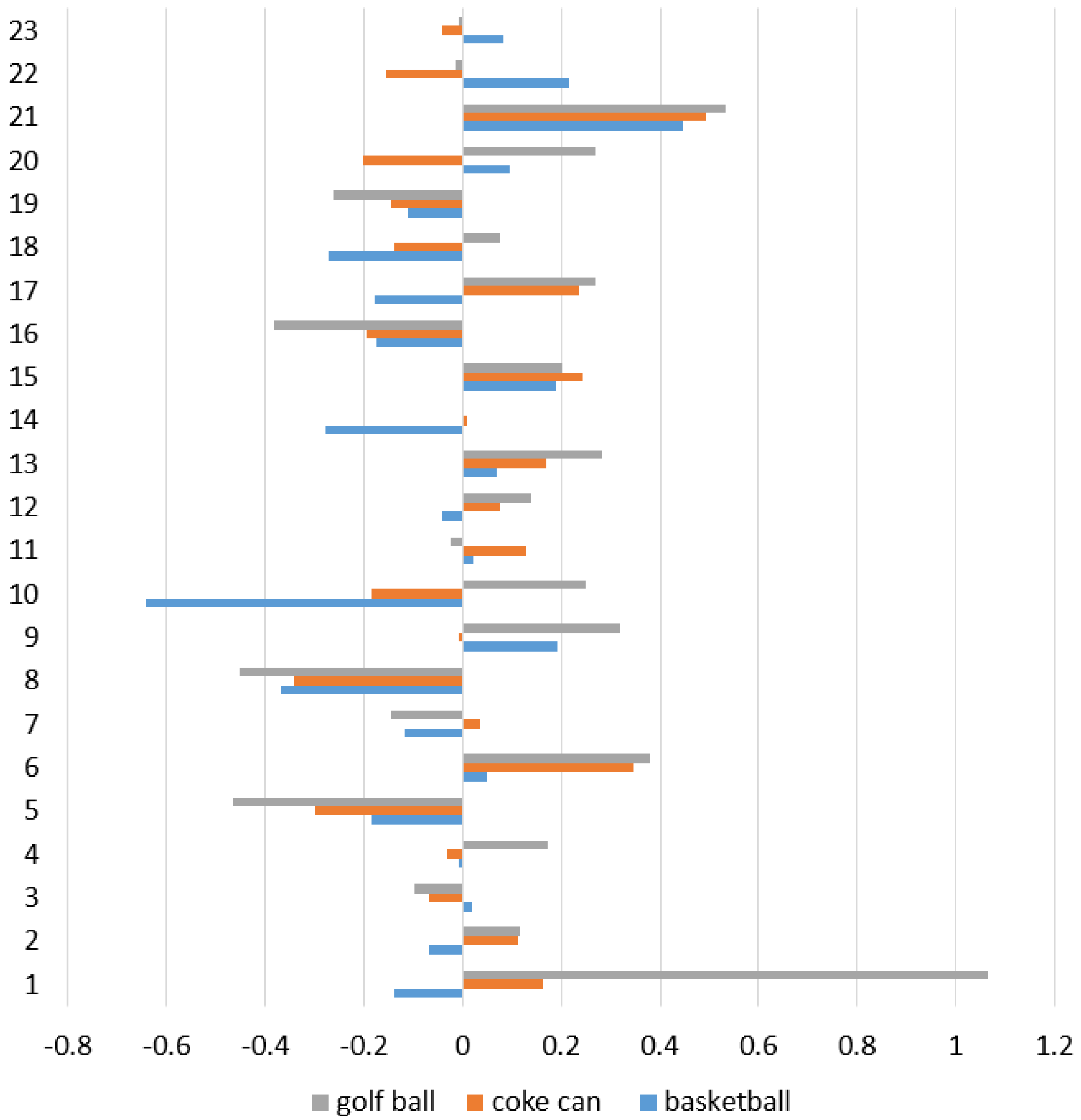


Figure 4.4. The correction factors derived for the internal standard for familiar object size for each subject and object, by normalizing the observed threshold value to a value of 1 (representing the intrinsic internal familiar object size standard). X axis – the amount of difference from the standardisation value of 1 (negative values – the observed thresholds were higher than 1; positive values – the observed thresholds were lower than 1). Y axis – the 23 subjects tested in the current experiment, who finished all of the testing blocks.

Five subjects were excluded from the analysis due to the high variability in their responses compared to other participants. These subjects had corrected alpha values for some viewing conditions and distances that were larger than 2 (double the value representing the veridical object size), and these values did not follow any observable or logical patterns. Therefore 4 control subjects (participant number 1, 2, 8, and 10) and 1 subject with no stereovision (participant number 17) were eliminated from the further analysis. The eliminated control subjects 1 and 10 also had the largest corrections for individual objects (Figure 4.4), which further suggests these individuals were not engaged with the task which in turn affected their performance. Detailed visual information about all 23 subjects is provided in the Appendix 4.2, whilst the information for the 18 participants used in the analysis is summarised in the Table 4.3.

None of the subjects with no/limited binocular stereovision expressed any visual discomfort linked to the binocular-stereoscopic viewing condition. Some reports of ghosting due to the active shutter 3D TV was received from all groups of participants, however, none of them identified it being distracting or making the size judgments difficult.

Table 4.3. Participants classification based on their clinically measurable binocular stereovision and descriptives of these groups.

Classification group	**N (18)**	**Average age**	**Physiology**
1. No stereovision	5	44	4 corrected strabismus (3 with tropias, 1 with phoria), 1 intermittent strabismus
2. Local stereovision	2	35	1 corrected strabismus (phoria), 1 amblyopia (phoria)
3. Stereo-normal	11	21	None

4.3.3. Perceiving a proxy for absolute size of familiar objects

4.3.3.1. Accuracy and precision

Figure 4.5 presents examples of psychometric functions fitted for a control subject, and a strabismic subject with no binocular stereovision (all psychometric functions in Appendix 4.1.). Overall, a large variability in the data was observed due to varying familiarity with the three objects, which had been verbally noted by a number of participants. The coke can had been reported as being the easiest to judge, matching of the visual inspection of the psychometric functions, and thus it has been chosen as example for observed S-curves (Figure 4.5). The accuracy at the near distance for the control subject is high, as the alpha value (point of subjective equality) is close to the veridical 1, while at the far distance the size is underestimated as the subject's point of subjective equality is above the veridical 1 and is approximately 1.5 (Figure 4.5). A similar pattern between the alpha values for the near and the far viewing distances is observed for the strabismic participant as well, even though the near distance point of subjective equality is less accurate (Figure 4). The precision (beta – the slope) of the control participant's size judgments at the near distance increase from monocular-pictorial to binocular-pictorial viewing conditions, and the binocular-stereoscopic viewing condition yields the most precise judgments for both viewing distances. This trend seems to be reversed for the strabismic subject, as the precision for the near distance is the highest during monocular-pictorial viewing, and at the far distance is the highest for binocular-pictorial viewing, while binocular-stereoscopic viewing has the least precise judgments (Figure 4.5).

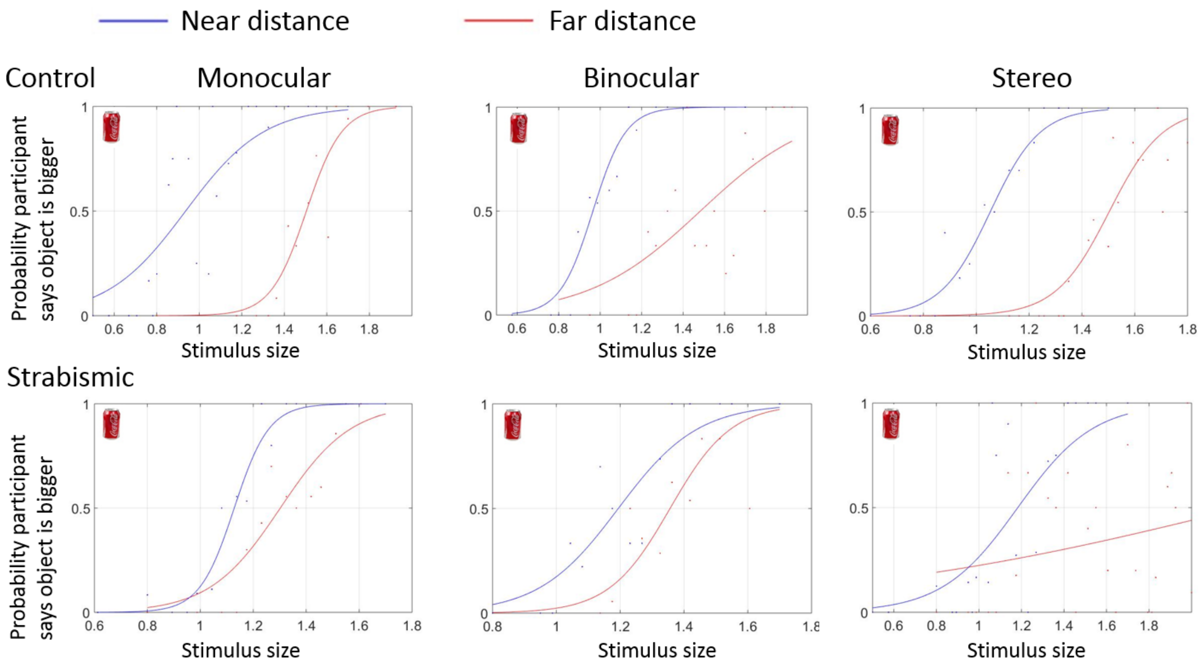


Figure 4.5. Examples of psychometric functions fitted for a control subject with typically developed binocular stereovision (top three panels), and a strabismic subject with no measurable stereovision (bottom three panels). The familiar object - coke can. All three different viewing conditions: monocular-pictorial (left panels), binocular-pictorial (middle panels), binocular-stereoscopic (right panels). Near viewing distance – blue function; far viewing distance – red function.

The summary of the alpha values, after normalization for the internal standard, for each object and each participant group are presented in Table 4.4. They support the observed far vs. near viewing distance trends in psychometric function examples in Figure 4.5. Participants, on average, for all objects, had required a larger object size in order to perceive it as being equal to their internal size standard at the far distance than at the near viewing distance (i.e. size underestimation, which implies distance underestimation). Paired samples t-tests were run for each participant group and object separately, thus resulting in six comparisons and the adjusted significance level of 0.008 (0.05/6 according to Bonferroni correction). The only significant change based on these paired samples t-tests was found in the local binocular stereovision group, as their average point of subjective equality for the coke can was significantly larger at a far than near viewing distance under binocular-stereoscopic viewing (paired samples t-test: t(1)=106.757, p=0.006). However, the local stereovision group included only two subjects. Due to the limitations in this group's size, for further analysis and data representations the local and no binocular stereovision groups were combined into a single group (no/limited binocular stereovision group).

Table 4.4. Averages of the normalised alpha values (1=binocular near distance for each participant each object) with standard deviation in the brackets, for each participant group, each viewing condition, at near (1.75m) and far (3.5m) viewing distances.

	Monocular		**Binocular**		**Stereo**	
	Near	Far	Near	Far	Near	Far
Control N=11						
Basketball	1.055 (0.076)	1.191 (0.190)	1	1.118 (0.221)	1.150 (0.116)	1.240 (0.219)
Coke can	1.055 (0.104)	1.248 (0.229)	1	1.135 (0.213)	1.174 (0.146)	1.346 (0.277)
Golf ball	1.052 (0.130)	1.376 (0.740)	1	1.123 (0.193)	1.173 (0.134)	1.260 (0.218)
Local stereo N=2						
Basketball	0.987 (0.089)	1.163 (0.152)	1	1.079 (0.107)	1.002 (0.174)	1.219 (0.110)
Coke can	1.005 (0.048)	1.212 (0.192)	1	1.156 (0.100)	**1.040 (0.031)**	**1.202 (0.029)**
Golf ball	0.980 (0.060)	1.113 (0.057)	1	1.094 (0.022)	0.910 (0.065)	1.137 (0.055)
No stereo N=5						
Basketball	1.014 (0.139)	1.302 (0.356)	1	1.319 (0.178)	1.030 (0.111)	1.375 (0.265)
Coke can	0.951 (0.113)	1.119 (0.293)	1	1.152 (0.282)	1.038 (0.072)	1.205 (0.249)
Golf ball	1.024 (0.131)	1.110 (0.271)	1	1.088 (0.276)	1.012 (0.218)	1.108 (0.289)

The summary of the alpha value averages for the stereonormal and the no/local binocular stereovision groups are presented in Figure 4.6. In all cases with increasing viewing distance there is a notable increase in the stimulus size chosen as being true to the subjects' internal object size standard. Stereonormal subjects' stimulus size point of subjective equality varied depending on the viewing condition, as the largest alpha values on average were in binocular-stereoscopic viewing, followed by monocular-pictorial viewing, and then by binocular-pictorial viewing. This trend was largely absent in the no/limited stereovision subjects, with average alpha values being slightly higher for basketball and coke can under binocular-stereoscopic then binocular- and monocular- pictorial viewings (Figure 4.6). However, the standard deviation of the mean values are high and vary between the objects and viewing conditions in no logical pattern. The high variability in the data is also evident in the beta values (Figure 4.7), with the only observable generic trend being higher variability in points of subjective equality obtained at far distance rather than near distance viewings.

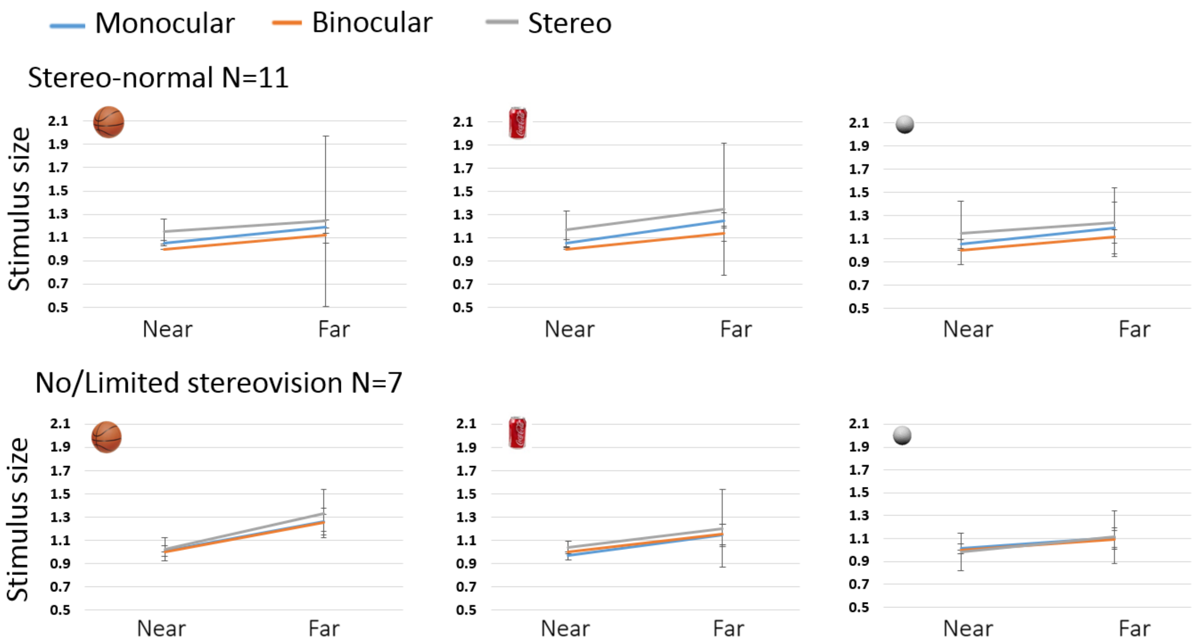


Figure 4.6. Summary of the alpha value averages for control subjects and strabismic subjects (local and no binocular stereovision) for each of the three objects and viewing distances. Error bars – standard deviation of the mean.

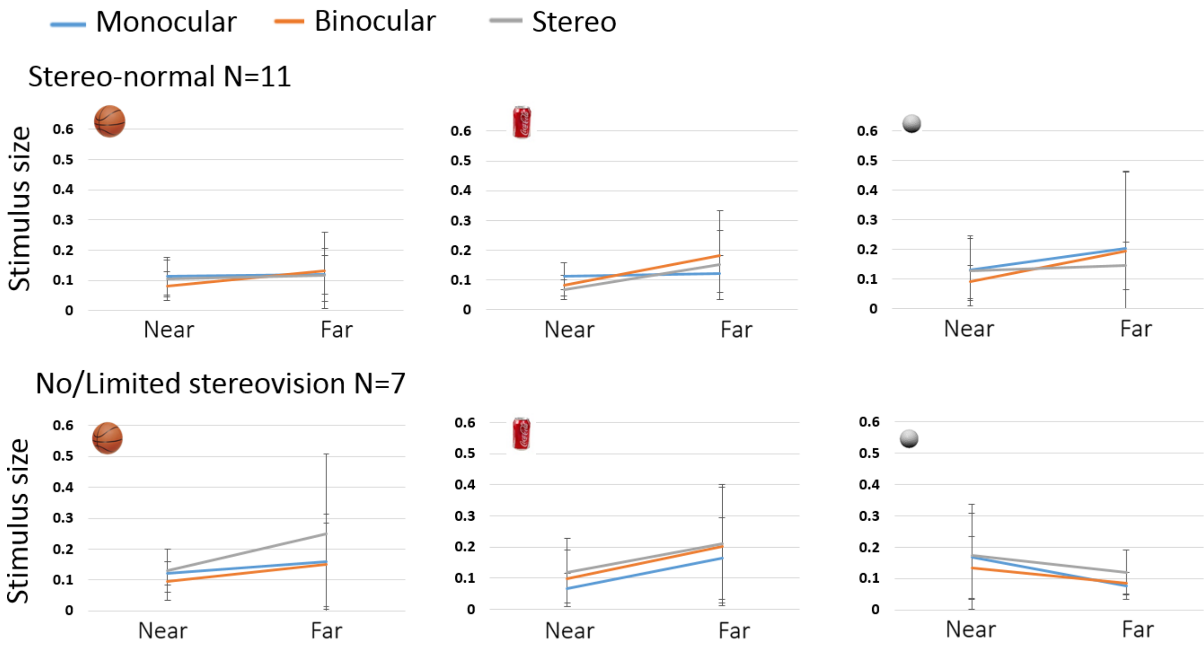


Figure 4.7. Summary of the beta value averages for control subjects and strabismic subjects (no/local binocular stereovision) for each of the three objects and viewing distances. Error bars – standard deviation of the mean.

4.3.3.2. Effects of viewing condition, distance, and level of binocular stereoacuity

Mixed design ANOVA was performed for the two groups of subjects (stereonormal n=11, and no/limited stereovision n=6) to explore the effects of viewing condition (monocular-pictorial, binocular-pictorial, binocular-stereoscopic), and viewing distance (near, far). There was no significant between subjects effect of controls with normal binocular stereovision versus strabismics with no/limited binocular stereovision (1.150 and 1.094 (SE: 0.033 and 0.041), respectively; $F(1, 16)=1.118$, $p=0.306$). The within subjects factor of viewing distance was found to be significant, as significantly larger object sizes were perceived as being equal to subjects' internal standard of the familiar object sizes at the far than near viewing distance (1.206 and 1.038 (SE: 0.048 and 0.014), respectively; $F(1, 16)=13.383$, $p=0.002$). The second within subject factor - viewing condition - also had a significant effect with overall alpha values being 1.123 (SE = 0.035) for monocular-pictorial, 1.072 (SE = 0.023) for binocular-pictorial, and 1.170 (SE = 0.034) for binocular-stereoscopic viewings ($F(2, 32)=5.7$, $p=0.008$). Pairwise Comparisons with Bonferroni corrections found that alpha values under binocular-pictorial viewing (1.027) were significantly smaller than under the binocular-stereoscopic viewing (1.170) ($p=0.001$), indicating that sizes were underestimated in binocular-stereoscopic compared to binocular-pictorial viewing condition. On the other hand, even though the average alpha values under binocular-pictorial viewing (1.027) were smaller than under monocular-pictorial viewing (1.123) this difference was not significant (Pairwise Comparisons with Bonferroni correction $p=0.363$). Similarly, they were not significantly smaller under monocular-pictorial viewing (1.123) than binocular-stereoscopic viewing (1.170) (Pairwise Comparisons with Bonferroni correction $p=0.547$).

Within subjects factorial ANOVAs were carried out for each participant group separately: stereonormal subjects, and subjects with no/limited binocular stereovision. The prior observed differences were found to be significant in the stereonormal group. The viewing condition had a significant effect ($F(2, 20)=7.034$, $p=0.005$), implying that size underestimation varied between the viewing conditions. The average stimulus size being perceived as equal to the subjects' internal familiar object size standard was 1.163 (SE=0.045) for monocular-pictorial, 1.063 (SE=0.028) for binocular-pictorial, and 1.224 (SE=0.045) for binocular-stereoscopic viewing. The Pairwise comparisons with Bonferroni corrections showed significant difference between binocular-pictorial and binocular-stereoscopic viewing ($p=0.001$), whilst the differences between monocular-pictorial and binocular-pictorial viewings, and monocular-pictorial and binocular-stereoscopic viewings were not significant ($p=0.172$, and $p=0.776$, respectively). Therefore, indicating that in the stereonormal subject group familiar object sizes were significantly underestimated in binocular-stereoscopic compared to binocular-pictorial viewing condition. The second within subject factor - viewing distance – in the stereonormal subject group was also found to be significant ($F(1, 10)=7.281$, p=0.022). Stereonormal subjects had significantly higher average alpha values at the far (mean = 1.226, SE = 0.057) than near (mean = 1.073, SE = 0.019) viewing distance, which implies that on average in this group the familiar object sizes were significantly underestimated at the far compared to near viewing distance.

Even though the no/limited stereovision subjects chose larger stimulus sizes as matching their internal standard for the familiar object size at the far (mean = 1.175, SE = 0.095) rather than near (mean = 1.00, SE = 0.020) viewing distance, this effect was not significant (F(1, 5)=4.048, p=0.1). Similarly to the stereonormal subjects group, in the no/limited binocular stereovision group the smallest average alpha values were in binocular-pictorial viewing (mean = 1.074, SE = 0.044), followed by monocular-pictorial viewing (mean = 1.082, SE = 0.064), and the largest alpha values were in binocular-stereoscopic viewing (mean = 1.106, SE = 0.056), which implies that similarly to the controls subject with no/limited stereovision underestimated the sizes the most in binocular-stereoscopic viewing compared to binocular-pictorial viewing. However, these differences were small and the viewing condition effect was not significant in the no/limited stereovision group (F(2, 10)=0.838, p=0.461).

4.4. Discussion and limitations

Participants with varying levels of binocular stereovision showed a tendency to choose a larger stimulus size at the far distance to match their internal standard for the familiar object size. This suggests that in accordance with our prediction, objects viewed at the far (after ~2m) are perceived as smaller, i.e., distance is underestimated, leading participants to choose a larger object size as being matched to their internal standard. However, only the stereonormal subjects required significantly larger stimulus sizes in order to perceive them as matching their internal familiar object size standard at the far rather than near viewing distances. That being said, individuals with no/limited stereovision expressed the same tendencies which may have shown significance if the sample sizes were larger. Further data gathering is necessary to ensure that egocentric distance is processed in individuals with no/limited stereovision in a similar way to the stereonormal subjects.

We had hypothesised that binocular-stereoscopic viewing in controls with normal binocular stereovision would allow them to make the most accurate size estimates. However, whilst the viewing condition was found to have a significant effect in controls, binocular-pictorial viewing condition provided the most accurate judgment, i.e. closest to the veridical size of the familiar object. This was followed by monocular-pictorial viewing, while under binocular-stereoscopic viewing, participants chose the least accurate judgments. Further, the control subjects were found to choose significantly larger stimuli sizes as being equal to their internal standard under binocular-stereoscopic than binocular-pictorial viewing for both distances combined. It is uncertain if the observed differences were purely due to actual perceptions, as other, for instance, corrections applied to the data may have led to an artificially significant difference. As discussed in Section 4.3.1 the familiarity with the three objects greatly varied between the participants, which required to perform data corrections adjusting the intrinsic standard for the familiar object size. The data corrections normalised alpha values for the near distance binocular-pictorial viewing condition to one and thus eliminated variability at this viewing condition. Having one viewing condition without any variance in its responses in the statistical analysis could have led to erroneously significant findings. From this perspective the two debated methods of correction (difference and ratio between the observed alpha and a value of one as representing the veridical object size) would have resulted in the same limitations. On the other hand, the considered ratio correction (scaling all observed alphas for all viewing conditions and distances based on the near distance binocular-pictorial viewing condition ratio between the observed alpha and number one) would have excessively enlarged the difference magnitudes between the viewing conditions, which could have also led to additional erroneous significant differences between the viewing conditions. Thus a more complex method for correcting data for variability in the subjects' intrinsic size standards has to be developed. On the other hand, using any type of correction raises the possibility of eliminating or reducing inter-subject differences that are representative of their groups' characteristics (e.g. differences between control and strabismic subjects). Therefore, the testing method should be adapted to allow to standardise subject performance prior or during the testing process.

The hypotheses related to individuals with strabismus were limited due to lack of research in this area involving individuals with clinically limited or non-measurable binocular stereoacuity. All individuals, despite their lack of binocular stereovision were able to perform the tasks to their completion. The strabismics did show a tendency to underestimate object size at the far compared to near viewing distance, similarly to the control subjects. However, there were no significant trends or differences between their performances under different viewing conditions. It had been hypothesised that individuals with no/limited binocular stereovision should not exhibit differences in their stimuli size choices under different viewing conditions. In fact, the strabismics judged similar stimuli sizes as being equal to their internal familiar object standard under all viewing conditions, though in some cases (for the basketball and coke can familiar objects) under binocular-stereoscopic viewing condition the strabismics showed a trend to choose larger stimulus sizes as matching their internal standard, thus resembling performance of the controls. It is possible that familiarity plays a key role in the strabismics performance, as it has been highlighted in anecdotal reports (Barry, 2009; Godber, 1981). Therefore, further data collection is required to explore if familiarity to the presented objects influence the strabismics' performance.

Additional issues in the current study were linked to the experimental set up and the code written to run the experiment. In this experiment 3D image rendering was linked to the subject interpupillary distance, but not to the specific viewing distance. This may have affected the subjects' perception of object sizes under binocular-stereoscopic viewing, as the amount of binocular disparity is inversely related to the square of the viewing distance. Another issue noted during the testing was the limited range of possible stimulus sizes, as in order to carry out the two-alternative forced choice staircase method task the minimum and maximum stimulus sizes must be defined. If participants' subjective point of equality was beyond the set stimulus size limits (Min: 0.5 and Max: 2.0), the staircase would reach one of the limits and would continue displaying the same image until a sufficient amount of reversals had been performed, which may have forced subjects to falsely start changing their response. However, if the subjects did not change their response, the reversal number remained the same and the said staircase would continue indefinitely. This was observed in the case of one subject, which required the experimenter to change the stimulus size limits halfway through the testing of experiment 4.1. An additional issue is one of the duration of the stimulus presentation, as a number of older subjects noted the stimulus to disappear too quickly, not giving enough time to focus on its size. Thus, alternative testing designs must be considered to make the task easier for subjects to perform and in order to increase the reliability of the data sampling. These issues are addressed in the design of experiment 4.2.

Experiment 4.2.

The aim of this experiment was to further investigate how individuals with strabismus perceive egocentric distance in comparison to typically developed binocular individuals by using object size judgments as the proxy for perceived distance. In addition to the three familiar objects used in experiment 4.1, three non-familiar abstract objects were added to the stimuli to further assess accuracy and precision at perceiving the absolute size of objects in the presence or absence of familiar size information. In this experiment, the method of adjustment, rather than the two-alternative forced choice method, was used, which together with visual access to the real objects during judgements, was aimed at eliminating the need of internal size standard. We hoped this would reduce the inter-participant variability and thus the need for data corrections. The performance of both participant groups' was explored: strabismics with no/limited binocular stereovision, and control subjects with normal binocular stereovision.

4.5. Methods

4.5.1. Stimuli

The stimuli rendering and display were identical to those used in the experiment 4.1. Three non-familiar objects were added to the set of stimuli: three different size and colour cubes, with a yellow cube being the smallest (5.8cm), followed by a grey cube (8.7cm), and a red cube being the largest and identical to the height of can of coke (11.7cm). Even though the real abstract objects were different in size, the corresponding three stimuli displayed on the 3D monitor were within the same size range with the veridical object size corresponding to 1 being 9.5cm. This choice was made in order to avoid any possible cognitive biases linked to the initial display size, for instance, to avoid subjects choosing smaller stimulus size as equal to the size of the yellow cube than for the other two cubes, purely because the yellow stimuli had been displayed as being smaller in comparison to the stimuli corresponding to the other two cubes. This was aimed to ensure that participants would take time to look at the real abstract object and assess its size, i.e., to make sure that participants adjust displayed stimuli based on the real abstract object they were viewing.

In experiment 4.1 stereoscopic rendering did not take into account the change in viewing distance (this was an error identified after testing). Binocular disparities are inversely related to the viewing distance, which means that as the viewing distance increases the binocular disparities should decrease. Therefore, in the current study the stereoscopic objects were rendered using both inter-pupillary distance (IPD) and viewing distance. Both of these values were inputted by the experimenter before the start of each trial.

4.5.2. Stimuli presentation

To standardise the participants' internal standard of object size while making judgments of the stimulus size, reference real objects could be viewed by the participants at any time during the duration of the experimental trial. The reference objects were located at a reaching distance (approximately 60cm) on the right side of the participant. This was done so that participants' would not base the stimulus size judgments on the retinal comparisons, but rather use the displayed objects as references to the veridical object sizes. The object was illuminated with a remote controlled halogen light strip. Examples of the stimuli and the experimental set up are presented in Figure 4.8.

The experimental set up was altered to allow a new near viewing distance of 1m. The other two distances from experiment 4.1 were kept, but 1.75m was now the middle viewing distance, while 3.5m remained to be the far viewing distance. This change from the experiment 4.1 was performed in order to ensure that at least one of the experimental conditions provided egocentric distance information closely resembling that of the real reference object viewing, and thus a baseline for within-participant performance comparison. Accommodation, or accommodative vergence has been found to potentially provide egocentric distance information up to around 1m viewing distance (Fisher & Ciuffreda, 1988), therefore performance under near distance 3D stereoscopic viewing should be the most accurate and precise, as it most closely resembles the cue conditions matching the reference object viewing.

Otherwise the stimuli presentation was identical to that of experiment 4.1.

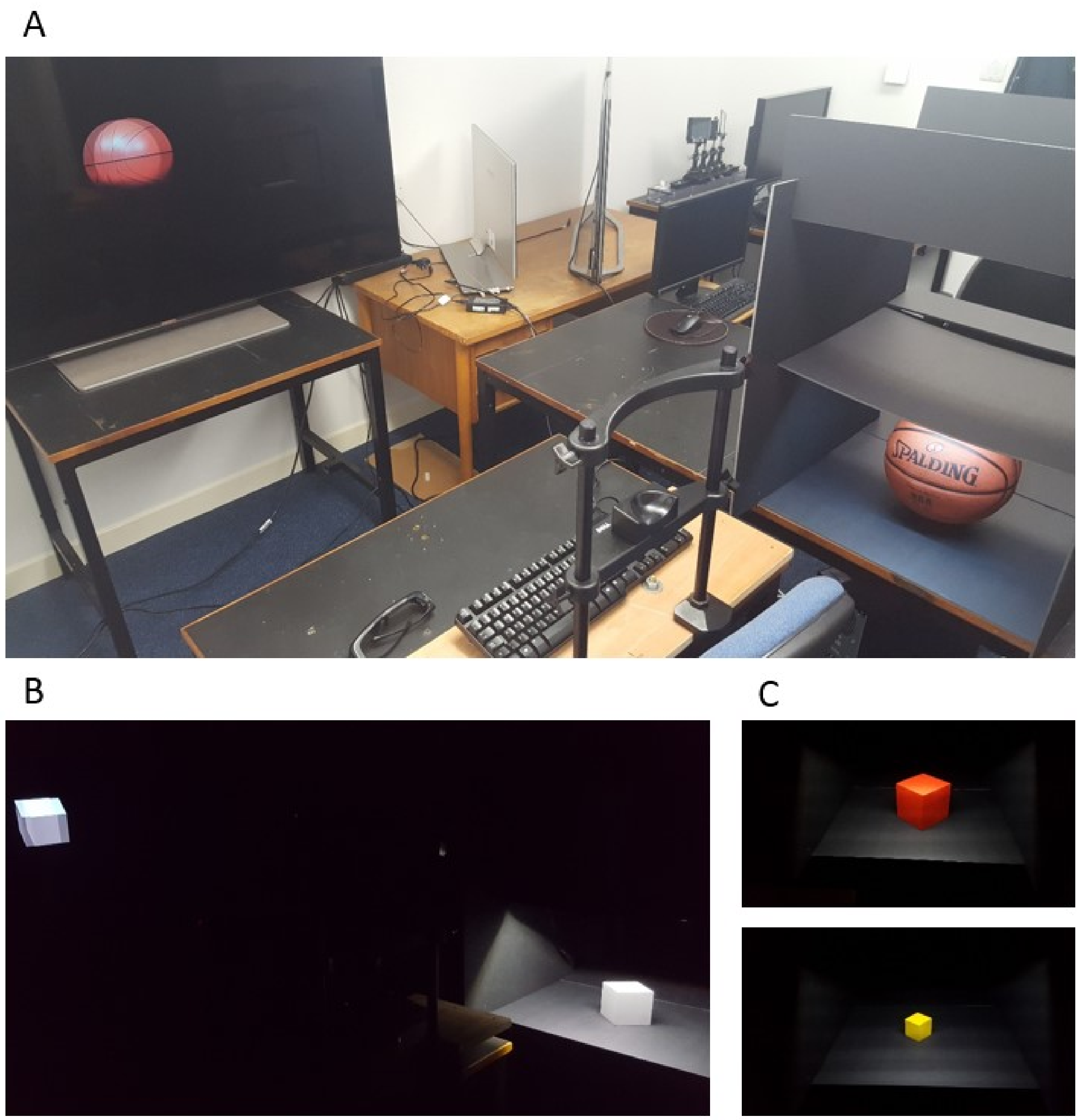


Figure 4.8. Experimental set up and stimulus used in experiment 4.2. *Panel A*: Experimental set up under full light condition, middle distance (1.75m), familiar object (basketball) displayed in stereoscopic mode. The basketball (reference object) displayed as a reference to the veridical object size at a reaching distance on the right hand side of a participant. *Panel B*: experimental set up under testing conditions (lights turned off) in stereoscopic presentation, middle distance (1.75m), non-familiar object (grey cube). Panel C: Two other non-familiar objects added to the experimental stimuli, presented at a reaching distance. Objects were presented inside a box, with an opening on one side, where the subject could view the object from approximately 60cm distance, and the experimenter could remove and replace objects from the other end. Objects were lit from above with a halogen light.

4.5.3 Procedure

The demonstration given to participants about how object sizes (retinal) change with viewing distance even though we continue to perceive the object size as being correct was identical to experiment 4.1. Participants were given the six objects and were asked to hold each of them whilst thinking about their size.

The method of adjustment task was explained to participants before the start of the experiment. They were asked to adjust the displayed object size until they perceived it as matching the size of the real reference object. They were told that once one of the stimuli appeared on the screen, the experimenter would place the real object in the box on their right hand side. Participants were instructed to look at the reference object before adjusting the size of the object displayed on the monitor. They were asked to look at the object on the monitor and the real object at least three times, to ensure that their judgments are accurate. In order to avoid retinal comparisons, subjects were told to keep their heads on the chinrest when looking at the monitor, and to slightly lean back and turn to their right to look at the reference object whilst avoiding looking at the monitor. Participants were reminded regularly during the testing by the experimenter to make sure they followed these instructions. Additionally, participants were reminded to use the real object only as a reference for the object size, as a reminder of how big the object is when it is at a reaching distance from them and not use it as a retinal match.

Participants initiated the trial via keyboard press ('Space bar'), at which time one of the six objects appeared on the monitor. Participants adjusted the displayed object by pressing '4' – to make it smaller, or '6' – to make it larger. The object display time was unlimited. Once they were happy with their adjustment, they pressed 'Space bar' to input their response. After their response a new stimulus would appear, until the end of the trial. The task was identical under all viewing conditions and distances. The lights were switched off during the testing, but they were turned back on before starting another block of trials under different viewing condition or distance. Subjects were asked to report any visual discomfort during the stereoscopic viewing condition, and were informed that they could stop at any point during the testing.

The testing procedure was carried out in a single session, lasting no longer than one hour.

4.5.4. Stimuli tested

The testing session consisted of 9 blocks of trials: three viewing conditions tested at near, middle, and far viewing distances. The choice of these viewing conditions and distances were discussed in Table 4.1, and in Stimuli presentation Section 4.5.2. The order of the 9 blocks were pseudo-randomised between participants, by testing either far or near distance first and reversing the viewing condition order (Table 4.5). This viewing condition order was based on the one used in experiment 4.1, as allowing gradual change in the available visual information, and, as in experiment 4.1, was repeated every four participants.

Within each block, each object was presented three times, resulting in the total of 18 object presentations. Four computer generated randomised sequences were used to arrange the object presentations within each block. This object testing order randomisation was repeated for every four participants, and was manually changed in the code before the start of testing by the experimenter.

The veridical object size of the familiar object on the monitor plane was attributed a value of 1 (basketball 22cm, coke can 11.5, golf ball 3.9cm). For the non-familiar objects the value of 1 was attributed to the object size 9.5cm, whilst the actual sizes were 11.7cm (red cube), 8.7cm (grey cube), and 5.8cm (yellow cube). Therefore, if participants chose veridical non-familiar object size, their responses should be 1.23, 0.92, and 0.61, for the red, grey, and yellow cubes, respectively. The minimum displayed object size was 0.2, and the maximum was 2.0. The step size factor was set to 0.05 of the currently displayed object size, i.e. it was calculated anew from the last object size displayed.

Table 4.5. Block randomisation in experiment 4.2 repeated every four participants, resulting in 9 blocks per participants. M – monocular-pictorial viewing; B – binocular-pictorial viewing; S – binocular-stereoscopic viewing.

Participant	Viewing distance								
1	Far (3.5m)			Middle (1.75m)			Near (1m)		
	M	B	S	M	B	S	M	B	S
2	Far (3.5m)			Middle (1.75m)			Near (1m)		
	S	B	M	S	B	M	S	B	M
3	Near (1m)			Middle (1.75m)			Far (3.5m)		
	M	B	S	M	B	S	M	B	S
4	Near (1m)			Middle (1.75m)			Far (3.5m)		
	S	B	M	S	B	M	S	B	M
Block	1	2	3	4	5	6	7	8	9

4.5.5. Participants

Information about newly recruited participants' vision was gathered in the same manner as in experiment 4.1. All participants had their stereoacuity tested using the three stereotests: Fly (a.k.a. Titmus), TNO, and RanDot. The inter-pupillary distance (IPD) was measured by the experimenter using a ruler. If the participant was wearing corrective glasses during the testing, the IPD was measured with glasses. All typically developed binocular individuals were new recruits. Four strabismic participants from experiment 1 were able to take part in the current experiment, and an additional seven strabismic participants were newly recruited (see Appendices 4.2. and 4.3.).

4.5.6. Statistical analysis

Matlab was used to process the raw data and calculate the averages of the responses. The obtained values were further processed in Excel, where data adjustments were made and figures were created. SPSS was used for statistical analysis of the data.

4.6. Results

4.6.1. Data adjustment for non-familiar objects

Adjustments were performed for the non-familiar object data, as even though the real abstract objects were different in sizes, they were displayed within the same size range on the monitor with correct (equal to 1) size being 9.5cm (see 4.5.1. and 4.5.4. Sections). The large red cube size was 11.7 cm, thus the veridical size to be chosen by participants had to be 1.2316. The middle grey cube size was 8.7 cm, which corresponded to 0.9158 veridical size. The small yellow cube was 5.8 cm, which corresponded to 0.6105 veridical size. The differences between 1 and the veridical size were calculated and added to participants' responses. For instance, in the case of the large cube the difference between the assigned veridical value of 1 and the actual veridical value of 1.2316 was -0.2316. Similarly, for the middle grey cube the difference was 0.0842 (1 – 0.9158), and for the yellow cube the difference was 0.3895 (1 - 0.6105). These differences were added to all the participants' data. Thus, for instance if a participant inputted a response for the yellow cube which was recorded as equal to 1.4316, the value used for the analysis was 1.2 (1.4316 + (-0.2316)). This allowed a direct comparison between familiar and non-familiar objects, as after the adjustments were made the veridical size for all objects was equal to 1. This allowed a more logical statistical analysis as the values for the data could be collapsed between objects.

4.6.2. Participants

In total 27 people were enrolled to take part in this experiment. One of the subjects was not tested, because she was a control subject but was extremely short-sighted and even with her corrections had extremely poor far distance visual acuity.

Visual inspection of the data did not reveal any considerable outliers. Even though performance varied between participants, these variations were consistent within participants' judgments, and thus are most likely representative of perceptual differences between participants rather than variability linked to difficulty of the task or its performance. All subjects followed the task instructions and made a suitable number of size adjustments before submitting their final choice. From the total of 1404 size judgements made by participants in this experiment (26 participants x 54 choices per each) only 10 erroneous inputs were made, i.e. participants pressed the space bar before making the adjustment. These trials were eliminated from the analysis and the corresponding averages were comprised from the two remaining values for that object under that viewing condition and testing distance. Together with the experimental design, these observations suggest that participants were engaged with the task and followed instructions to the best of their abilities. Therefore, none of the subjects were eliminated from the analysis. Visual information on all 26 subjects is summarised in Table 4.6 (more detailed information in Appendix 4.3.).

Due to limited size samples for no- and local-binocular stereovision groups, for any further analysis and data representations, data for these groups were collapsed (no/limited binocular stereovision group).

Table 4.6. Participants classification based on their clinically measurable binocular stereovision and descriptives of these groups.

Classification group	N (26)	Average age	Physiology
1. No stereovision	5	38	4 corrected strabismus (4 with tropias), 1 intermittent strabismus
2. Local stereovision	6	27	3 corrected strabismus (1 with phoria, 1 with tropia) 3 amblyopia (1 with phoria, 1 with tropia)
3. Stereo-normal	15	23	None

4.6.3. Participants who took part in both experiments 4.1 and 4.2.

Four participants from experiment 4.1 took part in experiment 4.2. All of the subjects were individuals with strabismus, three of which had no measurable binocular stereovision and one had only local binocular stereovision (see Appendices 4.2 and 4.3).

Differences were calculated for these participants for corresponding viewing distances by subtracting the familiar object sizes chosen in experiment 4.2 from those that were perceived as being equal to their intrinsic familiar object size standard in experiment 4.1. Figure 4.9 shows the average differences for each object individually. Overall for all objects at all viewing conditions and distances the difference between experiment 4.1 and 4.2 was positive, which means that on average participants were choosing values which were higher (i.e. choosing larger object sizes) in experiment 4.1. This trend is especially evident at the far viewing distance under binocular-pictorial and binocular-stereoscopic viewing, as in these conditions all subjects show positive difference for basketball and coke can. However, the variability between subjects is much higher for monocular-pictorial far distance viewing for the basketball and coke can, making it difficult to reach any conclusion about the subjects' performance. At the near distance viewing for the basketball and coke can the difference values were much smaller, which together with error bars (standard deviation) suggest that the sizes chosen at this viewing distance were similar between experiment 4.1 and experiment 4.2 (Figure 4.9). Differences in the chosen sizes for the golf ball do not follow the same trends as those for the basketball and coke can. It had widespread high variability for all viewing distances and conditions (error bars for standard deviation in Figure 4.9) indicating that the judgements for the golf ball were not stable. However, overall it is still possible to conclude that in experiment 4.2, on average, participants chose a smaller golf ball size than in experiment 4.1.

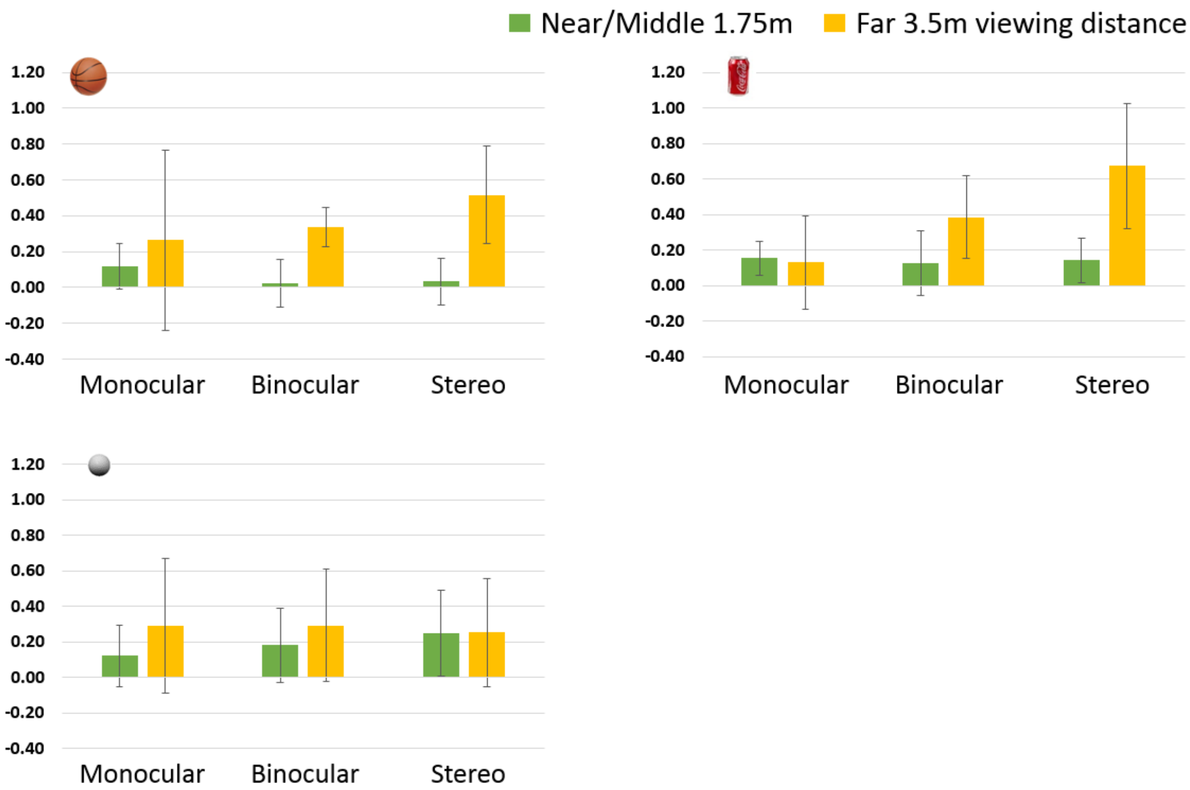


Figure 4.9. Average differences calculated for the 4 participants who took part in both experiments by subtracting the familiar object sizes chosen in experiment 4.2 from those that were perceived as being equal to their intrinsic familiar object size standard in experiment 4.1. Data is summarised for all viewing conditions and distances for each object separately. Only corresponding viewing distances were used from the experiment 4.2 (middle testing distance, which was near testing distance in experiment 4.1; 1.75m). Error bars indicate standard deviation of the average size.

4.6.4. Familiar and non-familiar objects

The stimuli size values assigned to the six real objects used in this experiment had been collapsed to familiar (basketball, coke can, and golf ball) and non-familiar (big, medium, and small cubes) objects. The averages for the familiar vs non-familiar objects across all viewing distances for normal and no/limited stereovision subjects are presented in Figure 4.10. In this figure we have collapsed data for all viewing conditions (their effects are discussed in the following Results section). In both the stereonormal and the no/limited stereovision individual groups' familiar objects, on average, were assigned a larger stimulus size to match the real object than non-familiar objects. For stereonormal subjects, standard error of the mean bars did not overlap for the two groups of objects at the middle (1.75m) and far (3.5m) viewing distances, while for no/limited stereovision subjects they did not overlap only for the far viewing distance (3.5m).

Mixed factorial ANOVA was performed for statistical analysis. Viewing distance (3 levels), viewing condition (3 levels), and object familiarity (2 levels – familiar vs. non-familiar), were analysed as within subject factors. While the participant group (2 levels – stereonormal vs. no/limited stereovision) was analysed as between subjects factor. On average participants assigned significantly larger stimulus sizes to match the real familiar objects than to match the real non-familiar objects (mean = 0.919 SE = 0.024, and mean = 0.848, SE = 0.028, respectively; $F(1, 24) = 18.834$, $p<0.001$). Additionally, significant interaction was found for objects and viewing distance ($F(2, 48)=19.096$, $p<0.001$), as both familiar and non-familiar real objects on average were assigned smaller stimulus sizes with the increasing viewing distance (Near: mean = 0.973, SE = 0.033, and mean = 0.943, SE = 0.034, respectively; Middle: mean = 0.914, SE = 0.027, and mean = 0.845, SE = 0.032, respectively; Far: mean = 0.869, SE = 0.023, and mean = 0.755, SE = 0.025, respectively).

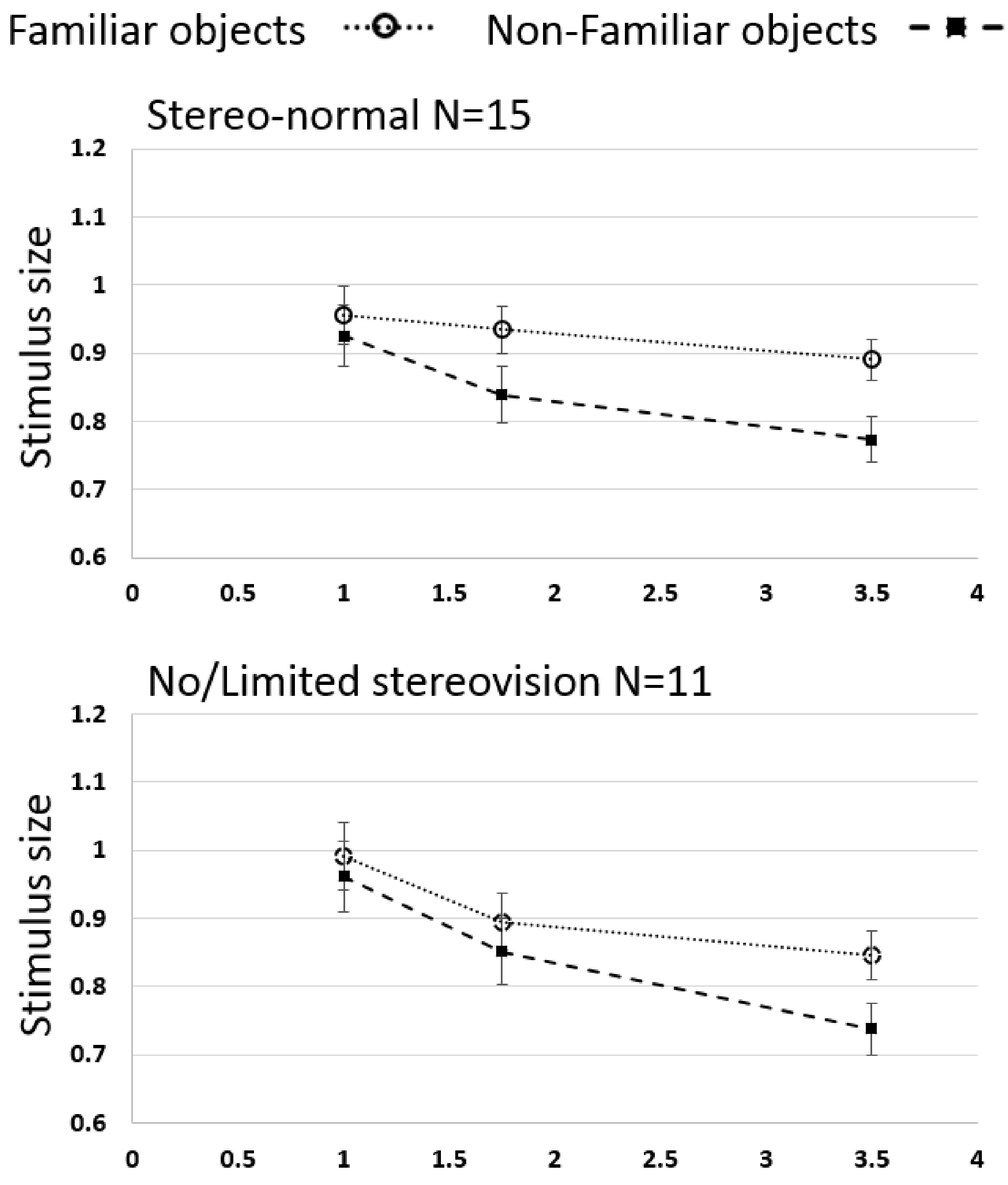


Figure 4.10. Averages of familiar objects (basketball, coke can, golf ball) and non-familiar objects (three different size cubes) collapsed across all viewing conditions, presented for controls and strabismics separately at the three different viewing distances. X axis – viewing distance in meters. Error bars indicate standard error of the mean.

There has been great variability between the sizes chosen for each of the 6 objects. However, for each object participants consistently chose smaller values with increasing distance. Figure 4.11 shows the data summarised across all participants for each out of 6 objects, for each viewing condition separately. All objects have similar sizes for monocular and binocular viewing, while under 3D stereo viewing higher stimulus sizes were chosen for respective viewing distances.

The basketball (purple line) under all viewing conditions and distances was assigned the largest stimulus size values (Figure 4.11). It is followed by the coke can (red line), which overlaps with stimulus sizes assigned to other real objects only at the near distance (1m) under binocular-pictorial and binocular-stereoscopic viewing. In contrast, stimulus sizes assigned to the golf ball (grey line) follow those of non-familiar objects and no unique trends are distinguishable. This is true for all the non-familiar objects, as, contrary to the basketball and the coke can, stimulus sizes assigned to these objects overlap throughout the viewing distances. It seems that under monocular- and binocular- pictorial viewing the middle cube (blue line) and the big cube (yellow line) have been attributed the smallest sizes, while the small cube (green line) was assigned stimulus sizes most similar to the coke can, but under binocular-stereoscopic viewing these trends are reversed (Figure 4.11). The relatively small number of participants and large number of objects does not allow to carry out reliable significance tests beyond these observations. Therefore, for the further statistical analysis the objects had been collapsed to familiar (basketball, coke can, and golf ball) and non-familiar (big, medium, and small cubes) objects.

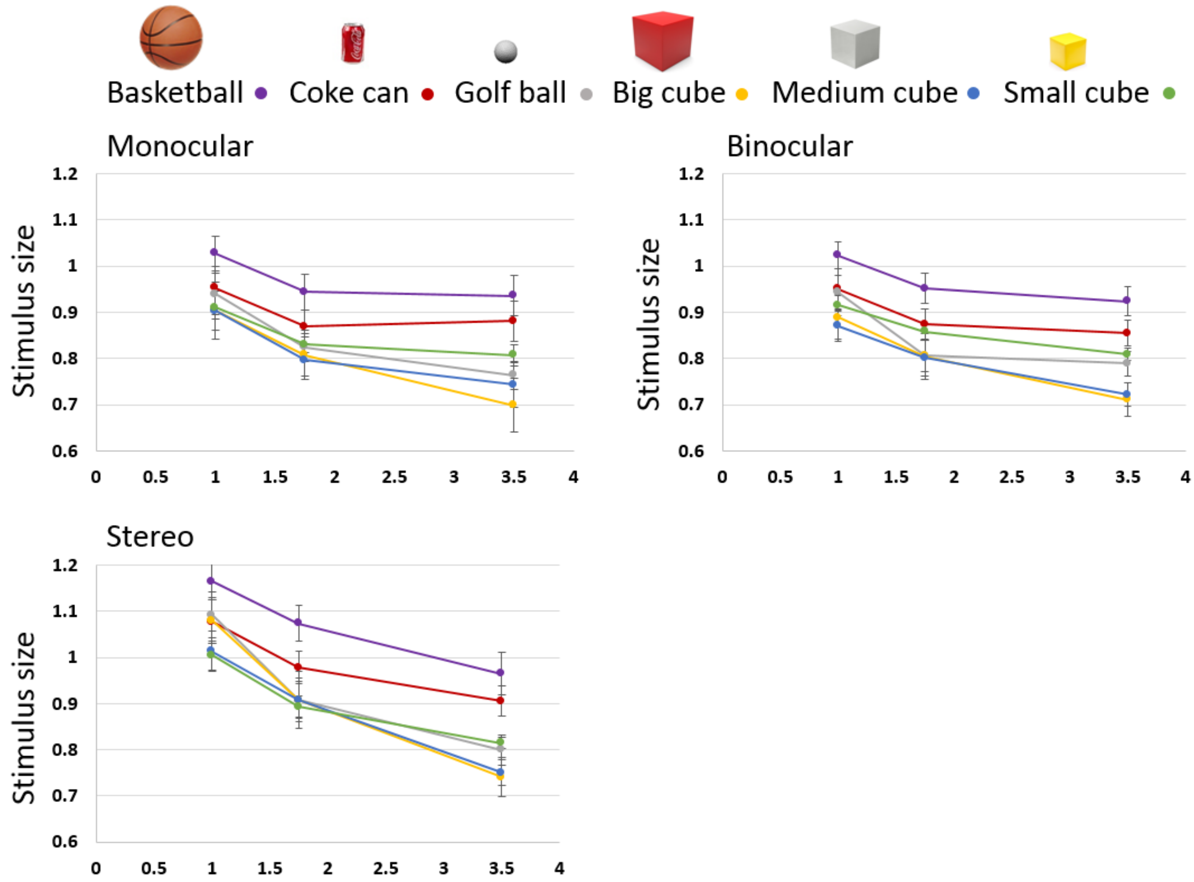


Figure 4.11. Averages across all participant groups for each object at the three different viewing distances presented for each viewing condition separately. X axis – viewing distance in meters. Error bars indicate standard error of the mean.

4.6.5. Distance and Viewing conditions

The trends observed for each of the six objects, or familiar and non-familiar objects, remained when the data for them was collapsed. The summary of selected stimulus size averages chosen under the three viewing conditions at three different distances by stereonormal and no/limited stereo individuals, is provided in Figure 4.12. It is clear that both groups of participants chose smaller stimulus sizes to match the same real object with increasing stimulus viewing distance. Mixed factorial design ANOVA (described in 4.6.4 section) found viewing distance to have a significant effect on the chosen stimulus sizes ($F(2, 48)=18.364$, $p<0.001$). The largest stimulus sizes were chosen under near (1m) viewing distance (mean = 0.958, SE =

0.032), followed by middle (1.75m) viewing distance values (mean = 0.880, SE = 0.028), while the smallest stimulus size values were chosen at the far (3.5m) viewing distance (mean = 0.812, SE = 0.023). Pairwise comparisons with Bonferroni corrections were significant ($p<0.005$ in all cases).

Viewing condition was also found to be a significant factor in the mixed factorial ANOVA analysis ($F(2, 48)=8.415$, $p=0.001$). However, looking at the Figure 4.12 it becomes clear that the only consistent difference between the viewing conditions is that under binocular-stereoscopic viewing both participant groups were assigning larger stimulus sizes to match the real objects. In contrast, monocular- and binocular- pictorial viewing had very similar values that overlap in both participant groups with increasing viewing distance. This was supported by the pairwise comparisons with Bonferroni corrections, as binocular-stereoscopic viewing had significantly larger chosen stimulus size values (mean = 0.925, SE = 0.025) than binocular-pictorial viewing (mean = 0.861, SE = 0.025; $p=0.002$) or monocular-pictorial viewing (mean = 0.863, SE = 0.030; $p=0.023$). However, no significant difference was found between monocular- and binocular- pictorial viewing (Pairwise comparisons with Bonferroni corrections, $p=1.000$). The interaction between the factors viewing distance and viewing condition was found to be non-significant (Mauchly's test was significant $p<0.001$, thus correction was used: Greenhouse-Geisser $F(2.761, 66.268)=2.199$, $p=0.101$).

On the other hand, interaction between the factors viewing condition and object familiarity was found to be significant (Mauchly's test was significant $p=0.029$, thus correction was used: Greenhouse-Geisser $F(1.582, 37.977)=5.285$, $p=0.014$). The trend observed in Figure 4.11 remained when objects were collapsed into familiar and non-familiar groups, as under binocular-stereoscopic viewing both groups of objects were assigned the largest stimulus sizes (mean = 0.950, SE = 0.023 and mean = 0.901, SE = 0.030, respectively), while monocular- and binocular- pictorial viewing had similar stimulus size values for the two object groups (monocular-pictorial: mean = 0.904, SE = 0.028 and mean = 0.822, SE = 0.033, respectively; binocular-pictorial: mean = 0.902, SE = 0.025 and mean = 0.820, SE = 0.027, respectively). Lastly, the consistency in the observed trends in Figure 4.11 and Figure 4.10 is also strengthened by the significant interaction between the factors viewing distance and viewing condition and object familiarity (Mauchly's test was significant p=0.003, thus correction was used: Greenhouse-Geisser F(2.420, 58.079)=14.397, p<0.001).

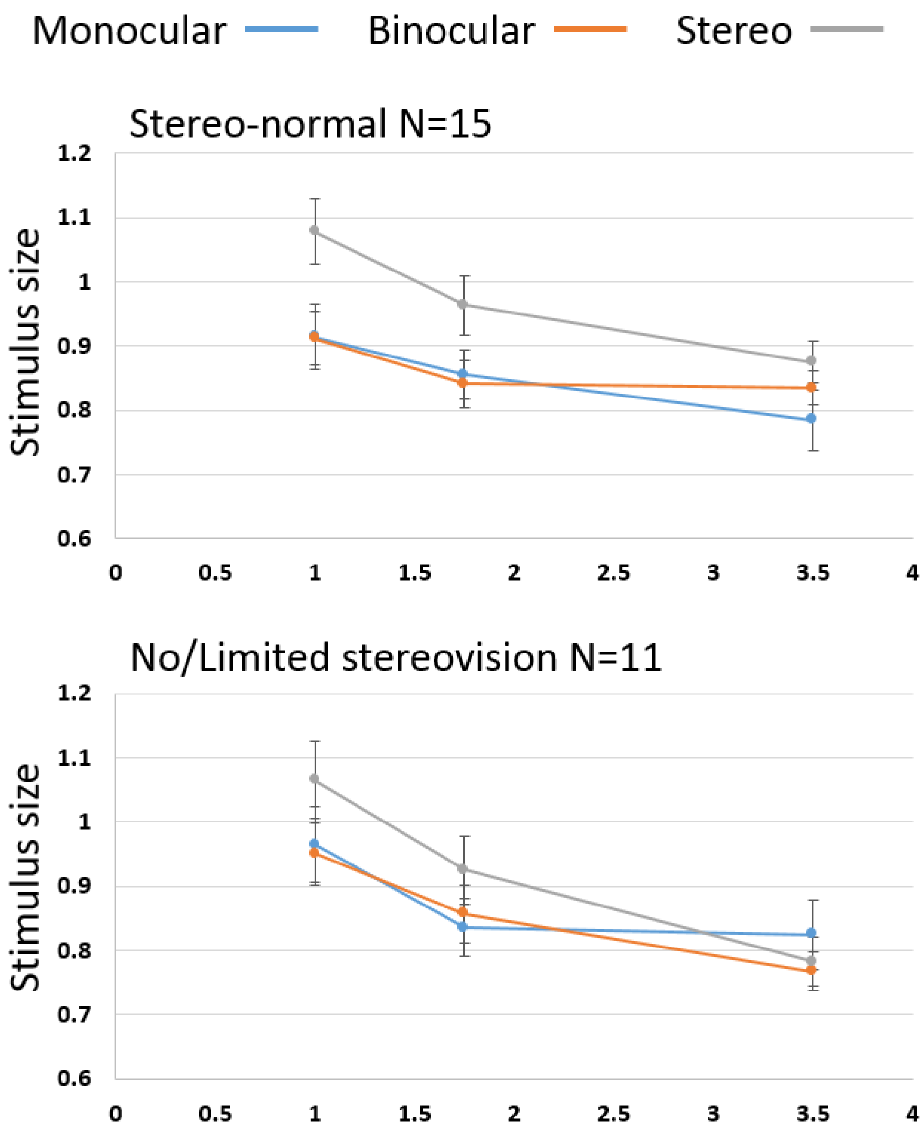


Figure 4.12. Averages across all objects for each of the three viewing conditions (Monocular-Pictorial – Blue, Binocular-Pictorial – Orange, Binocular-Stereoscopic – Grey colour), presented for controls and strabismics separately at the three different viewing distances. X axis – viewing distance in meters. Error bars indicate standard error of the mean.

4.6.6. Typically developed individuals vs. individuals with strabismus

The between subject factor in the mixed factorial ANOVA (described in 4.6.4 section) was found to be non-significant ($F(1, 24)=0.013$, $p=0.909$; all interactions including participant group factor >0.1). However, looking at the Figure 4.12 there is a clear alteration in trend for assigned smaller stimulus size values to match the real objects with increasing viewing distance between the two groups from the medium (1.75m) viewing distance under monocular- and binocular- pictorial viewing conditions. While at the near viewing distance (1m) both stereonormal and no/limited stereovision subjects chose similar stimulus size values under monocular- and binocular- pictorial viewing (stereonormal: mean = 0.914, SE = 0.051 and mean = 0.912, SE = 0.041, respectively; no/limited stereo: mean = 0.965, SE = 0.059 and mean = 0.951, SE = 0.048, respectively), the two groups performance was reversed at the medium (1.75m) and far (3.5m) viewing distances under these conditions. At 1.75m (middle) viewing distance the participants with no/limited stereovision chose larger stimulus sizes under binocular- than monocular- pictorial viewing (mean = 0.858, SE = 0.045 and mean = 0.836, SE = 0.044, respectively), while the stereonormal participants chose larger stimulus values under monocular- than binocular- pictorial viewing (mean = 0.855, SE = 0.038 and mean = 0.841, SE = 0.038, respectively). In contrast, at 3.5m (far) viewing distance, the participants with no/limited stereovision chose larger stimulus sizes under monocular- than binocular- pictorial viewing (mean = 0.825, SE = 0.054 and mean = 0.768, SE = 0.031, respectively), while the stereonormal participants chose larger stimulus size values under binocular- than monocular- pictorial viewing (mean = 0.835, SE = 0.027 and mean = 0.785, SE = 0.047, respectively). This shift in trend can be observed for all objects: familiar (Figure 4.13) and non-familiar (Figure 4.14). Therefore, even though these differences are small, particularly in comparison to the standard errors of the mean (especially at the middle (1.75m) viewing distance) it is clear that this is a consistent trend.

Lastly, while binocular-stereoscopic viewing yielded the largest stimulus size setting for stereonormal subjects at all viewing distances, for the participants with no/limited stereovision this was true only for near and middle viewing distances (Figure 4.12). At the far (3.5m) viewing distance the subjects with no/limited stereovision chose larger stimulus size values under monocular-pictorial (mean = 0.825, SE = 0.054), compared to binocular-stereoscopic (mean = 0.783, SE = 0.037), or binocular-pictorial viewing conditions (mean = 0.768, SE = 0.031).

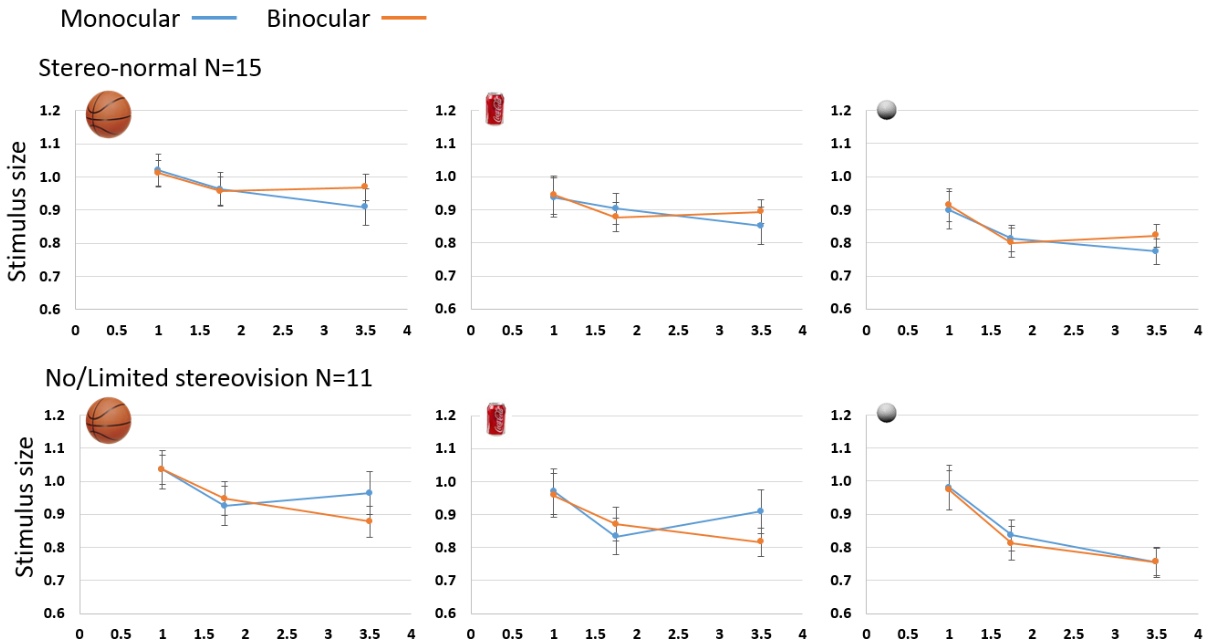


Figure 4.13. Monocular- and binocular- pictorial viewing condition averages summarised for each familiar object (basketball, coke can, golf ball), and presented for controls and strabismics separately at the three different viewing distances. X axis – viewing distance in meters. Error bars indicate standard error of the mean.

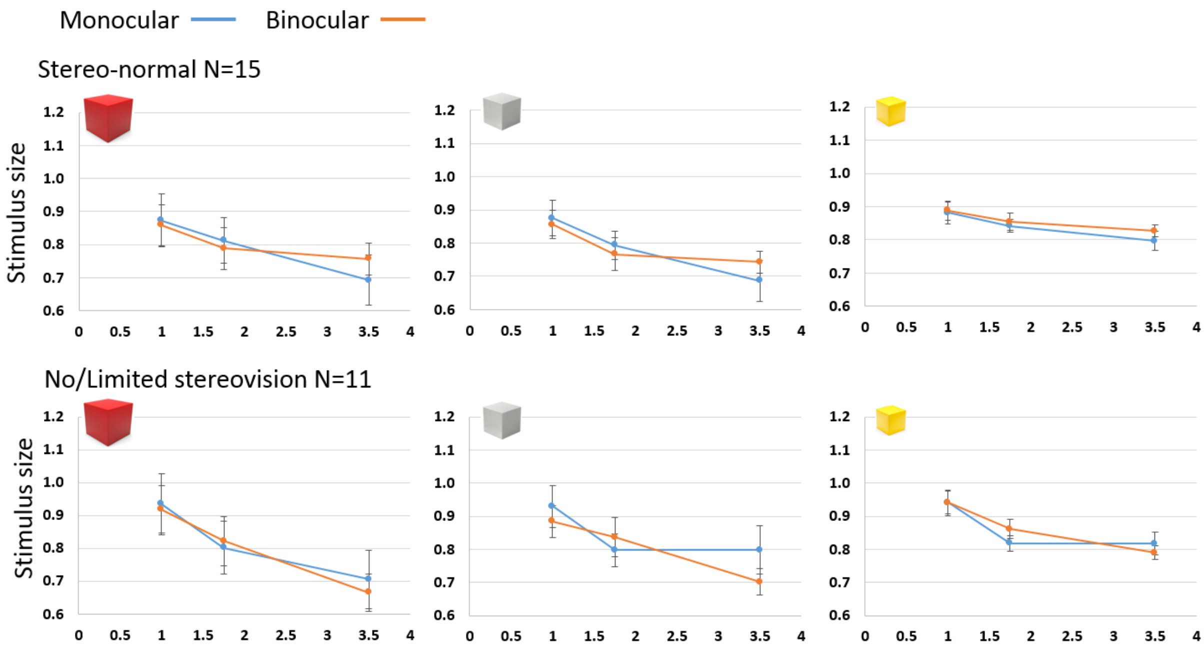


Figure 4.14. Monocular and Binocular viewing condition averages summarised for each non-familiar object (Big red, medium grey, and small yellow cubes), and presented for controls and strabismics separately at the three different viewing distances. X axis – viewing distance in meters. Error bars indicate standard error of the mean.

4.7. Discussion and limitations

In contrast to the results of experiment 4.1, participants with varying levels of binocular stereovision showed a tendency to overestimate the object size as they perceived veridical stimuli size to be larger than the real object and chose smaller stimuli sizes to match the real object. This implies that participants had a tendency to overestimate the viewing distance. All subjects had a highly significant and consistent trend to choose increasingly smaller stimulus size to match the real object with increasing egocentric distance. Therefore, in contrast to findings discussed by Epstein et al. (1961), participants in the current study can be interpreted as having overestimated egocentric distance and perceived displayed object as being further away than the actual display distance. To our knowledge this is the first study to show such findings and suggest that this may be the result of a complex interaction of cognitive effects with the specific task (comparing sequentially with a real visible object). W. C. Gogel and da Silva (1987) have discussed the importance of cognitive aspects in familiar object size judgments and egocentric distance perception. Further studies are necessary to ensure that the method of adjustment with a size reference 3D object creates a testing environment in which object size and egocentric distance are overestimated.

Consistent with experiment 4.1, in the current experiment under stereoscopic viewing participants chose significantly larger stimuli sizes for all viewing distances. It is plausible that the 3-dimensionallity of displayed objects ("pop out" of 3D rendered object) has affected the participants' perceived egocentric distance, making them perceive objects as being closer to them and choosing larger stimuli sizes to match the real objects. In contrast, monocular and binocular viewing yielded similar stimuli size choices. These results were obtained despite high variability between the sizes attributed to the six objects. There was a significant difference between the three familiar (basketball, coke can, golf ball) and three abstract non-familiar object (3 different size cubes), as all subjects chose significantly larger stimuli size values for familiar than non-familiar objects. However, even though the golf ball was considered to be a familiar object, it was assigned size values more closely resembling the abstract objects, suggesting that it is not an object that most observers have a strong familiarity with in terms of size, and therefore it behaved as a non-familiar object. This raises questions about the stimuli choices in future experiments examining or utilizing familiar size.

Both the typically developed individuals and the individuals with no/limited stereovision consistently overestimated object sizes with increasing viewing distance. This was observed for all viewing conditions, but there was a notable switch in the monocular- and binocular-pictorial conditions between these two groups. At the far viewing distance, the stereonormal subjects chose larger stimulus size values to match the real objects, and thus were more accurate, under binocular- than monocular- pictorial viewing. This trend was reversed for the strabismic observers with no or limited binocular stereovision. In fact at the far (3.5m) viewing distance the subjects with no/limited stereovision chose the largest stimulus size values under monocular-pictorial viewing, in contrast to the stereonormal subjects who chose the largest stimulus size values under binocular-stereoscopic viewing closely followed by binocular-pictorial viewing. This is consistent with anecdotal reports (Barry, 2009; Godber, 1981; Sacks, 2006) which suggest that individuals with limited or no binocular stereovision rely more on monocular cues, while typically developed individuals depend more on binocular cue information. However, it is important to note that at the near distance viewing the strabismics with no/limited stereovision and the stereonormal subjects' performance did not vary between monocular and binocular viewing, thus suggesting that the strabismics are able to obtain reliable egocentric distance information at the near viewing distance of one meter, in a similar way as the stereonormal subjects.

The current experiment had a slightly larger sample size than experiment 4.1, but future experiments should further increase not only the sample size, but also the consistency in the strabismic subject cohort in terms of their specific binocular deficit. Alternatively, to ensure that the observed effect in the current experiment exists, the study could be replicated only with a large sample of control subjects, and using multiple methods (internal standard, matching to real object). Additionally, due to testing time constraints this experiment had a limited number of trials per each object, viewing conditions, and testing distance. This may not necessarily been an issue, considering that less than 1% of trials were mistakes (which shows high compliance rate), and that the participants in this experiment had the real object at a reaching distance throughout the testing (size reference present at all times). However, in the future, more trials could be involved, possible by performing testing in two sessions as in experiment 4.1.

4.8. General discussion

The two experiments presented in this study found contradictory results. Experiment 4.1 followed the predictions of underestimation of size and distance at farther distances (over 3 meters) due to the diminishment in the effectiveness of egocentric cues and the corresponding action of the specific distance tendency. In contrast, in experiment 4.2 all subjects overestimated the object sizes (selected a smaller matching size) with increasing viewing distance, thus overestimating the egocentric distance. The latter findings are contradictory to prior research, as according to Epstein et al. (1961) a frequently confirmed finding is that with increasing egocentric distance object size is underestimated as subjects choose larger stimulus sizes than veridical object sizes. This has been found by W. C. Gogel (1963, 1976) for familiar object sizes under diminished viewing conditions. Work by W. C. Gogel and da Silva (1987) does place emphasis on cognitive aspects in familiar object size judgments, which may have played a more significant role in the second experiment as participants had unlimited time to make their adjustments. It is possible that participants tried to remember the lay out of the room and the distance to the monitor, rather than trying to base their responses on their perception of depth. In fact, prior research has shown participants' responses to vary based on instructions for judging playing card size either according to their apparent size or objectively taking into account the way objects appear at different viewing distances (W. C. Gogel & da Silva, 1987). However, in our study, the instructions provided in both experiments were identical, the only clear change was the testing method. This raises considerations about the choice of testing method, as two different groups of researchers could be asking the same experimental question but getting opposite findings due to the testing method they use. Further research could test replicability of the experiment 4.1 and 4.2 findings, as well as try to reveal the factors affecting change in subjects' responses by providing different instructions (e.g., asking subjects to make judgments based on apparent size or objectively taking into account the way objects appear at different distances, as in the experiment by W. C. Gogel and da Silva (1987)), reversing the task (i.e., stimulus displayed on the monitor is the reference object, while one of the real objects varying in size at the reaching distance has to be chosen as a match), adding conditions with full visual information cues (e.g., performing experiment with turned on lights, or presenting all real objects at the same time and thus providing relative size information).

The second important difference between the experiments was the constant visual access to the real 3D object as an absolute size reference in the Experiment 4.2. Its presence was intended to help minimise variability of the internal familiar object size standard (or memory of size) between the participants. In order to avoid retinal comparisons the objects were located on the subject's right hand side. Thus in order to see them, participants had to turn their head to a position from which they could not see the monitor. It is possible that instead of using the object as a reference for the absolute size allowing them to adjust their internal familiar object size standard, participants used the reference 3D object by mentally carrying it the perceived distance, i.e. a number of subjects made verbal comments that they were imagining carrying the object to the distance at which the stimulus was observed (mentally carrying the real 3D object). On the other hand, this suggestion does not account for the variation between the objects, as the basketball and coke can from the six objects used were assigned largest stimulus size values across all viewing conditions and distances in the experiment 4.2. If it was all just a process of mentally carrying the real 3D object, there should be no observed division between the stimulus sizes assigned to familiar and non-familiar objects. However, variability between the stimulus size values assigned to different objects was great, and while the basketball and the coke can were consistently attributed the largest stimulus size values, the other four objects (including the third familiar object – golf ball) were assigned similar stimulus size values that varied between viewing conditions. In fact, the responses for the golf ball suggest that there is no clear distinction between the familiar (basketball, coke can, golf ball) and non-familiar (three different size cubes) objects. Therefore, in future research, the choice of objects has to be carefully considered, even though the real 3D objects are planned to be presented during the testing.

In both experiments, performance of strabismic individuals with no or limited binocular stereovision closely resembled that of stereonormal subjects. This suggests that mechanisms of object size judgment and egocentric distance perception are essentially the same for all individuals, and at the near viewing distance similarly accurate values are obtained despite presence of a strabismus, history of strabismus surgery or amblyopia. This is in accordance with Barry (2009) and her ability to regain the use of normal vergence in her 40s. Another similarity between no/limited stereovision and stereonormal subjects was that in both experiments, under stereoscopic viewing, larger stimulus size values were attributed to the objects. There is no clear explanation for familiar size overestimation under stereoscopic viewing, as, to our knowledge, the current study was unique in its experimental design. It is possible that the underestimated distance affects binocular disparity processing in such a way that under binocular-stereoscopic viewing the displayed stimuli is perceived as being closer to the viewer than the monitor. Whilst under monocular- and binocular- pictorial viewing the displayed stimuli is perceived to be on the monitor, which is known to be at the far end of the room. Additionally, it is likely that viewing stimulus displayed stereoscopically makes half of it appear outside the plane of the monitor, thus creating the “pop out” effect and creating perception of being at a closer distance than it is. In fact, the majority of participants made verbal comments noting this effect at one meter viewing distance, while some subjects even enquired which distance they should use to make their judgments about the stimuli (the distance to the monitor or the distance to where the stimuli appears to be). If that is the case, the fact that individuals with no clinically measurable binocular stereovision chose larger stimulus size values under binocular-stereoscopic viewing would suggest that they were affected by this effect, and thus would support research showing that strabismic individuals can gain some depth information from stereoscopic viewing (Tidbury, Black, & O'Connor, 2014; Tidbury et al., 2015). To verify this assumption reaching and grasping studies could be performed at the near distance, as they would show if participants are actually trying to grasp closer to them under 3D viewing, or, potentially, if being asked to interact with the object would eliminate the observed size overestimation or underestimation. Distance beyond reaching and grasping could possibly be explored using virtual reality set ups, such as HTC vive, which have two trackable hand held controllers that could be programmed to appear in virtual reality as long reaching devises, or purely be used by participants to change the displayed object sizes via clicks of buttons on the controllers. Lastly, the fact that all subjects had a tendency to choose larger stimulus size values under the binocular –stereoscopic viewing highlights the need to consider inclusion of a number of different viewing conditions in experimental designs, as testing exclusively stereoscopic viewing condition might not provide accurate insight.

The findings of the current study suggest another previously unreported trend. There was an observable difference between the size judgments made by the no/limited stereovision and the stereonormal subjects under monocular and binocular viewing in the second experiment. Opposite trends were present between the two groups between the middle and far viewing distance, at which accommodation and vergence information is generally not thought to be useful (Cutting, 1997; Fisher & Ciuffreda, 1988; Viguier et al., 2001). Under these conditions individuals with no/limited stereovision chose stimulus sizes to match real objects that were closer to the veridical size under monocular- than binocular- pictorial viewing, while stereonormal subjects chose less erroneous stimulus size estimates under binocular- than monocular- pictorial viewing. These findings correspond to prior research showing that strabismics with no or limited binocular stereovision perform less accurately under binocular viewing than stereonormal subjects in blind walking tasks or complex motor tasks (O'Connor, Birch, Anderson, & Draper, 2010; O'Connor, Birch, Anderson, Draper, et al., 2010; O'Connor & Tidbury, 2018; Ooi & He, 2015), which is also supported by anecdotal reports (Barry, 2009). However, in the first experiment individuals with no/limited binocular stereoacuity showed highly similar performance under the two viewing conditions (monocular- and binocular- pictorial viewing). This could suggest that if, in fact, object size judgments in experiment 4.2 are more based on cognitive processing and in contrast in experiment 4.1 it is more based on perceptual process, the monocular vs. binocular difference between the no/limited stereovision and stereonormal subjects is more cognitively than perceptually driven. Further studies are required for exploring this possibility and its implications.

This study had limitations to its design, including limited participant number, which led to variability in strabismus history and its manifestations in the group of individuals with no or limited binocular stereovision, which included individuals with amblyopia. The use of the active 3D display resulted in a ghosting effect, which, even though according to subjects was not distracting or visually uncomfortable, could have affected how images appeared, and thus in future research passive 3D displays should be used. Lastly, it is possible that adaptation to the dark allowed participants to see other objects in the room besides the display, which could have allowed subjects to use relative distance cues in order to make size judgments (e.g. according to the adjacency principle by W. C. Gogel (1963)). Creating a tunnel from black cloth or black foam boards between the subject and the display would allow to eliminate this possibility in the future studies. However, these limitations were present in both experiments, still they yielded contrasting findings highlighting the importance of considering method of testing when exploring egocentric distance and familiar object size perception.

Chapter 5

Pictorial depth perception in strabismus: perspective

5.1. Introduction

Strabismus (a.k.a. strabismus) is an ophthalmological condition resulting in a misalignment of the eyes. Due to numerous reasons individuals with a strabismus are unable to coordinate their eye muscles to fixate the two eyes on a single target point in space (von Noorden & Campos, 2002; Wright et al., 2006). This results in the two eyes receiving information from two non-corresponding areas of space, which the brain still tries to process as being in the same direction and location in space (Motley, 2018). However, as binocular disparities cannot be matched individuals with strabismus experience diplopia (double vision), which, if sufficient alignment cannot be achieved, in childhood onset strabismus the visual system avoids by supressing visual information from one of the eyes (Motley, 2018; von Bartheld et al., 2010). According to the critical period theory if congenital strabismus is not corrected during infancy and early childhood, it affects or prevents development of binocular disparity neurons, thus resulting in permanent lack of binocular stereovision and consequential deficiency in 3D space perception (Hubel & Wiesel, 1965; Ogle, 1950; Sherry et al., 2005).

Exploring the extent of these limitations is important considering that approximately five percent of the adult population are diagnosed with strabismus (von Bartheld et al., 2010). Researchers have looked at the functional capacities of people with strabismus, asking them to perform high visual precision requiring tasks, such as bead threading and pouring water, without any haptic response (O'Connor, Birch, Anderson, & Draper, 2010; O'Connor, Birch, Anderson, Draper, et al., 2010). Strabismics showed difficulty in performing these tasks, as well as blind walking tasks with the target object suspended mid-air (O'Connor, Birch, Anderson, Draper, et al., 2010; O'Connor & Tidbury, 2018; Ooi & He, 2015). Apart from these studies, most of the understanding of depth perception in strabismus is limited to anecdotal reports (Barry, 2009; Sacks, 2006). The most famous instance being that of Susan Barry (a.k.a. Stereo Sue), who had a congenital strabismus and recovered eye alignment with binocular depth perception in her 40s (Barry, 2009). Stereo Sue made researchers question if individuals with infantile strabismus can reverse their limitations in 3D space perception. Current research on individuals with none or limited stereovision suggests that improvement is possible even in early adulthood (Ding & Levi, 2011), however, this research is largely limited to amblyopia (see for a review Levi et al. (2015)). Overall, studies on strabismus focus on exploring functional limitations in motor task performance (Bloch et al., 2015; O'Connor, Birch, Anderson, Draper, et al., 2010), or assessing accuracy of binocular stereoacuity tests (Fielder & Moseley, 1996; Read, 2015; Tidbury, Black, & O'Connor, 2014).

However, no studies, to our knowledge, have asked how individuals with strabismus perceive depth, and the existing understanding is based on anecdotal reports which provide a mixed picture. For instance according to Susan Barry before she gained binocular stereovision, she felt that she could judge depth as well as anybody using monocular cues, such as perspective and parallax obtained by moving her head (Barry, 2009). In fact she started seeking to improve her binocular vision only in her 40s, because she started to experience diplopia at further distances, which had affected her driving. Susan Barry performed a number of ophthalmological exercises, but she specifically noted the Brock string exercise focused at improving vergence, which allowed her to train her eyes to focus on a single point in space (ball on a string) at various distances (Barry, 2009). This is one of the examples she gave about the change in her depth perception:

"I noticed the edge of the open door to my office seemed to stick out toward me. Now I always knew that the door was sticking out toward me when it was open because the shape of the door, perspective and other monocular cues, but I had never seen it in depth. It made me do a double take and look at it with one eye and then the other in order to convince myself that it looked different." (Sacks, 2006)

Susan Barry emphasised change in the qualitative aspect of depth perception, as after gaining binocular vision she started seeing "palpable volume[s] of empty space" and every-day objects, such as sink faucets, "popping out", from her personal experience using a stereoscope she concluded that perceived depth is inferior if the eyes are crossed (misaligned) (Barry, 2009). Susan Barry's report suggests that monocular cues available to individuals with strabismus provide necessary information about depth, but overall it is inferior to perceived depth binocularly. However, anecdotal reports provide only unique personal experiences and most importantly do not differentiate between the types of depth perception.

In order to systematically explore depth perception in strabismus, firstly, it is important to distinguish different types of depth. Often depth perception is described in a generic way, for instance, as the ability to judge the distance of objects and the spatial relationship among objects at different distances (Sekuler & Blake, 1994). Here the initial part of the definition would be referring to the egocentric distance, which is the distance between an observer and the object he/she is focusing on (Loomis et al., 1996), while the second part of the definition refers to depth, i.e. distances between one object and another or between different parts of a single object. A further distinction is between relative and absolute depth perception. When an observer views a 3D scene, the retinal image provides relative information about the proportional differences and depth relations between the objects in the 3D scene. The observer may perceive only the order of objects in depth without a sense of a magnitude of separation between them (ordinal depth), or perceive ratios of magnitudes of separation between the objects (depth ratios). This information is also available in pictures (painting, photographs, and movies) and allows relative depth perception which includes the perception of 3D shape and relative layout. However, it does not allow the observer to perceive exact values of the object sizes and distances between them. In order to do so, relative depth and size information in the retinal image must be scaled using egocentric distance information (Figure 5.1). Only in this case will the observer then perceive absolute depth, i.e. perceive absolute sizes and depth values of the 3D scene, which also means that the observer, in effect, knows egocentric distances to each point and object in that 3D scene.

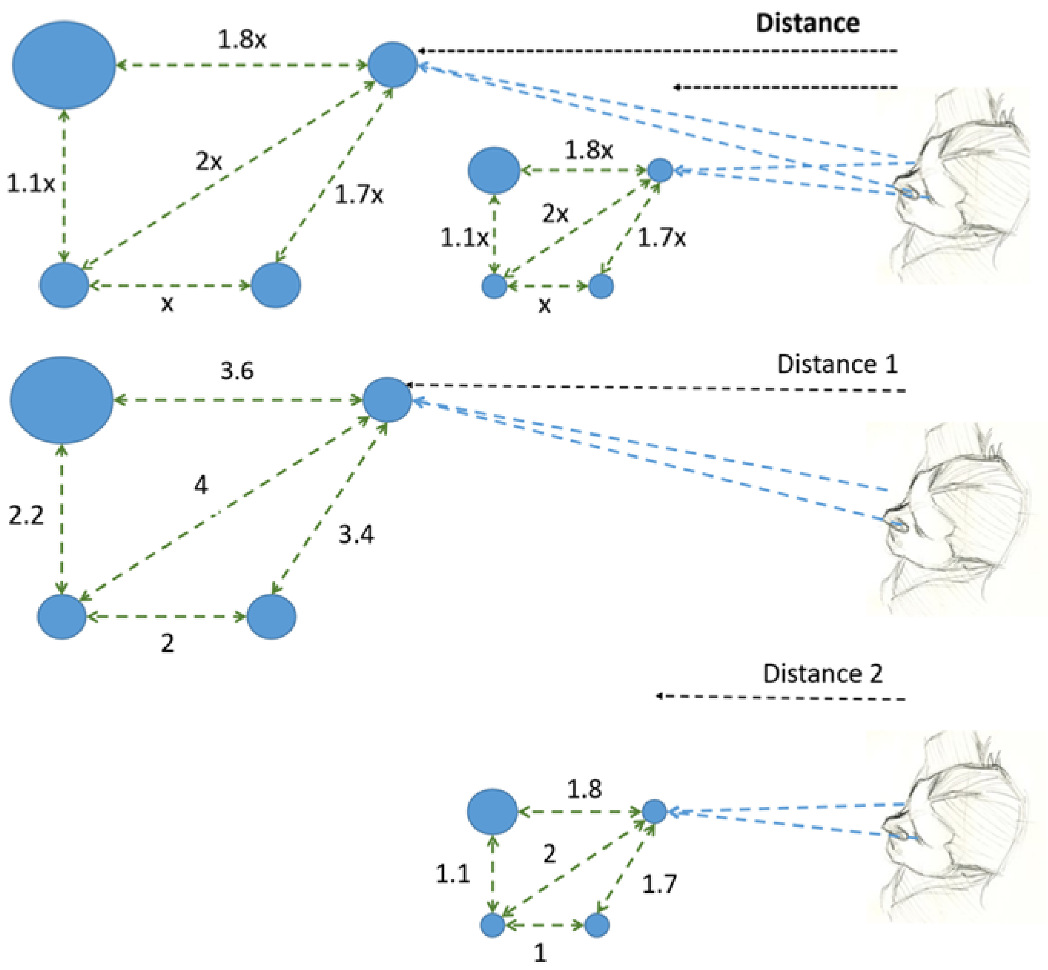


Figure 5.1. An observer looking at an arrangement of objects can perceive either relative (top panel) or absolute (lower two panels) depth, which depends if the observer can perceive the egocentric distance to the object he/she is focusing on (in the image marked as distance; line of sight marked with converging lines). Top panel: the egocentric distance to the object in focus is unknown, thus only relative depth is perceived. The observer can tell the magnitudes of depth between the objects (e.g. 2x is twice longer than x), but the exact values are unknown. In this case the observer could perceive same relative depth ratios from two different size arrangement of objects, i.e. the smaller one viewed from a closer distance, and the larger one viewed from further away, would elicit identical relative depth. Lower panels: the observer perceives egocentric distance to the object he/she is focusing on and thus is able to perceive absolute depth values. In this example distance 1 is twice of distance 2, thus the perceived absolute depth in the two arrangements differ, i.e. the depth values in the larger arrangement viewed from distance 1 are double of those in the smaller arrangement viewed from distance 2.

In order to obtain absolute depth, the visual system uses a number of information sources (cues). Egocentric distance is estimated with high precision at a near distance (up to 1m) using oculomotor information: accommodation and vergence (Fisher & Ciuffreda, 1988; Viguier et al., 2001). Additionally, distance information is received from blur gradient (depth-of-focus gradient) (Vishwanath & Blaser, 2010) and eye declination level, which has been show to provide distance information up to 12 m (Loomis et al., 1996). Relative depth is perceived using either static or kinetic information. The kinetic cue is motion parallax and can be obtained monocularly by moving one's head and processing differences between the consecutive retinal images, which allows highly precise relative depth estimation (DeAngelis, 2000; Ono et al., 1986). Static cues that allow to perceive relative depth monocularly (a.k.a. pictorial cues) traditionally are interposition (occlusion), shading and shadow, perspective convergence, relative size (perspective scaling), perspective foreshortening, atmospheric perspective, elevation (relative height), and texture gradient (arguably, combination of relative size and linear perspective effects on the elements comprising a pattern) (for a review see Kubovy (1988)). The static binocular source of information is binocular disparity, which is considered to provide the most precise information about relative depth, however it still needs egocentric distance estimate as angular disparities vary as the inverse square of the viewing distance (Ogle, 1950; Ponce & Born, 2008). Therefore, in order to be able to perceive 3D space in a way that allows us to manipulate it and interact with it, relative depth information is scaled according to the estimated egocentric distance to obtain absolute depth (Vishwanath, 2014). As discussed previously, current knowledge on the way individuals with strabismus see depth provides a mixed picture. Considering that binocular disparity and vergence information is not available to strabismics, it would suggest that at the near distance they should experience deficiencies in their perception of absolute depth. This is consistent with deficits in motor task performance, e.g. bead threading (O'Connor, Birch, Anderson, & Draper, 2010; O'Connor, Birch, Anderson, Draper, et al., 2010). Due to their limited binocular stereovision it is has been traditionally assumed that when strabismics view a static 3D scene (no motion parallax information), their perception is based on static monocular cues (a.k.a. pictorial cues), providing only relative depth information. On the other hand, at the far distance strabismics have been shown to correctly judge absolute depth using declination from eye level information for estimating egocentric distance to the ball placed on a floor in blind walking tasks (Ooi & He, 2015). This seems to support the idea that monocular relative depth cues should be available and allow strabismics to successfully interact with the space around them. However, Stereo Sue's anecdotal report seems to claim that they are inferior to the perception one has using binocular vision, or provide inferior information due to the eye-misalignment (Barry, 2009; Sacks, 2006). Therefore, it is not clear how well relative depth cues can be processed and used by strabismics.

In the current study we wanted to examine the perception of relative depth in strabismics. For individuals with stereonormal vision it seems that perception of monocular relative depth cues is automatic and is part of bottom-up perceptual processing. This is evident in paintings and photographs, when an observer is looking at a painting or a photograph, he/she clearly knows that they are looking at a flat surface or a picture, but it does not stop the observer to perceive pictorial space as being 3-dimensional. Perception of pictorial depth cannot be suppressed by disparity information, either monocular (motion) or binocular, which is clearly demonstrated by the unavoidable effects of visual illusions (deLucia & Hochberg, 1991; Ninio, 2014). The automatic bottom-up processing of pictorial depth has been suggested at the beginning of the last century in Thouless's experiments (1931), revealing subjects' inability to suppress perspective size and shape constancy. Participants showed systematic misperception of object size and shape with their responses falling between the properties of the stimulus and the real object, named 'phenomenal regression to the real object' and measured using Thouless ratio (Thouless, 1931). The fact that the participants systematically judged farther objects as larger than indicated by the retinal image (Thouless, 1931), suggest that the visual system is adapted to automatically process relative depth information in order to perceive objects as having a constant size even though their retinal image would change in response to them moving further away or closer to the viewer. The size constancy effect has been found even among well trained artists, trying to supress background information in size matching tasks, which clearly indicates that it is a bottom-up automatic process (Ostrofsky, Kozbelt, & Seidel, 2012). This illusionary effect can be observed in the stimuli created for the current study (see Figure 5.2), which were based on photographic images used by Erkelens (2016). The image presented in the Panel A (Figure 5.2) has four lines that are separated by equal intervals on the 2-dimension plane of the monitor, however, due to automatic processing of linear perspective information, the interval between the two shortest lines appears to be larger than others, as it is perceived to be the furthest away in space. This indicates that we are susceptible to linear perspective information, as it is still processed even though we are trying to supress it. In fact, Erkelens has discussed that visual space, is the space which appears to be correct but in fact is between the veridical flat 2D surface of the picture, and the geometrically correct 3D space captured in the photograph (Erkelens, 2015a, 2015b, 2016). Further indication that monocular relative depth cues are part of automatic bottom-up process is entailed in the maximum-likelihood estimation (MLE) model, according to which all available visual cues are weighted by their relative reliability (Hillis, Watt, Landy, & Banks, 2004). Therefore, in order to obtain a reliable estimate of the 3-dimension space, in the MLE model pictorial cues must be lawfully combined with disparity. Measuring susceptibility to pictorial relative depth cues, such as perspective, in individuals with strabismus, would show if in their case, this information is also part of bottom-up automatic visual processing.

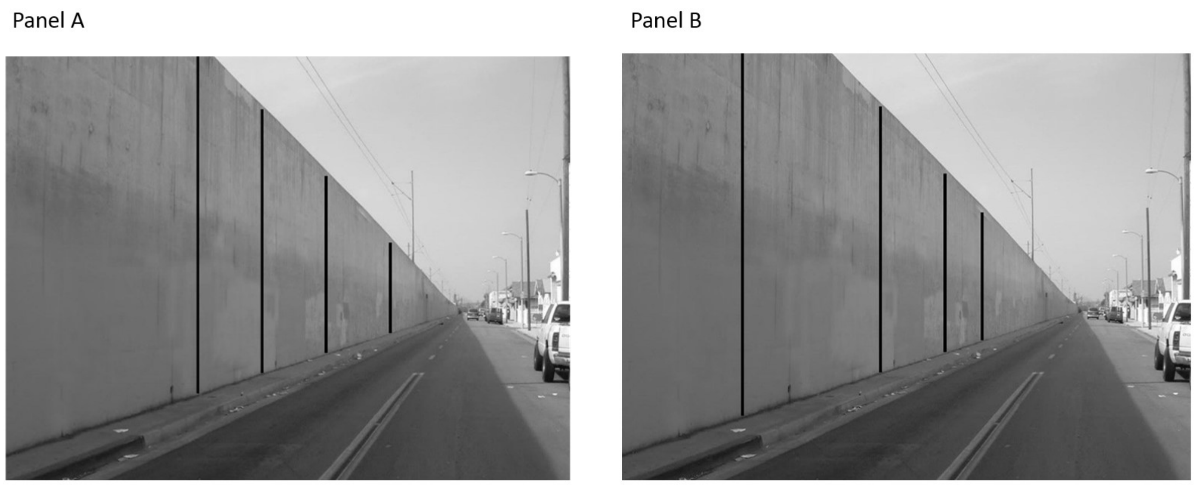


Figure 5.2. Example of the stimuli used in the current study, showing the role perspective information has in interval equidistance judgments. Consider the apparent equidistance of intervals between the four lines in each of the pictures. *Panel A* – the intervals are equidistant on the 2-dimensional plane of the surface of the photograph. However, due to the automatic processing of relative depth information in the image, the interval between the two shortest lines is perceived as being the largest, as linear perspective indicates that it is furthest away. *Panel B* – the intervals are equidistant within the depicted 3-dimensional pictorial space. This image reveals how accurately perspective information is used to judge relative depth ratios of the intervals. Images based on Erkelens (2016).

On one hand, if in typically developed binocular individuals the relative depth information is learned in conjunction with binocular disparity, then individuals with infantile or congenital strabismus during the critical period would not develop this link and thus may not be using bottom-up processing for relative depth information (Hubel & Wiesel, 1965; Wright et al., 2006). Instead, individuals with infantile strabismus may develop cognitive top-down strategies of using relative depth cues, which may lead to them having different relative depth perception to that of typically developed binocular individuals. On the other hand, monocular relative depth cues may be processed independently from binocular disparity, in which case deficits experienced by individuals with strabismus during the critical period would not carry an effect and their relative depth perception should be similar to that of typically developed binocular individuals. Examining similarities and differences between strabismics with none or limited binocular stereovision and stereonormal subjects would allow to address twofold aspects of the relative depth processing. Firstly, strabismics' susceptibility to relative depth information, as demonstrated in the illusions among stereonormal subjects (Ninio, 2014), would indicate it being a bottom-up process independent of binocular disparity. Secondly, if strabismics are using a top-down cognitive process for deriving relative depth information, it may affect how well they can use the information entailed within such cues as perspective. For instance, if the visual information of perspective is processed together with binocular disparity, strabismics' cognitive inferences may not be accurate beyond the reaching distance (i.e., space where they could learn to adjust their judgments via haptic feedback).

The current study tries to explore this by systematically comparing pictorial depth perception of individuals with typically developed binocular vision to the ones with strabismus. Consider the apparent equidistance of intervals between four lines in each stimuli presented in Figure 5.2. If strabismics, when asked to ignore the background image and judge interval equidistance on the 2-dimensional plane (Panel A, Figure 5.2), showed bias for underestimating the size of the interval which is the furthest in pictorial relative depth, it would indicate that the perspective cue is part of automatic bottom-up visual processing. Any difference in the susceptibility bias between the stereonormal and strabismic individuals would suggest possible differences in processing of monocular relative depth cues. The second aspect of relative depth processing can be explored by providing identical visual stimuli, but this time asking to imagine the intervals to be equidistantly separate within the depicted pictorial space (Panel B, Figure 5.2). If strabismics are accurately using the information provided by the monocular perspective cue, they should be able to perceive relative depth ratios of the intervals, and their judgments would be similar to those with normal binocular stereoacuity. If the pictorial cues are used to cognitively reconstruct 3-D space and strabismics perceive limited depth on everyday basis, their internal representation of 3-D space may lead them to choose a more shallow relative depth. Therefore, exploring relative depth defined by linear perspective in individuals with strabismus would add to our understanding about the limitations people with no or limited stereovision experience on daily basis.

Experiment 5.1

In this experiment we investigated if participants were susceptible to pictorial depth information, i.e. if participants' judgments about interval equidistance on a 2D plane will be biased by perspective information in the background images. Additionally, we explored the participants' capacity to use perspective information for accurately judging relative depth, or the quantity of relative depth perceived among participants with and without strabismus.

5.2. Methods

5.2.1. Stimuli

Stimuli created for the current experiment were based on perspective photographs used by Erkelens (2016) to show how appearance of intervals between four lines interposed on a perspective image change if they were equidistant in the picture plane, visual space, and physical (3D) space. Three types of stimuli images were created with three intervals between four lines: Control (C), Control Perspective (CP), and Pictorial Perspective (PP) (Figure 5.3). In the Control condition four lines were equal in length and were displayed either horizontally or vertically. The CP condition included perspective convergence information and had tapering lines matching PP stimulus. Three different images were used for PP stimulus. For vertical stimulus images of a road or river, with black or white lines, respectively, and for horizontal orientation, left and right orientation images of a wall. To match the horizontal PP condition stimuli, the CP vertical stimulus had two variations: white or black lines. Thus, in total, C condition had 2 unique stimuli, while CP and PP had 4 unique stimuli (Figure 5.3).

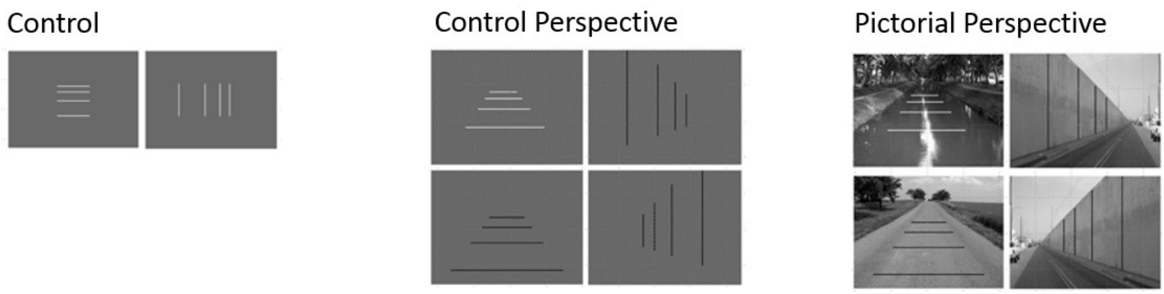


Figure 5.3. The horizontal and vertical variations of stimuli created for the Control, Control Perspective, and Pictorial Perspective conditions.

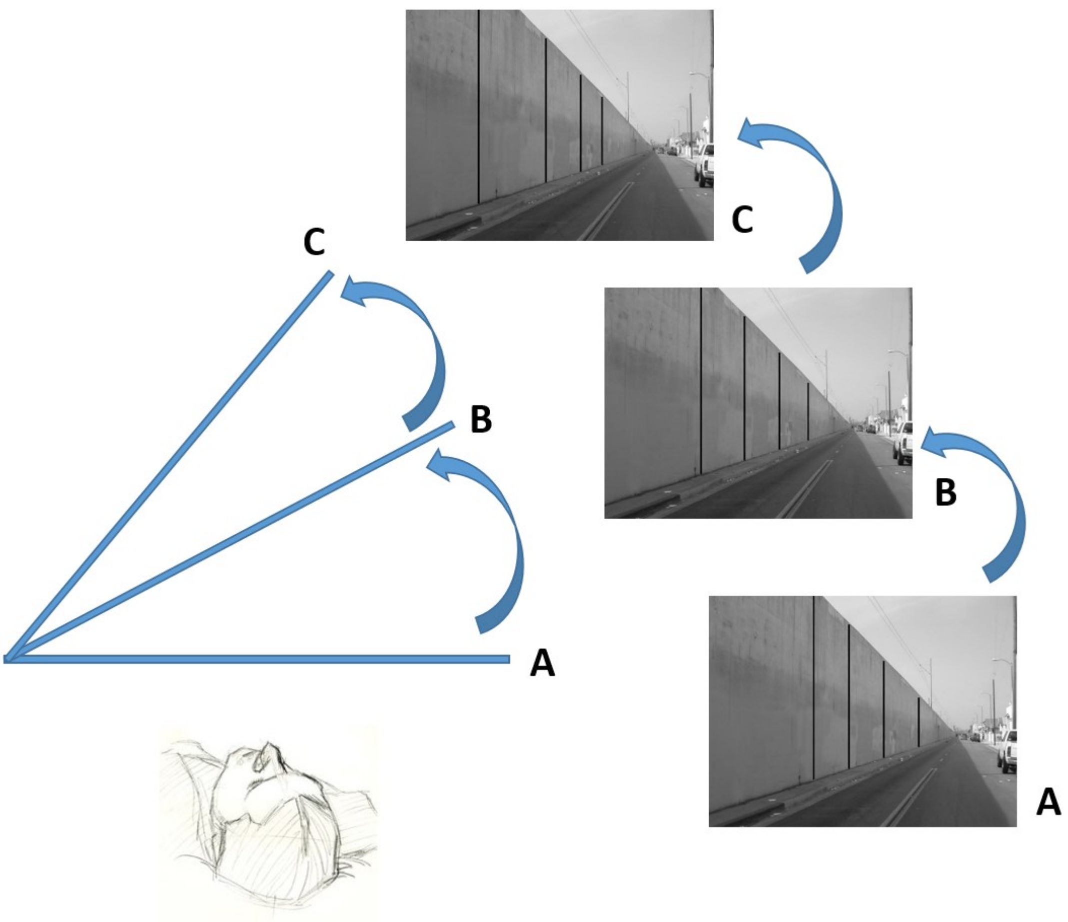


Figure 5.4. Example of pictorial perspective image with equidistant intervals between four lines. A – equidistant in the 2D plane of the image, B – appears to be equidistant in the 2D plane, C – equidistant in the 3D depicted space.

5.2.2. The interval ratio

For each of the unique stimuli, 32 images were created with position of the lines changing according to the geometric rules of pictorial perspective. If intervals between four lines are equidistant on a 2D flat surface, appearance of these intervals will alter based on the angle the 2D surface is viewed from, i.e. the slant of the surface which can be calculated knowing the vanishing point in the picture. Examples of these changes for a PP image of a wall are shown in the Figure 5.4. Here image A has equidistant intervals on a 2D surface of the image (plane A), while image C has equidistant intervals on the surface of the wall in the depicted 3D space (plane C).

The dependent measure for the perceived interval equidistance was the ratio of the judged interval and the comparison interval (see Figure 5.5). The middle interval always stayed the same. The total ratio range was from 0.2497 (Image 1) to 1.2234 (image 32), thus there were a total of 32 unit steps in the full stimulus set. Ratio 1.00 (image 29) was veridical judgment for interval equidistance on the 2D plane, and ratio 0.317 (image 4) was veridical judgment for interval equidistance in the depicted 3D space.

5.2.3. Stimuli presentation

Stimuli were presented on a 1920x1080 px resolution LCD monitor set at a fixed distance of 60 cm. Participants viewed images binocularly under normal lighting conditions, thus the whole monitor, including its frame, was visible during the task performance.

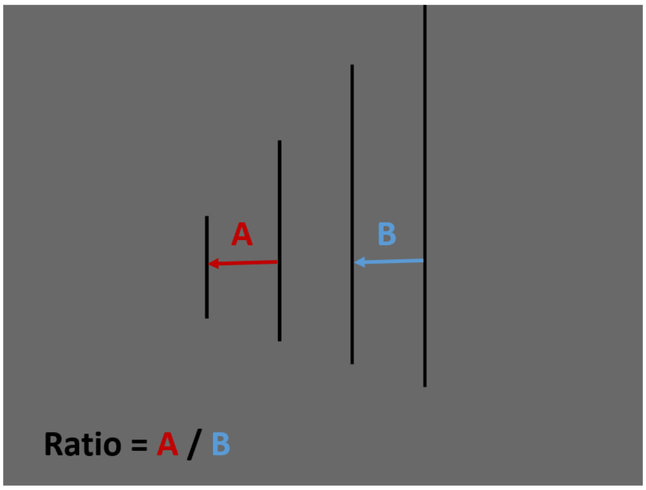


Figure 5.5. The dependent measure: the interval equidistance ratio: A/B, where A – judged interval, B – comparison interval. (Example stimuli from 2D CP condition)

5.2.4. Task

Participants were asked to make interval equidistance judgments between lines either on the 2D plane of the monitor or in the depicted 3D pictorial space. In the first part of the experiment participants were asked to make judgments on the 2D plane of the monitor ignoring any additional information within the stimuli. Using the two-alternative forced choice staircase method task participants judged one of the intervals as being shorter or longer than the second interval (Figure 5.6, panel A). This part of the experiment looked at the possible bias for underestimating the size of the interval which is the furthest in pictorial relative depth, and thus suggesting the automatic bottom-up processing of perspective information. Any difference in the susceptibility bias between the stereonormal individuals and individuals with none/limited binocular stereovision would suggest possible differences in processing of monocular relative depth cues.

In the second part of the experiment participants were asked to adjust the position of the lines until the intervals appeared equidistant within the depicted 3D space (Figure 5.6, panel B). This second part of the experiment addressed ability to use information provided by monocular relative depth cues. If individuals with none/limited binocular stereovision are accurately using the information provided by the monocular perspective cue, they would perceive relative depth ratios of the intervals, and their judgments would be similar to those with normal binocular stereoacuity.

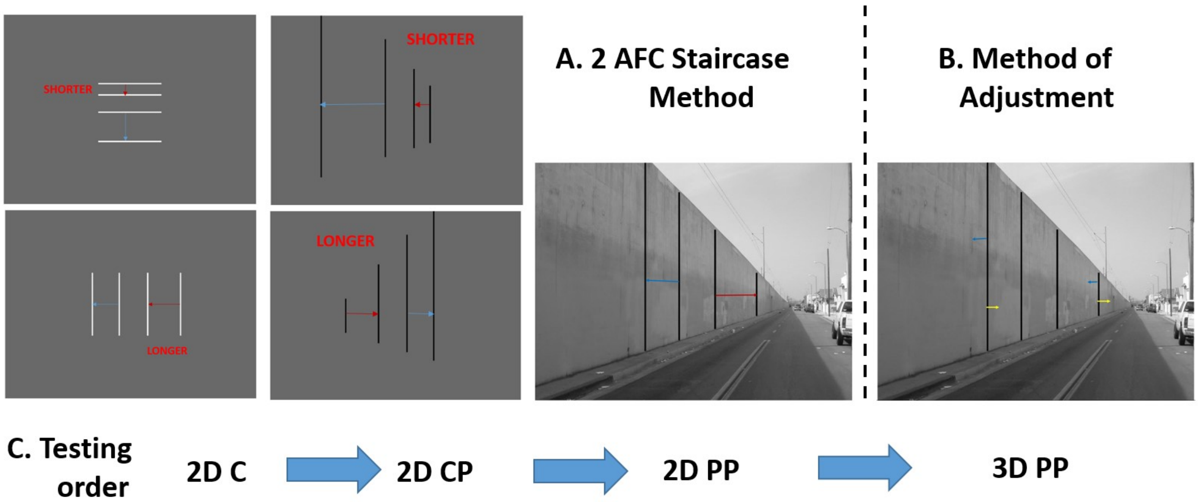


Figure 5.6. Summary of tasks and testing order in experiment 5.1. Panel A – examples for judgments to be made in 2D C, 2D CP, and 2D PP conditions 2-alternative forced choice method tasks. Panel B – examples of judgments to be made in 3D PP condition method of adjustment task. Panel C – testing order.

5.2.5. Procedure

Participants were given instructions using a PowerPoint presentation before each task (Figure 5.6, panel C). Initially participants were asked to make 2D judgments for Control (2D C), Control Perspective (2D CP), and Pictorial Perspective (2D PP) conditions. Before each of these conditions instructions specified which interval participants were to judge against which reference interval (examples in Figure 5.6, panel A). Additionally participants were instructed to ignore the background image in the 2D PP condition and perform the task as before, judging intervals on the 2D plane of the monitor. Participants initiated the trial via a keyboard key press (Enter), at which time the stimulus was displayed for a total of 1.75 s. When the stimulus disappeared participants responded via mouse keys (right key for longer, left for shorter). After their response, a new stimulus would appear (in 1.05 seconds). For the 3D judgment task participants were instructed to imagine that the lines were equally separated within the 3D space depicted in the background image (3D PP). Participants adjusted the positions of the two border lines by pressing the two mouse keys and submitted their response via a keyboard key press (Enter). The stimulus display time and number of position adjustments were unlimited. Participants viewed the stimuli binocularly and could freely look around the screen while the stimulus was displayed.

5.2.6. Stimuli tested

In the 2D judgment tasks, using the two-alternative forced choice staircase method, there were two staircases for each unique stimulus, terminating at the maximum count of five reversals. Staircase step size was 3 units (on the 32 step range). In the 3D adjustment method task each of the PP stimulus was presented 4 times, thus in total containing 16 adjustment trials. Each key press adjustment resulted in a change of size of 1 unit. Stimuli in all the tasks were presented in a computer generated randomised sequence.

5.2.7. Participants

Information about participants' vision was gathered using a number of ophthalmological tests as well as self-reports about participants' clinical history. RanDot stereotest was used to measure stereoacuity of all participants, while individuals with strabismus were also tested using the Fly (a.k.a. Titmus) and TNO, stereotests, thus assessing the full extent of stereovision deficits (Lee & McIntyre, 1996). The type of strabismus was determined using Cover and Cover-Uncover tests as well as self-reported history of the disorder.

5.3. Results

5.3.1. Participants

In total 32 people took part in this experiment. 24 control subjects with typically developed binocular vision. 8 were individuals with none or limited stereovision, one of whom was the author of the current thesis.

Three control participants' data were excluded from the analysis due to the high variability in responses compared to the other subjects (>0.3 difference in ratios for the same stimuli), which indicated that they were likely to be not following instructions or attending to the task (further discussed in limitations). Another control participant was eliminated due to an incomplete data set. Therefore, 20 control participants were used for the analysis. More information about participants used in the analysis is provided in Table 5.1 and in Appendix 5.1.

Table 5.1. Participants classification based on their clinically measurable binocular stereovision and descriptives of these groups.

Classification group	**N (28)**	**Average age**	**Physiology**
None/limited stereovision	8	34	4 corrected strabismus (all current deviations/tropias) 4 amblyopic (one phoria)
Stereonormal	20	21	None

5.3.2. Interval equidistance on a 2D plane

Figure 5.7 summarises the average ratios at which the intervals were perceived to be equidistant for the two groups: stereonormal subjects, and subjects with none/limited stereovision. All participants were able to perform the task accurately in the 2D Control condition, and chose ratios close to the veridical ratio of one (average = 1.018, standard deviation = 0.047). Overall, participants' judgments about interval equidistance on a 2D plane of the monitor were affected by perspective information in the stimuli (in 2D CP and 2D PP conditions). Repeated measures ANOVA revealed that this effect was significant for both groups: stereonormal subjects $F(2, 38)=78.18$, $p<0.001$, and subjects with none/limited stereovision $F(2, 14)=201.96$, $p<0.001$.

The sparse perspective convergence information in 2D CP condition had a small (~15%) but significant effect in both groups (planned pairwise comparisons with Bonferroni corrections, $p<0.001$). The pictorial perspective information (2D PP) had an unexpectedly large effect, resulting in approximately a 40% error in the interval ratio. In both groups the 2D PP ratio was significantly smaller than in the 2D CP condition and in the 2D C condition (Bonferroni pairwise comparisons, $p<0.001$). There were no significant differences in the responses for interval equidistance judgments on the 2D plane between the two subject groups (Mixed design ANOVA, between subjects factor stereovision: $F(1, 26) = 0.306$, $p=0.585$).

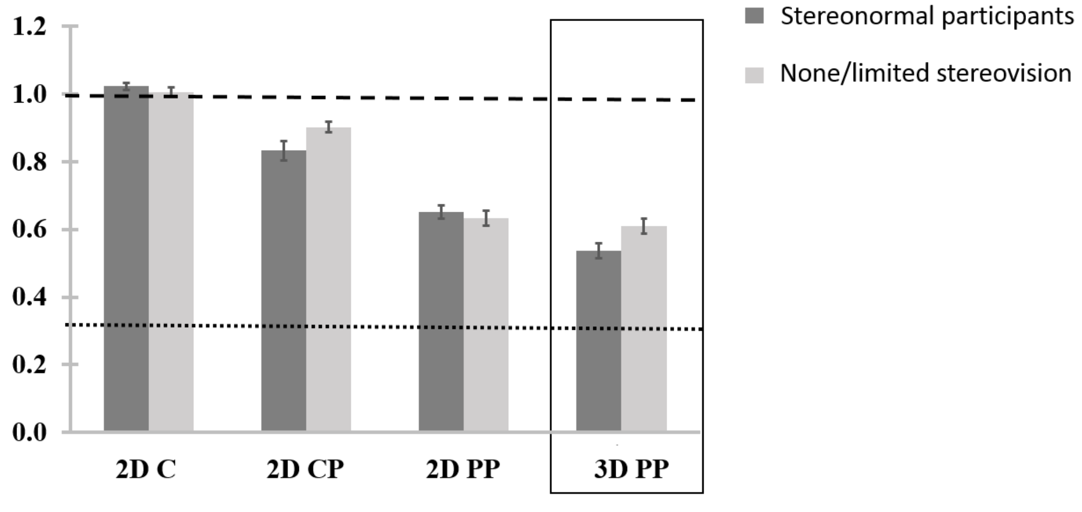


Figure 5.7. Average ratios at which intervals were perceived to be equidistant on a 2D plane of the monitor (2D conditions), and in the depicted 3D pictorial space (3D condition). Error bars indicate standard error of the mean. Dashed line indicates veridical ratio for 2D judgments, while dotted line indicates veridical 3D judgments.

5.3.3. Interval equidistance in a 3D pictorial space

The participants' ratios for judgments in a 3D pictorial space (3D PP) were similar to 2D PP judgments (Figure 5.7). For individuals with none/limited stereovision perceived amount of pictorial depth (3D PP ratio average = 0.61, standard deviation = 0.062) was almost identical to the interval equidistance error in 2D PP (ratio average = 0.63, standard deviation = 0.062). For stereonormal subjects this difference was larger: 3D PP ratio average = 0.54, standard deviation = 0.103; 2D PP ratio average = 0.65, standard deviation = 0.089. However, the independent sample t-test showed that a difference between the stereonormal and none/limited stereovision participants' pictorial depth judgments (3D PP) was not significant ($t(26)=1.879$, $p=0.072$). As 3D PP condition used the method of adjustment, it could not be directly compared with 2D conditions, which were measured using the two-alternative forced choice staircase method. This is further addressed in limitations and experiment 5.2.

5.4. Discussion and limitations

Participants accurately judged interval equidistance on the 2D plane of the monitor when there was no perspective information in the stimuli. However, their responses were significantly affected by the pictorial depth information, even when they are asked to ignore it. Moreover, the sparse visual signal in stimuli with perspective convergence alone (CP condition) was enough to significantly affect participants' interval equidistance judgments. All individuals, despite the varying levels of binocular stereovision, were susceptible to perspective information. This suggests that pictorial depth information entails automatic bottom-up processing and cannot be out-weighted by such highly reliable cues as binocular disparity. Testing all conditions, under both binocular as well as monocular viewing, would allow us to further explore the effect binocular disparity has on pictorial depth perception and how it varies between people with normal and none/limited stereoacuity.

There were no significant differences between individuals with strabismus and typically developed binocular individuals, when they were asked to make judgments about interval equidistance within the depicted 3-D pictorial space. However, participants' ratios for judgments in a 3D pictorial space were highly similar to when they were asked to ignore the background picture and judge interval equidistance on the 2-D plane of the monitor. It is plausible that this similarity is due to methodological issues, rather than actual lack of a capacity to perceptually differentiate between 2-D and 3-D judgments. Firstly, the 2-D judgment tasks used a two-alternative forced choice staircase method, while the 3-D judgments were performed using the method of adjustment. Additionally, participants might have not sufficiently understood the tasks, as the difference between the two is quite subtle. The fact that 2-D and 3-D judgments involved different testing methods might have been misinterpreted to be the same task tested in two different ways. Furthermore, the testing order might have affected participants' ability to differentiate between the 2-D and 3-D judgments. Both tasks involved identical stimuli with pictures in the background. Specifically, the appearance of the lines on the pictorial image encourage a natural tendency to make the judgment within the 3D pictorial space. Because the 2D PP condition was done before the 3D PP condition, participants may not have effectively understood the goal of the 2D task in contrast to the more natural 3D task. Participants may better understand the 2D task if they first do the 3D task (the more natural one) and then are told about a new and different task, where they are told to ignore the background image and try to judge as best they can the equidistance in the 2D plane of the monitor. These issues were addressed in designing experiment 5.2.

Experiment 5.2

In this experiment we explored further participants susceptibility to pictorial depth under more rigorous testing methods. In the prior experiment the task was performed only under binocular viewing conditions, in which binocular disparity identifies the stimulus as being flat, and thus the addition of conflicting and less precise pictorial perspective information should allow to perceive only shallow pictorial depth, i.e. depth of minimal magnitude (cue-coherence theory, Ames (1925)). Therefore in this experiment we additionally explored the monocular viewing condition for both individuals with strabismus, with none or very limited stereovision, and typically developed binocular individuals with normal stereovision.

5.5. Methods

5.5.1. Stimuli and their presentation

Stimuli images, identical to those used in the experiment 5.1, were displayed on a 1920x1200 px resolution LCD monitor. Subjects' viewed the images from a fixed 60 cm distance with their head position stabilized using a chin rest. All tasks within this experiment were performed under two viewing conditions: binocular and monocular (dominant eye). The experiment was carried out under normal lighting conditions, thus the whole monitor, including its frame, was visible during the task performance.

5.5.2. Task

As in the experiment 5.1 participants were asked to judge equidistance of intervals either on the 2D plane of the monitor or the depicted 3D space. However, to improve the comparability of effects found in 2D and 3D pictorial perspective tasks (experiment 5.1) all stimulus conditions were tested using both types of methods: two-alternative forced choice staircase method and adjustment method. In the two-alternative forced choice staircase method participants had to judge one interval as being either shorter or longer than the comparison interval in the 2D plane (conditions 2D C, 2D CP, 2D PP), or in the depicted 3D space (condition 3D PP). In the method of adjustment tasks participants had to adjust the position of the lines until the intervals appeared equidistant in the 2D plane (conditions 2D C, 2D CP, 2D PP), or in the depicted 3D space of the image (condition 3D PP).

5.5.3. Procedure

Participants were provided with detailed instructions using a PowerPoint presentation before the start of the experiment and further before each different task. The current experiment had 3 parts: 2D C and CP conditions, 3D PP condition, 2D PP condition. Each of these three parts were performed under monocular and binocular viewing, the order of which was randomised between participants.

The specific testing order (Figure 5.8 Panel A) had been chosen considering methodological limitations raised in experiment 5.1. To allow participants to familiarise themselves with the stimuli, adjustment tasks were performed first for all conditions with the exception of 2D CP. For the 2D CP condition, the staircase method task was performed first, as it had been noted that additional dynamic perspective convergence information in the 2D CP condition is induced while dynamically adjusting the lines by the sequential changes in their position and size. Additionally, the testing order was changed for 2D PP and 3D PP conditions compared to experiment 5.1. Both these conditions use identical stimuli, but participants are asked to perform different tasks: judging when the intervals appear equidistant on the 2D plane of the monitor, and equidistant in the depicted 3D space of the depicted scene.

As argued in the discussion above (Section 5.4.), we reasoned that doing the 3D task before the 2D task, would allow participants to more clearly understand the goal of the 2D task.

The current experiment followed the same procedure as experiment 5.1 with the following changes. For the staircase method, stimuli in the 2D C condition stimulus were displayed for 1.25 seconds, while for all other conditions they were displayed for 1.75 seconds. This was done in order to reduce testing time, as the 2D C is a very straightforward task which participants had no difficulty performing in experiment 5.1. A fixation response image was displayed until participants responded (Summarised in Figure 5.8 Panel B). In the method of adjustment tasks, a fixation image was displayed before the onset of the stimulus for 1 second. The stimulus display time and number of ratio adjustments were unlimited. Participants were permitted to freely look around the screen while the stimulus was displayed.

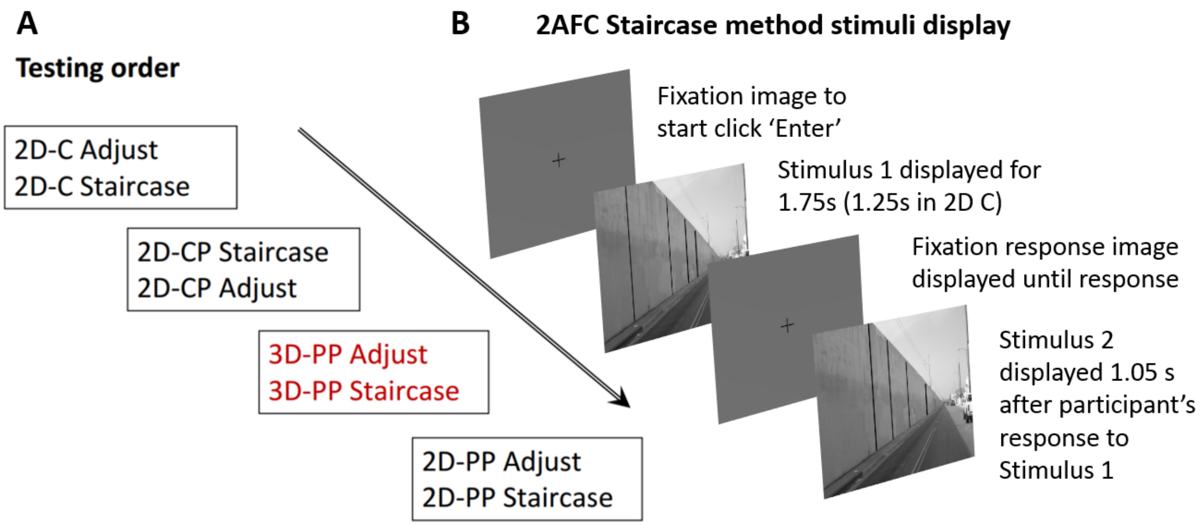


Figure 5.8. Summary of procedure in Experiment 5.2. Panel A - Testing order for experiment 5.2. Panel B – example of the 2AFC Staircase method stimuli display sequence.

5.5.4. Stimuli tested

For all stimulus conditions in the two-alternative forced choice (2-AFC staircase) tasks, there were 2 staircases for each unique stimulus, terminating at the maximum count of four reversals. The staircase step sizes were adaptive: 4 units before the first reversal, 2 after the first reversal, and 1 after the second reversal. In the method of adjustment tasks all stimulus type conditions had 16 trials. In 2D CP, 2D PP and 3D PP, each unique stimulus was presented 4 times, while in 2D C each unique stimulus was presented 8 times. Each adjustment resulted in a change of ratio of 1 unit (out of 32 steps in total). In all the tasks stimuli presentation order was a computer generated randomised sequence.

5.5.5. Participants

Information about newly recruited participants' vision was gathered in the same manner as in experiment 5.1. All participants had their stereovision tested using all three stereotests: Fly (a.k.a. Titmus), TNO, and RanDot. All typically developed binocular individuals were new recruits. Five strabismic participants from the experiment 5.1 were able to take part in the current experiment, and an additional six new participants were recruited (Appendix 5.2.)

5.6. Results

5.6.1. Participants

In total 26 people took part in the second experiment. 12 were control subjects with typically developed binocular vision. 14 were individuals with none or limited stereovision, one of whom was the author of the current paper.

Four participants were excluded from the analysis: the author, to avoid possible biases; one control participant due to incomplete data set; and two strabismic participants showing high variability in responses compared to the other participants (>0.3 differences in ratios for the same stimuli), which suggested limited engagement with the tasks. Consequently, 22 participants (11 in each group) were used for the analysis. More information about participants used in the analysis is provided in Table 5.2 and in Appendix 5.2.

Table 5.2. Participants classification based on their clinically measurable binocular stereovision and descriptives of these groups.

Classification group	**N (22)**	**Average age**	**Physiology**
None/limited stereovision	11	34	8 corrected strabismus (6 with tropias, 1 with phoria, 1 with no current deviations) 1 intermittent strabismus 2 amblyopic (one phoria)
Stereonormal	11	25	None

Five of the no/limited stereovision participants had taken part in the experiment 5.1. Using their data for the corresponding tasks it was possible to compare their performance in experiments 5.1 and 5.2, indicating that the changes in testing order and more detailed explanation of the tasks revealed the expected differentiation between 2D and 3D judgments due to the change in order of presentation in Pictorial Perspective tasks (see Appendix 5.3.). Additionally, even though the chosen interval equidistance ratios varied individually among participants within the experimental conditions, participants' performance was consistent through the conditions (see Appendix 5.4.).

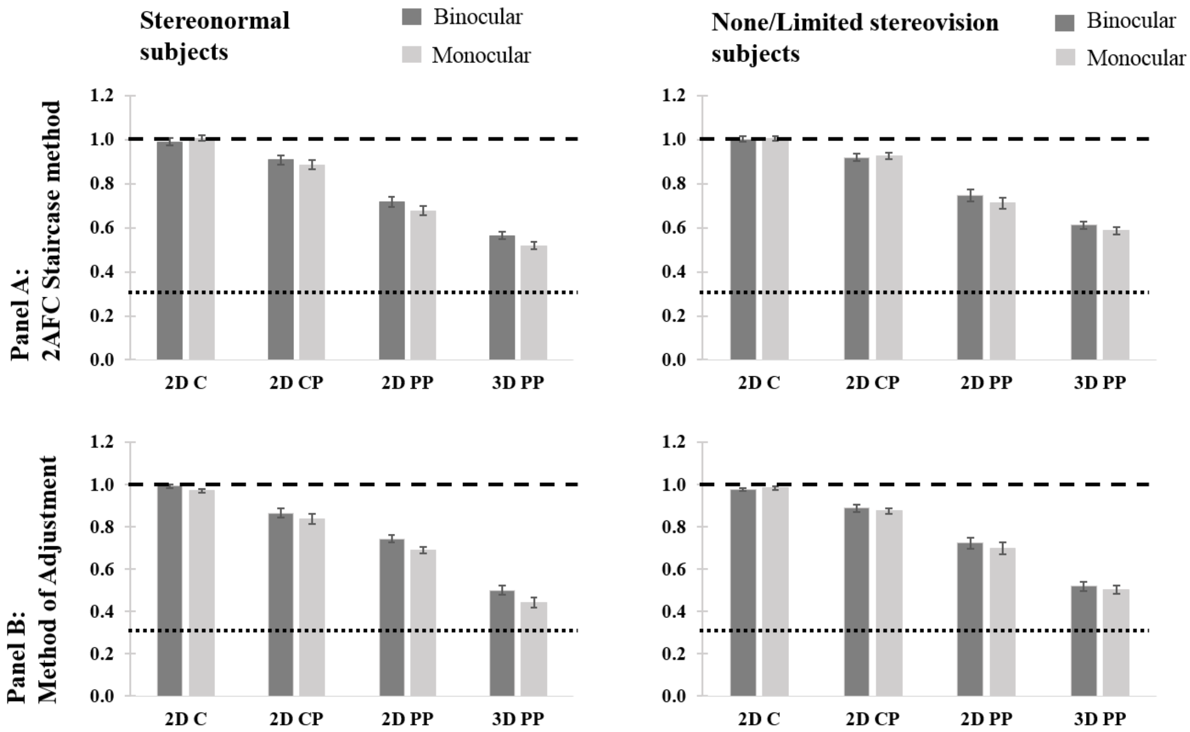


Figure 5.9. Average ratios at which intervals were perceived to be equidistant on a 2D plane of the monitor (2D conditions), and in the depicted 3D pictorial space (3D condition), for each participant group under monocular and binocular viewing. Error bars indicate standard error of the mean. Dashed line indicates veridical ratio for 2D judgments, while dotted line indicates veridical 3D judgments. Panel A – 2-AFC staircase method. Panel B – Method of Adjustment.

5.6.2. Interval equidistance on a 2D plane

Figure 5.9 summarises the average ratio thresholds at which intervals were perceived to be equidistant, under binocular or monocular viewing, for the two groups: stereonormal subjects (controls), and subjects with none/limited stereovision (strabismics). As in experiment 5.1, all participants were able to perform the task accurately in the 2D Control condition, and when tested using 2-AFC staircase method or method of adjustment showed ratio thresholds close to the veridical ratio of one (staircase method: average = 1.001, standard error = 0.008; method of adjustment: average = 0.98, standard error = 0.005). Overall, the findings of the current experiment support the perspective information effect found in experiment 5.1, and extends it further to monocular viewing and tasks with method of adjustment.

5.6.2.1. 2-AFC staircase method tasks

The findings of experiment 5.1 were replicated, as repeated measures ANOVA found a significant perspective effect for both groups: control subjects $F(2, 20)=108.827$, $p<0.001$, and strabismic subjects $F(2, 20)=81.348$, $p<0.001$. Further replicability of experiment 5.1 data was found in planned pairwise comparisons with Bonferroni corrections. The sparse perspective convergence information in 2D CP condition had a small (~10%) but significant effect in both groups: control subjects $p=0.001$, subjects with none/limited stereovision $p=0.004$ (Bonferroni pairwise comparisons). The pictorial condition (2D PP) had resulted in approximately a 30% error in the interval ratio. In both participant groups the 2D PP ratio was significantly smaller than in 2D CP condition, or in 2D C condition (Bonferroni pairwise comparisons $p<0.001$).

There were no significant differences in the responses for interval equidistance judgments on the 2D plane between the two subject groups (Mixed design ANOVA, between subjects factor stereovision: $F(1, 20)=1.406$, $p=0.25$). The performance of the two groups differed in relation to their responses under monocular vs binocular viewing (see Figure 5.9, panel A). The control subjects made significantly larger errors under monocular than binocular viewing conditions (repeated measures ANOVA $F(1, 10)=6.832$, $p=0.026$). However, no such difference was found for none/limited stereovision participants (repeated measures ANOVA $F(1, 10)=0.683$, $p=0.428$).

5.6.2.2. Adjustment method tasks

The current experiment extended the findings of experiment 5.1 to method of adjustment tasks, as repeated measures ANOVA found a significant perspective effect for both groups: control subjects $F(2, 20)=87.713$, $p<0.001$, and strabismic subjects $F(2, 20)=59.96$, $p<0.001$.

Similar to the findings from the staircase method tasks, the error in the 2D CP condition was small (~10%), but significant in both groups (Bonferroni pairwise comparisons p=0.001). For the pictorial condition (2D PP) participants in both groups showed a slightly smaller error than in the staircase method task (~26%), but it was still significantly different from their responses in 2D CP or 2D C conditions (Bonferroni pairwise comparisons, $p<0.001$).

Similar to the 2-AFC staircase method, there were no significant differences between the two subject groups (Mixed design ANOVA, between subjects factor stereovision: $F(1, 20)=0.290$, $p=0.596$), but their performance differed in relation to their responses under monocular vs binocular viewing (see Figure 5.9, panel B). The control subjects made significantly larger errors under monocular than binocular viewing conditions (repeated measures ANOVA $F(1, 10)=25.966$, $p<0.001$). However, no significant difference was found for none/limited stereovision participants (repeated measures ANOVA $F(1, 10)=1.676$, $p=0.225$).

5.6.3. Interval equidistance in a 3D pictorial space

Ratios at which intervals were perceived to be equidistant in a 3D pictorial space (3D PP) were notably smaller than any ratios chosen for 2D judgments, and closer to the veridical 3D space judgments (see Figure 5.9). Mixed design ANOVA found this difference to be significant in both testing methods: Staircase method $F(1, 20)=75.112$, $p<0.001$; Method of Adjustment $F(1, 20)=85.036$, $p<0.001$. Together with prior mentioned supplementary analysis on subjects who took part in experiments 5.1 and 5.2, this indicate that in experiment 5.2 participants were performing different tasks (2D vs 3D judgments).

Figure 5.10 summarises average ratio thresholds at which intervals were perceived to be equidistant on a 2D plane of the monitor (2D PP) or in a 3D pictorial space (3D PP) for the two groups: stereonormal subjects and none/limited stereovision subjects. Similarly to the interval equidistance on a 2D plane analysis, there were no significant differences between the two subject groups for either testing methods (Mixed design ANOVA, between subjects factor stereovision: Staircase method F(1, 20)=4.171, p=0.055; Method of Adjustment F(1, 20)=1.172, p=0.292), but the two participant groups' ratios for intervals equidistant in a 3D pictorial space differed in relation to monocular vs binocular viewing.

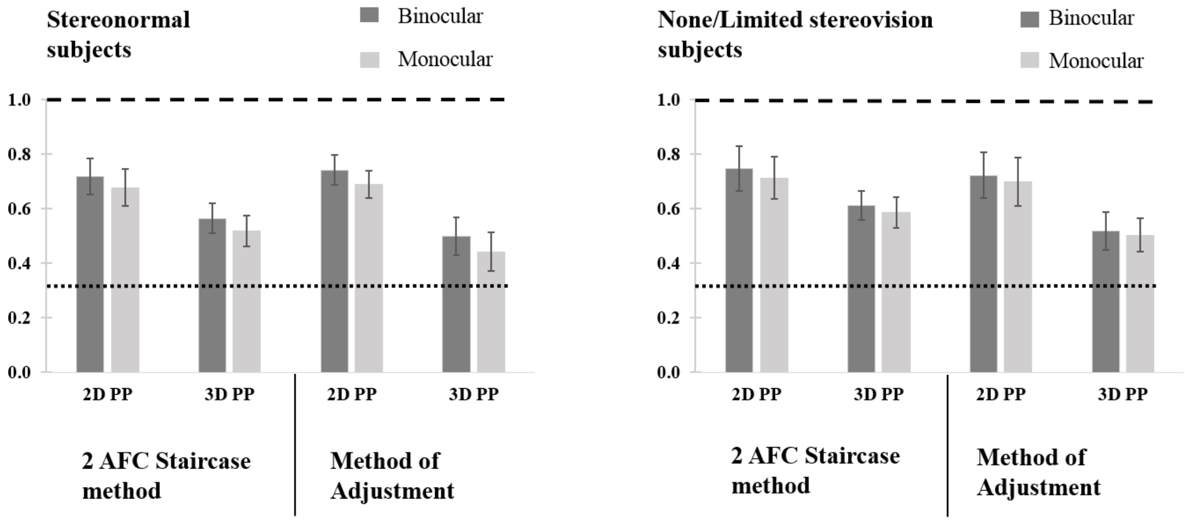


Figure 5.10. Average ratios at which intervals were perceived to be equidistant on a 2D plane of the monitor (2D PP) or in the depicted 3D pictorials space (3D PP), for 2-AFC Staircase method and Method of Adjustment, under monocular and binocular viewing. Error bars indicate standard deviation. Dashed line indicates veridical ratio for 2D judgments, while dotted line indicates veridical 3D judgments.

Independent samples t-tests found that under monocular viewing, control (stereotypical) participants choose significantly lower ratios than strabismics for staircase method (difference = 0.0669, t(20)=2.671, p=0.015), while for method of adjustment the difference was not significant (difference = 0.0607, t(20)=2.043, p=0.054). However, under binocular viewing the difference between the stereonormal and none/limited stereovision participants' pictorial depth judgments (3D PP) was not significant for both: staircase method (difference=0.0468, t(20)=1.902, p=0.072), and method of adjustment (difference=0.0188, t(20)=0.606, p=0.551).

Furthermore, paired samples t-test revealed that control subjects had significantly lower interval ratios in monocular than binocular viewing in 2D as well as 3D pictorial perspective judgments (Staircase Method: 2D PP $t(10)= -8.174$, $p<0.001$, 3D PP $t(10)= -2.636$, $p=0.025$; Method of Adjustment: 2D PP $t(10)= -4.173$, $p=0.002$, 3D PP $t(10)= -3.947$, $p=0.003$; significance corrected for multiple comparisons according to Bonferroni p=0.05/2=0.025). This means that the illusory effect on 2D judgements was slightly larger (average monocular = 0.69, binocular = 0.74), and the 3D judgement was slightly more accurate (average monocular = 0.44, binocular = 0.50) in the monocular condition, compared to the binocular condition. Meanwhile, differences were non-significant for participants with none/limited stereovision for either of the testing methods: staircase method (2D PP $t(10)= -1.982$, $p=0.076$; 3D PP $t(10)= -1.526$, $p=0.158$), or method of adjustment (2D PP $t(10)= -1.939$, $p=0.081$; 3D PP $t(10)= -1.094$, $p=0.3$; significance corrected for multiple comparisons according to Bonferroni p=0.05/2=0.025).

5.7. Discussion and limitations

Experiment 5.2 replicated the findings of experiment 5.1 in relation to interval equidistance judgments on a 2-D plane under both testing methods. All participants were able to correctly judge interval equidistance when there was no perspective information, but with the introduction even of sparse converge information produced a characteristic error in equidistance judgements (chose significantly lower equidistance ratios), indicating a bottom-up susceptibility to the perspective information. Pictorial Perspective information resulted in a larger and highly similar error under both viewing conditions and testing methods. However, participants made smaller errors for Pictorial Perspective 2-D judgments under method of adjustment than two-alternative forced choice method. This may suggest that when given additional time, participants are able to some extent to cognitively decrease the effect of automatically processed pictorial information, though the error still remained significantly large and thus this bottom up tendency cannot be cognitively supressed. The effect was consistently found for all participants under both monocular and binocular viewing, suggesting that despite conflicting binocular disparity information and varying levels of binocular stereoacuity, people are highly susceptible to pictorial depth. There were no significant differences in equidistance judgements overall between strabismic and typically developed binocular individuals. However, only typically developed subjects showed significant difference between monocular and binocular viewing, therefore suggesting that binocular disparity does have a small but reliable effect in counteracting the pictorial depth information when it conflicts with it. However, the size of this reduction is too small to be compatible with the standard MLE model of cue integration (Ames, 1925; Hillis et al., 2004), since according to that view the more reliable disparity cue should dominate and therefore stereonormal participants should make the 2D judgement much closer to veridical.

The experiment 5.2 showed that when the task instruction is clear, judgments of interval equidistance within the depicted 3-D pictorial space (3D-PP) are significantly different from 2-D judgments made in pictorial space (2D-PP), as people chose ratios closer to the veridical 3-D values. This difference was significant for all participants, the viewing conditions, and under both testing methods, thus showing that methodological improvement in experiment 5.2 has successfully differentiated the two different tasks. Therefore, the errors made in 2-D judgment tasks can be attributed to automatic bottom-up processing of perspective information. There were no significant differences between strabismic and control individuals for the 3-D space judgements, thus indicating that a similar amount of relative depth was perceived despite varying levels of binocular stereoacuity. On the other hand, control participants did perceive slightly more accurate relative depth under monocular than binocular viewing, which again indicates that there is a small “flattening” effect of binocular disparity in individuals with typically developed binocular vision. Strabismics with none/limited stereovision did not show this difference. It is plausible that individuals with none/limited stereoacuity are able to adjust perceived relative depth using cognitive processing. However, it is hard to draw such a conclusion based on a limited and highly varied sample of strabismic individuals. Ideally this study should be carried out with much larger samples and detailed history for participants eye conditions, which would allow to do further analyses based on the specific type of strabismus, its onset and causes.

5.8. General discussion

Both experiments found participants to be highly susceptible to pictorial depth information, including sparse perspective convergence information, even in the presence of conflicting binocular disparity information. This effect was found among both strabismic and typically developed binocular individuals and thus it is possible to conclude that despite variations in stereovision, relative depth perception from perspective cue involves bottom-up automatic visual processing that is largely intact in strabismic observers.

The findings of the current study show that individuals with no or limited binocular stereovision are as susceptible to monocular relative depth cues (perspective) as typically developed binocular individuals. The fact that there were no significant differences between typically developed binocular individual and strabismic group performance in the 2-D pictorial and 3-D pictorial space interval equidistance judgment tasks, suggest that relative depth pictorial information processing is not dependent on binocular disparity, and thus is not affected in infantile strabismics during the critical period. This further supports the idea that pictorial depth is not cognitively derived in strabismus, and involves the same bottom-up processing as perception of real 3-D space. This corresponds to the findings of the blind walking study by Ooi and He (2015), as strabismic participants were able to correctly judge the distance to a ball in a hallway and its position when it was on the floor, and only experienced difficulty indicating its position in space when it was suspended mid-air, breaking the visual relations to the ground plane, along which distance can be estimated more accurately. This shows that strabismic individuals, as in our study, were able to accurately use monocular relative depth cues, such as the linear perspective information in the hallway (e.g. texture gradient of the floor), while the object suspended mid-air from a static viewing point did not provide monocular relative depth information to allow to perceive absolute location of the object.

Typically developed binocular participants showed smaller susceptibility bias under binocular viewing conditions. According to the traditional theory of depth perception the coherence of available visual cues directly contribute to the amount of perceived depth (Ames, 1925; J. Koenderink et al., 1994). In the case of the observer viewing a picture on a flat computer monitor, this would suggest that the 2D interval equidistance judgement in the pictorial perspective condition should be veridical or near veridical for stereo typical observers. However, even though our findings from stereonormal subjects suggest a slight improvement in accuracy in the 2D task, there was still a large error due to the influence of the perspective information. Thus, even though, binocular disparity can counteract monocular cues such as perspective (when in conflict), the effect is much smaller than the error made due to automatic processing of perspective information. Therefore, cue-coherence theory cannot be withdrawn, but binocular disparities place within it should be reconsidered. A similar conclusion may be reached if we consider our findings in the context of the MLE model, which states that in order to provide the most reliable estimate of the 3-dimensional space (to perceive absolute depth), all available visual cues are weighted by their relative reliability (Hillis et al., 2004). According to this, as binocular disparity is the most reliable cue for relative depth (Ogle, 1950), it should "out-weight" the pictorial cues in the MLE model (Vishwanath, 2011). However, the error made due to the susceptibility to the perspective information is consistently found under binocular viewing in stereonormal individuals. Therefore, the weight attributed to monocular and binocular relative depth cues in MLE model when these cues are in conflict, should be reconsidered.

The use of two different testing methods did reveal that when participants were given more time to observe (Method of Adjustment) they made a somewhat smaller error in 2-D judgements and perceived more relative depth in 3-D judgments. On one hand this could be attributed to a view that observers cognitively derive the percept of the 3-dimensionality, "recreating" the scene and its specific properties based on the included pictorial information cues (Howard, 2012b; Kubovy, 1988). However, it cannot explain why this difference was relatively small, and why even when given unlimited amount of time to perform the task, participants still had significant bias even to sparse perspective convergence information in the 2-dimensional judgment task. More likely, participants given more time to do the tasks performed them more carefully, and thus had more accurate perceptual judgments within the constraints of automatically processed perspective information. The possibility of some level of cognitive processing cannot however be fully withdrawn, as to some extent it might be used to adjust automatically processed perspective information based on learned interaction with 3-D space on an everyday basis. This is in accordance with a recent paper exploring perceptual constancies as predictors of realistic drawing skills among artists and people without artistic training (Ostrofsky et al., 2012). Through the number of tasks targeting either bottom-up or top-down processing, it was found that neither of the processes seem to provide a full explanation, even for artists who have shown less size constancy bias. Instead the authors proposed a joint model where visual attention guides the shift between the bottom-up and top-down processes, according to the required tasks and strategical selection of information for completing them (Ostrofsky et al., 2012). This seems to explain why participants perceived more relative depth in 3-dimensional judgments. That being said, in the task where participants saw stimuli only for limited time (Two Alternative forced choice method) the 2-dimensional and 3-dimensional judgments for the identical stimuli were significantly different, indicating that participants were performing different tasks, rather than just cognitively extending the same percept between the tasks.

Chapter 6

General Discussion

Strabismus as a disorder has been known since the times of Hippocrates (Loudon & Simonsz, 2005). It can be defined as the inability to coordinate the eye muscles that ordinarily fixate the two eyes on a single target (Schiffman, 2001). The main perceptual implications of strabismus is lack of a single binocular vision, which is thought to be irreversible if strabismus develops under the age of five, a.k.a. the critical period (Hubel & Wiesel, 1965; Sherry et al., 2005; Wright et al., 2006). Restoration of motor fusion (i.e. ability to bring the two eyes into alignment) and possible sensory fusion (i.e. cortical process of joining the images from the two eyes into a single binocular image) is the main goal of the majority of research in strabismus (Read, 2015; Rutstein et al., 2011; von Noorden & Campos, 2002; Wright et al., 2006). However, research into the way individuals with strabismus or history of strabismus experience depth and space around them is limited. Therefore, the core aim of this thesis was to explore the extent of limitations in depth and distance perception strabismic individuals with no/limited binocular stereovision experience in comparison to typically developed binocular individuals. The key elements of static depth and distance perception were addressed: qualitative aspects of depth perception, egocentric distance perception, and relative pictorial depth perception.

<u>6.1. Qualitative aspects of depth perception in strabismus</u>

The aim of the experiments summarised in Chapter 3 (experiment 3.1 and 3.2) was to explore if individuals with infantile strabismus and no measurable binocular stereovision can experience monocular stereopsis, and if they do, then how it compares to depth they experience on an everyday basis. The special interest about the qualitative aspect of depth perception in strabismus had been raised by Susan Barry reports (Barry, 2009). Here is one of her accounts after gaining clinically measurable binocular stereovision in her 40s:

"… I was startled by my view of falling snow. The large wet flakes were floating about me in a graceful, three-dimensional dance. In the past, snowflakes appeared to fall in one plane slightly in front of me. Now I felt myself in the midst of the snowfall, among all the snowflakes." (Barry, 2009)

This anecdotal description highlights how differently individuals with strabismus may experience depth on everyday basis, how tangible and immersive it appears to them. In fact, some of the participants with no clinically measurable binocular stereovision who took part in the experiments of this thesis had mentioned reading Barry's book and were curious about the extent of limitations in their vision, trying to imagine how typically developed binocular individuals see things around them. To our knowledge, we were the first to carry out a study exploring whether or not strabismic individuals perceive the same variation in qualitative aspects of stereopsis (via monocular stereopsis) as non-strabismic individuals.

The findings of experiment 3.1 replicated the previous findings on monocular stereopsis in stereonormal typically developed binocular individuals (Vishwanath & Hibbard, 2013), and additionally showed that monocular stereopsis can be experienced by individuals with varying levels of binocular stereovision and manifestations of strabismus or amblyopia, including subjects with infantile uncorrected strabismus. According to the critical period theory, these latter individuals have irreversible limitations in binocular disparity processing, and thus should not be able to experience stereopsis (Hubel & Wiesel, 1965; Sherry et al., 2005; Wright et al., 2006). However, the current findings (experiment 3.1 and 3.2) suggest that stereopsis – immersive and tangible sensation of depth – is not uniquely associated with binocular stereovision, as it is commonly believed (Fielder & Moseley, 1996; Ogle, 1950; Wright et al., 2006). It suggests that if individuals with infantile uncorrected strabismus have an impaired binocular disparity processing pathway, but are able to experience monocular stereopsis, stereopsis is not necessarily tied to binocular disparity processing and is a distinct phenomenon. Further, it suggests that individuals with no/limited binocular stereovision are able to experience stereopsis and therefore the way they experience depth on an everyday basis, under certain conditions, might be more similar to that of typically developed binocular individuals than anecdotal reports would suggest. In fact, Susan Barry did not feel any need to improve her vision until her 40s, as only then did she start experiencing additional limitations to her vision, such as trouble reading road signs, and things around appearing jittery (Barry, 2009). If one would consider how uncertain this visual input would appear, it is not surprising that once the vergence muscles begin working together, eliminating erroneous visual signals, the improvement and the change in visual perception would seem drastic. Similar effect can be experienced by, for instance, an individual with myopia (near-sightedness) when they get long overdue update on their prescription and vision seems different the first couple days (personal communications).

We further explored the way individuals with strabismus experience depth on everyday basis in comparison to typically developed individuals in experiment 3.2 using a specially designed box that allowed blind comparisons between a real 3D object and its 2D image. All participants performed similarly and indicated that quality of depth experienced viewing a 2D picture through a monocular aperture (evoking monocular stereopsis) was better than viewing 2D pictures under any other conditions (including strabismics). The pattern of the changes in the quality of depth ratings across all viewing conditions were the same for all participant groups. For individuals tested in experiment 3.2, there appears to be a continuum of different levels of stereopsis (quality of depth spectrum), with binocular viewing of a real 3D object on the one extreme and binocular viewing of a 2D picture on the other. The quality of depth spectrum amplitude was the largest for stereonormal subjects, who on average rated binocular picture viewing to provide quality of depth exactly as in a picture, and the binocular real object viewing to provide the quality of depth exactly as when viewing a real 3D object. In contrast, the participants with no and local binocular stereovision exhibited a smaller quality of depth spectrum amplitude, as they rated the two extremes (binocular 2D picture and binocular real object) closer to neutral than stereonormal or anomalous stereovision groups. The fact that the quality of depth ratings of the anomalous stereovision group were similar to those of stereonormal group does suggest that global binocular stereovision (measured to be normal in anomalous stereovision group) plays a role in perceiving greater differences in the quality of depth between the binocular 2D picture and binocular real 3D object viewings.

Overall, findings of experiment 3.1 and 3.2 showed that the tested cohort of individuals with varying levels of binocular stereovision are able to perceive similar variation in the qualitative aspects of stereopsis as typically developed binocular individuals. Individuals with varying manifestations of strabismus were able to perceive monocular stereopsis. When making blind comparisons between a real 3D object and its 2D image, all participant groups exhibited the same pattern of changes in the quality of depth ratings across all viewing conditions. However, in comparison to stereonormal and anomalous stereovision groups quality of depth ratings assigned to the extreme viewing conditions (binocular 2D picture viewing and binocular real 3D object viewing) were closer to neutral in no and local stereovision groups.

6.2. Egocentric distance perception

The aim of the experiments summarised in Chapter 4 (experiment 4.1 and 4.2) was to explore egocentric distance perception by inferring it from the familiar object size judgments in individuals with strabismus and typically developed binocular individuals. Egocentric distance perception allows to scale relative depth information and know absolute object size values as well as absolute distances between them. This is essential in order to be able to interact with objects (move them, throw them), as well as act in the space between them (drive, walk, etc.). According to Susan Barry and other anecdotal reports individuals with strabismus are able to successfully interact with objects by using monocular information cues, such as motion parallax and pictorial depth cues (Barry, 2009; Sacks, 2006). Consequently, it is unclear how strabismics' egocentric distance perception compares to those of typically developed binocular individuals. Therefore, the experiments 4.1 and 4.2 included binocular-stereoscopic, binocular-pictorial, and monocular-pictorial viewing, and were carried out in a dark room at the personal and action spaces in order to observe changes in perceived size with visual information diminishment. Limitations in visual information allowed to eliminate such cues as eye declination level, ground plane information, or motion parallax.

One of the possible ways of investigating egocentric distance perception is by measuring perceived object size, because perceived size depends on perceived distance. According to a specific case of SDIH (size-distance invariance hypothesis), Emmert's Law: when the retinal size of an object is constant the perceived object size is proportional to the perceived distance (Epstein et al., 1961). Beyond 3 meter viewing distance, when the visual information is limited, and thus there is no available earth curvature or relative retinal comparison information, a "specific distance" tendency was found to take place in object size judgments of typically developed binocular individuals (W. C. Gogel, 1963; W. C. Gogel & da Silva, 1987). Specific distance tendency is the tendency to perceive an object at about 2-3 meters from the observer and thus to underestimate its size, when visual information cues to distance are reduced or eliminated (W. C. Gogel, 1969b, 1976). Most research on this tendency has been carried out using familiar objects (W. C. Gogel, 1969b, 1976; W. C. Gogel & da Silva, 1987), which allow to explore importance of monocular cue – familiar size – for perceived size and thus perceived distance judgments. This experimental design paradigm was used in experiments 4.1 and 4.2. In experiment 4.1 two-alternative forced choice method was used and participants were asked to make familiar object size judgments using their internal standard for the object size (remembered size of the familiar objects). In experiment 4.2 the method of adjustment was used and participants were asked to adjust the size of the displayed stimuli until it matched the real familiar object size, while reference real objects could be viewed by the participants throughout the duration of testing. In the two experiments participants with no/limited binocular stereovision and stereonormal individuals performed similarly and no significant differences were found between the two groups. In experiment 4.1 all participants underestimated the familiar object size with increasing viewing distance (at 3.5 meters), which is in accordance with the previous literature (W. C. Gogel, 1969b, 1976; W. C. Gogel & da Silva, 1987). On the contrary, in experiment 4.2 all the participants overestimate the familiar object size with increasing viewing distance. To our knowledge this is the first study to show such findings, which may be the result of a complex interaction of cognitive effects with the specific task (comparing sequentially with a real visible object). However, overall the results from the two experiments (Chapter 4) suggest that the mechanisms of object size judgment and egocentric distance perception are essentially the same for all individuals.

In the binocular-stereoscopic viewing condition, in addition to visual information cues present in other conditions, there were disparities specifying the shape and location of the object. All individuals with no clinically measurable binocular stereovision were able to perform under binocular-stereoscopic viewing conditions without experiencing any visual discomfort. Additionally, under this viewing condition they showed the same size underestimation bias at the near viewing distance as stereonormal subjects. This suggests that individuals with no clinically measurable binocular stereovision were able to incorporate some stereoscopic information in their familiar object size judgments. This is in accordance with prior research that has shown strabismics with no clinically measurable binocular stereoacuity to be able to differentiate depth in stereoscopic displays above chance (Tidbury, Black, & O'Connor, 2014), as well as to be able to process binocular disparities in the periphery of the visual field (Fronius & Sireteanu, 1989; Sireteanu & Fronius, 1989).

In the second experiment interesting differences were observed in size judgments between no/limited stereovision and stereonormal subjects at the middle and far viewing distances (1.75m and 3.5m) under monocular and binocular viewing conditions. At these viewing distances, egocentric distance information from accommodation and vergence is generally not thought to be useful (Cutting, 1997; Fisher & Ciuffreda, 1988; Viguier et al., 2001), and information from the eye declination level, as well as relative depth information allowing judgments based on information of adjacent objects was limited by the experimental set up. Under limited visual conditions at the far viewing distance (3.5m) individuals with no/limited stereovision showed less size overestimation under monocular than binocular viewing, whereas stereonormal subjects showed less size overestimation under binocular than monocular viewing. This difference was not significant, but it is not surprising considering prior research showing that individuals with strabismus with no/limited binocular stereovision perform less accurately under binocular viewing than control subjects in blind walking or complex motor tasks (O'Connor, Birch, Anderson, & Draper, 2010; O'Connor, Birch, Anderson, Draper, et al., 2010; Ooi & He, 2015). Additionally, it is plausible that individuals with no/limited stereovision perform better under monocular viewing, as it allows them to eliminate erroneous visual information from their misaligned or amblyopic eye and avoid binocular inhibition (Motley, 2018; von Bartheld et al., 2010; von Noorden & Campos, 2002).

Overall findings of experiment 4.1 and 4.2 suggest that individuals with varying levels of binocular stereoacuity use similar mechanisms of object size judgment and egocentric distance perception as stereonormal individuals. However, under specific conditions when visual information is limited individuals with no/limited stereovision were found to perform better under monocular than binocular viewing, while stereonormal subjects were found to perform better under binocular than monocular viewing.

6.3. Relative pictorial depth perception

The aim of the experiments summarised in Chapter 5 (experiment 5.1 and 5.2) was to explore the perception of relative depth in strabismus. If during the early stages of development the visual system processes all relative depth cues together, combining them for ultimately accurate representation of the surrounding world, it is possible that in individuals with infantile strabismus this process is disrupted by the lack of binocular disparity. If that is the case then their relative depth perception is not comparable to typically developed binocular individuals' monocular static viewing (i.e. viewing without binocular disparity or motion parallax). This is noted in one of Susan Barry's comments:

"… many people do not notice a great difference when viewing the world with one eye or two. When a normal binocular viewer closes one eye, however, he or she still uses a lifetime of past visual experiences to re-create the missing stereo information." (Barry, 2009)

She follows by explaining the change in her perception of relative depth after gaining normal eye alignment (vergence):

"I became convinced of these ideas on the day that the Star Wars movie Revenge of the Sith opened in movie theaters… I was overwhelmed by the sense of space and volume created in the movie. Scenes of spaceships flying through the universe were fantastic!.. Skilled cinematographers had used monocular depth and motion cues to create scenes on the flat, two-dimensional movie screen that suggested dramatic depth. Before my vision transformed, I could not experience this sense of space and volume while watching a movie because I had never experienced this sense of space and volume in real life." (Barry, 2009)

These comments suggest that information processed from the monocular relative depth cues are dependent on experience of depth from disparity, and thus the relative depth perception derived from pictorial cues will be different between strabismic and non-strabismic individuals.

There are two possible ways in which strabismics' relative depth perception could be impaired. Firstly, it can be impaired in a bottom-up sense as its development and calibration depends on having depth from binocular vision (von Bartheld et al., 2010; Wright et al., 2006). Secondly, it may be impaired in a top-down sense, as it is noted in the Barry's comments above, because cognitive inferences of depth from the relative monocular depth cues are developed from depth observed on an everyday basis, and if this is impaired (e.g. more shallow) due to lack of binocular disparity, the perception of relative depth from monocular cues would also be impaired due to impaired cognitive inferences (e.g. more shallow depth derived from perspective information). Both of these possibilities were addressed in experiments 5.1 and 5.2. The impairment in the bottom-up processing would be revealed if in contrast to the controls strabismic individuals were not susceptible to pictorial depth information (perspective). While the ability to use information within the pictorial cues (i.e. the amount of depth perspective information allows to perceive) would account for the possible impairment in the top-down cognitive processing.

In both experiments (5.1 and 5.2) all participants were found to be highly susceptible to pictorial depth information, including sparse perspective convergence information. This susceptibility was present among individuals with varying levels of binocular stereovision and manifestations of strabismus. According to the cue-coherence theory (Ames, 1925; Hillis et al., 2004) when viewing 2D pictorial images binocular disparity identifies the stimulus as being flat, and thus the addition of conflicting or less precise pictorial perspective information should allow to perceive only a shallow pictorial depth, i.e. depth of minimum magnitude. However, experiment 5.2 found perspective information to have a significant effect for all participants' equidistance judgments under both monocular and binocular viewing, suggesting that despite conflicting binocular disparity information people are highly susceptible to pictorial depth. These findings suggest that relative pictorial depth is part of the bottom-up processing that is independent from the binocular disparity processing pathways, and thus in infantile strabismics is not affected during the critical period. The experiment 5.2 not only replicated the findings but showed the effects to be present under both testing methods: two alternative forced choice method tasks and method of adjustment tasks. There were no significant differences found between the stereonormal individuals and individuals with no/limited stereovision not only in their 2D pictorial depth judgments, but also in the 3D pictorial space interval equidistance judgment tasks. The performance of the participants tested in experiments 5.1 and 5.2 suggests that in contrast to Barry's accounts above, individuals with varying levels of binocular stereovision and manifestations of strabismus do not have impairments in the amount of perceived relative depth (from perspective cue) in comparison to typically developed binocular individuals.

Overall findings of experiment 5.1 and 5.2 suggest that relative depth processing is not developmentally dependent on binocular vision or co-calibration with disparity processing, and thus should not be affected in infantile strabismics during the critical period. The fact that there were no significant differences found between typically developed binocular individuals and strabismics with no/limited binocular stereovision performance in the 3-D pictorial space interval equidistance judgment tasks supports the idea that pictorial depth is not cognitively derived in strabismus, and involves the same bottom-up processing as perception of real 3D space.

6.4. Post-hoc reflections on limitations and extensions of the research in this PhD project

This thesis addressed the key aspects of static depth and distance perception and serves as a stepping stone to understanding the capacities and limitations individuals with strabismus and no/limited binocular stereovision experience in comparison to typically developed binocular individuals. However, due to several factors we were not able to explore or address further a number of other possible aspects.

Due to the location of St Andrews University, which has a relatively small local population, the number of recruited strabismic individuals was quite limited. The experimenter presented her PhD project at the Scottish Ophthalmologist conference and was received with great interest, but none of the ophthalmologists in Fife were able to support the NHS ethical application, which was later disbanded due to time constrains. Some participants were recruited for experiment 3.1 in collaboration with the School of Optometry, Nova Southeastern University in Florida, USA. The collaboration with the Abertay University in Dundee not only allowed to publish a press release attracting participants, but also allowed to test them in Dundee. Therefore, the experimenter was able, through collaborations and extensive advertising to obtain a sufficient number of participants. However, the sample of participants obtained for the experiments discussed in this thesis was highly varied and included individuals with amblyopia, strabismus amblyopia, strabismus, and other unidentified visual disorders resulting in impaired binocular stereovision. The author of this thesis recorded subjects' self-reported information about their visual disorders, including history of neurological conditions, but it is possible that participants were not able to recall all information and/or specific medical terms used in relation to their visual disorder and any other linked medical conditions. Due to this high variability and lack of medical records, classification according to the history of strabismus was not available for the analysis. Therefore, ideally larger samples should be collected to allow statistical analysis comparing performance of individuals with infantile or late-onset strabismus, with amblyopic strabismus or just strabismus, or with exo- and eso-deviations.

The experimenter and the author of this thesis had no prior ophthalmological or orthoptist training, which resulted in limited clinical assessment of strabismus. The Cover and the Cover-Uncover tests were performed only at the near viewing distance, and thus deviations which are present at distance were not recorded. The deviations present at the distance Cover and Cover-Uncover tests could have been important considering that in the experiments described in Chapter 4 one of the viewing conditions was at 3.5 meter viewing distance. Similarly, the distance clinical binocular stereoacuity tests (e.g. Distance Randot) would have been beneficial for analysis of the experiment 4.1 and 4.2 findings. Further, the examiner might have not diagnosed deviations due to limited practice and use of pen tip in the Cover and Cover-Uncover tests, which is not a suitable accommodative target. Additional mistakes were made whilst measuring the IPD between the centres of the pupils rather than the temporal edge of one eye and nasal edge in the other, and using Snellen visual acuity chart, instead of a more accurate logMAR chart. While these limitations affected the quality of information gathered about participants' vision, it did not radically affect the findings described in the experimental chapters. The experimenter created a relatively coarse classification to refer to when performing statistical analysis or simply eye-balling the data in order to consider any possibly relatable trends in the data. The coding used for the participants was the following: C for controls, CS for surgically corrected strabismus, MS for mild angle surgically uncorrected strabismus, and SS for severe angle surgically uncorrected strabismus. Some participants, according to their self-reports, were not aware of their visual conditions, even though deviation was present under the Cover and Cover-Uncover tests. Additionally, some participants had only amblyopia. These subjects were coded under O, for other disorders. These codes are indicated next to subject numbers in the participants' visual information tables in the appendices. There were no observable trends between the visual disorder histories and participants' performance. The fact that there were no clear correspondences between the outliers in the experiments described in this thesis (e.g., experiment 3.1 participants who reported that they did not perceive any difference between binocular and monocular-aperture 2D picture viewing), highlights the observed similarities between performance of individuals with normal binocular stereovision and those with no/limited binocular stereovision. In order to further investigate and compare depth and distance perception in different types of strabismus and/or amblyopia, a much larger and homogeneous sample is required, as well as an assistance of a trained orthoptist.

6.4.1. Qualitative aspects of depth perception in strabismus

The average age of different binocular stereovision groups varied quite notably in experiments 3.1 and 3.2 as majority of participants with no binocular stereovision were over 40 years old, while stereonormal participants were undergraduate students in their 20s. This was addressed by recruiting postgraduate students as stereonormal subjects, as well as attempting to recruit at least a few younger individuals with strabismus. Considering the potential impact of accommodation information in providing egocentric distance information, which then allows to scale the 2D image and experience monocular stereopsis, participants' age in further work should be matched more accurately. Research has shown both static and dynamic accommodation to be affected by age, as the hardening of the crystalline lens capsule and atrophy of the ciliary muscles takes place (Kasthurirangan & Glasser, 2006; Lockhart & Shi, 2010; Mordi & Ciuffreda, 1998). It is possible that limitations in accommodative responses may lead to less strong monocular stereopsis in older individuals. On the other hand, research has found binocular stereoacuity decreases with increasing age in asymptomatic individuals with no ocular pathology, which 29% of 417 participants over 65 years of age being found stereoblind (Fielder & Moseley, 1996). Therefore, comparing matched age participants to individuals with strabismus might have resulted in misleading similarities. Comparing performance of older individuals' with strabismus to young stereonormal subjects with good stereovision, would suggest any of the observed similarities between the two groups as being more fundamental and extending throughout the individuals' lifetime.

The experiment 3.2 used a specially designed blind comparison box, which allowed a new paradigm of testing: blind comparisons of the quality of depth individuals perceived when viewing a real 3D object and its 2D image. There were 8 different viewing conditions in the 3.2 experiment: binocular, binocular-aperture, monocular, monocular-aperture viewing of 2D picture, and binocular, binocular-aperture, monocular, monocular-aperture viewing of real 3D object. The total number of the possible pairwise comparisons was 28. However, due to time limitations and concerns about the potential length or number of the testing trials, which would have limited the potential number of strabismic participants, 11 key pairwise comparisons were selected. Testing all possible pairwise comparisons would allow the use of statistical methods, that would better quantify differences between the perceived quality of depth under different viewing conditions. For instance, Thurstone scaling (Thurstone, 1927) allows to produce a quantitative continuum of all viewing conditions, while Multidimensional scaling allows to create a map displaying relative positions between all viewing conditions based on the mean ratings and standard deviations in all pairwise comparisons. Therefore, a redesigned version of the blind comparison box could be tested with typically developed binocular individuals for all 28 pairwise comparisons (in a number of sessions) creating enough data to statistically define differences in perceived quality of depth among the 8 viewing conditions.

6.4.2. Egocentric distance perception

Other experiments considered for this PhD research included a Virtual Reality stimulus experiment designed as an extension to experiments 4.1 and 4.2. The same three familiar objects (basketball, coke can, and golf ball) were to be presented using the HTC Vive VR system to participants who would then adjust the stimulus size to match their internal standard for the object using the two wireless hand controllers. The objects were to be displayed in darkness with a single light source above the object, thus trying to eliminate any additional visual information. Further, objects were to be presented in a room similar to the testing laboratory on a table under light conditions, thus containing all possible visual information sources for depth. Both of these conditions were to mimic the experimental testing conditions (experiments 4.1 and 4.2) and thus were to be presented at the same viewing distances (1m, 1.75m, and 3.5m). Additionally, viewing distances beyond personal space were to be explored by presenting objects in an alley between two buildings with repetitive patterns of windows and light fixtures, thus providing relative depth information, and in a football field with a visible line of horizon, thus addressing egocentric distance information from eye declination level and earth curvature. The setting up of this experiment was initiated in collaboration with Abertay University, but had to be terminated due to the termination of the master student's studies who was working on the experimental code for the HTC vive. VR experiments would allow to explore egocentric distance perception beyond the possibilities of experimental laboratory setting, due to the possibility to control all aspects of the stimulus parameters and conditions.

6.4.3. Relative pictorial depth perception

Other tasks considered as a way of exploring relative depth perception in strabismus were based on prior research. In the contour relief studies (J. Koenderink & van Doorn, 2003; J.

Koenderink et al., 1995; Wijntjes, 2012) object shape is assessed by measuring the observed perception of 3D surface relief using the gauge task. An example of this method is provided in Figure 6.1 (Wijntjes, 2012). Here the contour is created with a number of triangulations (points which are defining the shape of the contour), at which gauge figures (circular patches with a line at some angle to the surface) are displayed during the experiment and the participant is asked to adjust each gauge figure so it is perpendicular to the point on the surface of the contour. The following responses are used to reconstruct the shape in order to capture how much depth within the constructed contour was perceived by a participant. In prior research this method had been used to assess perceived depth differences under different viewing conditions, or the effects of different materials, such as concrete or shiny metal, or shading have on the amount of perceived depth within the relief (Doorschot, Kappers, & Koenderink, 2001; J. Koenderink & van Doorn, 2003; J. Koenderink et al., 1995; Wijntjes, 2012). In relation to the current PhD project this testing method was considered for assessing if there are differences in the perception of 3D surface relief between typically developed binocular individuals and individuals with strabismus. Testing this aspect of relative depth would allow to better understand the way strabismic and non-strabismic subjects perceive object shape at near viewing distance, which is a different aspect to relative depth perception from perspective information (as tested in experiments 5.1 and 5.2).

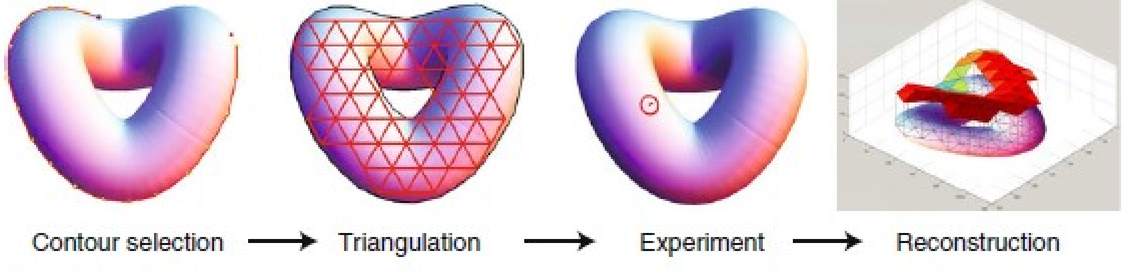


Figure 6.1. Example of experimental process exploring relative depth perception from contour relief. (Wijntjes, 2012)

3D surface relief (curvature in depth) has also been tested using stimuli representing elliptical hemicylinders defined by a pattern of randomly distributed dots under binocular and monocular-aperture viewing (Vishwanath & Hibbard, 2013). Inclusion of the monocular-aperture viewing condition would allow to explore if individuals who perceive a smaller magnitude of curvature in depth, would perform differently when viewing the stimulus through a monocular aperture (due to the evoked monocular stereopsis). This experiment in fact could be seen as the next logical step following our findings showing that individuals with strabismus and varying levels of binocular stereovision can experience monocular stereopsis (experiment 3.1 and 3.2), as well as findings suggesting pictorial depth information processing in individuals with strabismus to follow similar bottom-up processing as typically developed binocular individuals (experiment 5.1 and 5.2).

6.5. Future directions: interaction with space and objects within it

The natural development from the research presented in this thesis is towards exploring participants' ability to interact with space and objects within it. That was the main reason Susan Barry started looking for way of improving her vision, as she started having difficulty reading road signs or seeing people's faces at the back of the lecture theatre (Barry, 2009). In her book Susan Barry provides an account on the way one of her students, who developed strabismus at the age of 5 and since then had diplopia, is successfully interacting with her environment:

"I asked Sarah what her view of the world was like. "I see two images but only one is real. I can be driving and see two images of a car, but I know which one to steer around."… Then, she said that the car image seen by right eye was in context. In other words, the right-eye image of the car was located relative to other things in her surroundings. To Sarah, it had a defined location in space." (Barry, 2009)

This raises questions about the adaptability of the visual system of a strabismic individual and with what certainty they can interact with their environment. In fact, individuals with strabismus have been speculated to develop numerous biological adaptive mechanisms, for instance at the beginning of last century it was already known that in some cases of strabismus a new fovea is developed in the misaligned eye, and thus despite the misalignment images from both eyes are processed together (Verhoeff, 1902). However, adaptive strategies in strabismics' behaviour are mostly known only from the anecdotal reports (such as, prior described case of Barry's student).

Research on the importance of binocular stereovision for complex motor (e.g. water pouring, bead threading, peg placing) suggest that there is evidence of adaptation, but it depends on the task (O'Connor, Birch, Anderson, Draper, et al., 2010). When the tasks were performed by strabismics with no clinically measurable binocular stereoacuity and motor fusion, and individuals with binocular stereoacuity and motor fusion, significant differences were found only regarding the Purdue pegboard (placing pins in a vertical column of holes on a board in 30s) and bead tasks (placing 30 large or 22 small bead onto a needle, while performance time is measured) (O'Connor, Birch, Anderson, & Draper, 2010). Levels of stereoacuity and motor fusion were not found to produce significant differences in the water pouring task, i.e. pouring water from a jug into five measuring cylinders set in fixed positions up to 90ml line, while performance time is measured (O'Connor, Birch, Anderson, & Draper, 2010; O'Connor, Birch, Anderson, Draper, et al., 2010). It is possible that in water pouring task there is change in visual information that is registered together with the speed of action (increasing level of water with hand tilt), while in the tasks asking subjects to place pins or beads the focus is solely on the ability to judge a very specific location. On an everyday basis when pouring liquid into a measuring cup, while the location of the cup might be derived from haptic information (hand holding the cup), judgments about the level of liquid are usually based on relative visual information (level of water in a cup relative to the brim). Meanwhile, when putting beads on a needle participants on an everyday basis are likely to hold not only the beads but also the needle in their hands, thus getting relative information about the position of both objects via their motor response and haptic feedback. Therefore, in future work this information may be included to explore the change in strabismic participants' performance between conditions with and without the non-visual information.

Further it is interesting to consider possible adaptation mechanisms based on haptic response, when reaching or grasping for objects. Being able to accurately perform such actions is essential on a daily basis. Prior work on reaching and grasping revealed deficits in amblyopic strabismics only when they viewed objects with their amblyopic eye (Niechwiej-Szwedo et al., 2014). However, individuals with amblyopic strabismus and only strabismus showed lower peak acceleration which was also found to be longer than that of stereonormal participants (Niechwiej-Szwedo et al., 2014). This suggests that in comparison to typically developed binocular individuals, strabismics depend more on dynamic visual feedback during their reaching and grasping movements, as they are using this information to adjust the position of their hand as well as the grasping aperture. Research on reaching and grasping among typically developed binocular individuals has shown that binocular disparities can be scaled using hand position as a visual feedback for the egocentric distance of an object (Bozzacchi, Volcic, & Domini, 2016; Volcic, Fantoni, Caudek, Assad, & Domini, 2013). Visual feedback information was changed by displacing the reaching finger, as if the participant's arm is longer, and after haptic response the visual system was found to adapt to the "new" correct distance (Volcic et al., 2013). This is not surprising considering the adaptations to the "new" level of horizon in the eye declination level studies (Ooi et al., 2001; Wu et al., 2004). It is highly likely that individuals with strabismus on an everyday basis are able to adjust the visual information based on their haptic responses. Therefore, it would be interesting to explore individuals' with strabismus ability to adapt their reaching and grasping movement based only on the haptic response, or under varying levels of available visual and haptic information.

A final interesting aspect regarding the way individuals with strabismus may adapt in everyday environment in order to be able to interact with objects and space between them, is the position of the body and the skeletal muscle information. Body orientation has been found to affect perceived distance and object orientation, for instance, participants have been found to perceive the opposite wall as being closer when lying on their back than when sitting in an upright position (Harris et al., 2015). The importance of the position of the body may be noted clearly in strabismics with amblyopia, because they are often found to exhibit a correcting tilt of their head placing the non-amblyopic eye at the centre of the body and thus effectively making it the cyclopean eye (Motley, 2018; von Bartheld et al., 2010; von Noorden & Campos, 2002). Therefore it would be rewarding to explore multisensory integration in individuals with strabismus and none or limited binocular stereovision. This could be performed introducing sound stimulus for distance judgments, or including tasks that allow incorporation of skeletal muscle information, such as throwing objects at certain distance or between objects.

Together these tasks would allow to explore more clearly and systematically how depth and distance perception of individuals with strabismus is affected on an everyday basis whilst performing everyday tasks.

6.6. Conclusion

The work presented in this PhD thesis suggests that in the population tested strabismics' visual system processes static depth and distance information using the same mechanisms and processes as typically developed binocular individuals. The major trends observed in the experiments are present in all participants despite their level of binocular stereovision or manifestations of strabismus. Therefore, the current thesis suggests that there are more similarities between typically developed binocular individuals and individuals with strabismus and no/limited clinically measurable binocular stereovision, than the traditional views may suggest.

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Appendices

Appendix 2.1

Participants vision information sheet (Chapter 2).

Information about participant's vision

Participant ______________ Age __________

I. Strabismus Yes / No

1. Infantile / Developed later in life (age ______________)
2. Constant / Intermittent
3. History of surgeries ____
4. Other treatments ____
5. Cover Test

   Right eye ________________________

   Left eye _________________________
6. Self-reported deficits & other notes

____

____

____

II. Visual acuity

1. Far viewing Right eye ________ Left eye _________
2. Near viewing Right eye ________ Left eye _________
3. Monitor viewing Right eye ________ Left eye _________

III. Eye dominance Right eye / Left eye

IV. Stereovision

1. Local stereovision (Fly test)

The house Fly test Yes / No

The circle patterns Last one answered correctly __________________

2. Global stereovision (TNO test)

Presence of stereovision (Plates I-III)

Plate I   Butterfly   Yes / No

Plate II   Small circle   Yes / No   Large circle   Yes / No

Plate III   Disk Yes / No Triangle Yes / No Square Yes / No Diamond Yes / No

Stereoscopic sensitivity (Plates V-VII)

Plate V   top left ◯ top right ◯ bottom right ◯ bottom left ◯

Plate VI   top left ◯ top right ◯ bottom right ◯ bottom left ◯

Plate VII top left ◯ top right ◯ bottom right ◯ bottom left ◯

V.   Colour Deficiency

Plate 1 ______   Plate 2 ______   Plate 3 ______   Plate 4 ______   Plate 5 ______

Plate 6 ______   Plate 7 ______   Plate 8 ______   Plate 9 ______ Plate 10 ______

Plate 11 (traceable line)   Yes / No   Plate 12 ______   Plate 13 ______

Plate 14 (traceable lines) 1) purple line Strong / Mild   2) red line Strong / Mild

Vision info sheet #2

Participant code

RANDOT stereotest

Top panel:

Circle Yes / No Star Yes / No E Yes / No

Bottom panel:

Square Yes / No Triangle Yes / No Plus Yes / No

Circles:

Last one right ____

Eye dominance

Left Right Previously reported: L / R

IPD:

____________ cm

____________ m

Appendix 3.1

Experiment 3.1 (experiment 1 chapter 3) Part 2 questionnaire comprised of 10 Likert-scale items. One of the five possible randomised question orders: questions number 1, 4, 5, 7, 9 are target items; questions number 2, 3, 6, 8, 10 are control items.

For each of the 10 statements below, indicate your level of agreement or disagreement by circling one of seven possible levels indicated.

Remember, there are no right or wrong answers; just answer as best and as carefully as you can based on what you actually perceive.

Please view the pictures again as necessary in order to answer the question Ask the experimenter which picture you want to look at again.

1. There is a feeling that things stick out or come out of the screen when viewing with one eye through the hole but not when viewing with both eyes

   DISAGREE AGREE

   −−− −− − O + ++ +++

2. things in the picture that are closer appear blurred when viewing with one eye through the hole but not when viewing with both eyes

   DISAGREE AGREE

   −−− −− − O + ++ +++

3. The shapes of things appear different when viewing with one eye though the hole compared to viewing with both eyes

   DISAGREE AGREE

   −−− −− − O + ++ +++

4. There is a sense of real separation and space between things when viewing with one eye through the hole that is not experienced when viewing with both eyes

   DISAGREE AGREE

   −−− −− − O + ++ +++

5. It feels as though I am looking at something real, rather than a photograph, when viewing with one eye through the hole but not when viewing with two eyes

DISAGREE						AGREE
−−−	−−	−	O	+	++	+++

6. Things appear more transparent or translucent when viewing with one eye through the hole compared to viewing with two eyes

DISAGREE						AGREE
−−−	−−	−	O	+	++	+++

7. it feels like I could actually reach out and touch things when viewing with one eye through the hole but not when viewing with two eyes

DISAGREE						AGREE
−−−	−−	−	O	+	++	+++

8. Things appear to move or shift around in depth when viewing with one eye through the hole but not when viewing with two eyes

DISAGREE						AGREE
−−−	−−	−	O	+	++	+++

9. Things appear more solid or 3-dimensional when viewing with one eye through the hole compared to viewing with both eyes

DISAGREE						AGREE
−−−	−−	−	O	+	++	+++

10. The colour of things that are closer in the picture appear washed out when viewing with one eye through the hole, but not when viewing with both eyes

DISAGREE						AGREE
−−−	−−	−	O	+	++	+++

Appendix 3.2

Experiment 3.1 (experiment 1 chapter 3) participant vision information table.

No stereovision subjects

Nr.	Code	Age	Disorder history	Onset	Deviation at time of testing	Correction	Visual acuity			Dom eye	Stereovision		Colour def
							Far	Near	Monitor		Fly	TNO/ RanDot	
8	CS2	42	Strabismus R eye	Infantile	L eye hypertropia	Surgeries: 1-2, 11-12 years; patching & eye drops	R:20/30 L:20/26	R:20J2 L:20J2	R:20J2 L:20J2	Right	None	None	No
9	MS1	32	Strabismus L amblyopia	Infantile	L eye mild esotropia	Early patching	R:20/20 L:20/140	R:15J1 L:none	R:25J3 L:none	Right	800'	None	No
12	CS4	43	Strabismus R eye	Infantile	R eye esotropia	Surgery: ~1y; early patching	R: 20/30 L:20/20	R:50J8 L:15J1	R:50J8 L:20J2	Left	None	None None	No
21	CS8	54	Strabismus R amblyopia	Infantile	R esotropia	Surgery: 4y; early patching	R:no L:20/26	R:no L:20J2	R:no L:25J3	Left	None	None	No
23	CS9	19	Strabismus L eye	infantile	none	Surgery: 9 y; early patching	R:20/20 L:20/50	R:30J4 L:60J10	R:40J7 L:no	Right	None	None	No
24	001 CS10	31	Distance Cover test: 56 CLXT Near Cover test: 67CLXT			Surgery both eyes as child	R:20/20 L:20/200				None	None	
41	A1 CS12	68	Strabismus R amblyopia	infantile	exophoria	Surgery20-30s vergence exercise	R: 20/25 L: 20/20	R: 20J2 L: 15J1	R: 50J8 L: 50J8	left	400'	None None	No
42	A2 O8	30	Intermittent strabismus	--	exophoria	-	R: 20/13 L: 20/13	R: 20J2 L: 20J2	R: 25J3 L: 20J2	right	None	None None	No
43	A3 CS13	24	Lazy eye /amblyopia R	infantile	Exotropia Change between R&L	Surgery: <5y; patching, vergence exercises, drops	R: 20/15 L: 20/15	R: 15J1 L: 15J1	R: 25J3 L: 30J4	right	None	None None	No

46	A6 CS14	43	Esotropia L eye	infantile	Esophoria	Surgery: 8y vergence ex, patching	R: 20/10 L: 20/13	R: 30J4 L: 25J3	R: 25J3 L: 25J3	right	800’	None None	No
47	A7 CS15	71	Esotropia	infantile	R exotropia exophoria	Surgery: 7-8y patching, vergence exercises	R: 20/100 L: 20/15	R: no L: 20J2	R: no L: 40J7	left	400’	None None	No
48	A8 SS3	85	Strabismus R eye	infantile	R esotropia glaucoma, cataract	Surgery for glaucoma & cataract, prism in R lens	R: 20/200 L: 20/25	R: no L: 20J2	R: no L: 40J7	left	None	None None	yes
49	004 CS16	39	Distance Cover test: 14CLET 30LHypoT Near Cover test: 6CRET 30RHyperT			Surgery: 18 months, 6-7y	R: 20/20 L: 20/20				None	None	
51	006 SS5	28	Distance Cover test: 4CRET 4RHyperT Near Cover test: 6CRET 6RHyperT			none	R: 20/20 L: 20/15				None	None	
52	007 CS17	30	Distance Cover test: 12CRXT 6- 8LHyperPhoria Near Cover test: 6CRXT 3LHyperPhoria			Surgery: <1y for esotropia	R: 20/20 L: 20/20				None	None	
54	009	25	Distance Cover test: 35-40CLET Near Cover test: 35-40CLET			Possibly in infancy	R: 20/20 L: 20/40						

Did not perceive any difference between binocular and monocular-aperture viewing. Indicated depth perception to be better under binocular than monocular aperture viewing. Coding starting with “00” indicates participants tested in Florida, USA. Coding starting with “A” indicates participants tested in Abertay, Dundee.

Local stereovision subjects

Nr.	Code	Age	Disorder history	Onset	Deviation at time of testing	Correction	Visual acuity			Dom eye	Stereovision		Colour def
							Far	Near	Monitor		Fly	TNO/ RanDot	
10	CS3	31	Strabismus R esotropia	14	None	Surgery: 21 years	R:20/40 L:20/26	R:20J2 L:15J1	R:25J3 L:20J2	Left	140’	480’	No
17	O3	21	Intermittent strabismus?	--	none	--	R:20/30 L:20/26	R:15J1 L:15J1	R:20J2 L:20J2	Right	200’	None	No
20	O5	51	Amblyopia R eye	Infantile	none	none	R:20/200 L:20/30	R:no L:20J2	R:no L:20J2	Left	400’	None Test	No
22	O6	19	Amblyopia L eye	Infantile	exophoria	none	R:20/26 L:20/50	R:15J1 L:20J2	R:20J2 L:25J2	Right	400’	480’	No
25	**002 SS1**	40	Distance Cover test: 14CLET Near Cover test: 8CLET			History of surgery	R:20/25 L:20/30				400’	None	
26	003 CS11	32	Distance Cover test: 18CRXT Near Cover test: 25CRXT			none	R:20/25 L:20/25				70’	None	
27	SS1	21	Strabismus R amblyopia	Infantile	R esotropia	patching	R:20/200 L:20/30	R:no L:20J2	R:no L:20J2	Left	400’	None Test	No
28	O7	28	-	-	exophoria	-	R:20/30 L:20/30	R:15J1 L:20J2	R:20J2 L:25J3	Right	100’	None	No
29	SS2	30	Strabismus & farsighted	Infantile	exophoria L exotropia	Vergence exercises; childhood patching	R:20/10 L:20/15	R:15J1 L:20J2	R:20J2 L:30J4	right	140’	None 200’	No
44	A4 O9	21	Intermittent strabismus?	-	Exophoria	-	R: 20/13 L: 20/15	R: 15J1 L: 15J1	R: 20J2 L: 15J1	right	40’	480’ 400’	No
45	A5 O10	48	Amblyopia R eye	-	Exophoria	Patching, corrective lens	R: 20/15 L: 20/13	R:60J10 L: 20J1	R:60J10 L: 25J3	left	200’	None None	No
50	005 SS4	25	Distance Cover test: 25CAXT 10LHyperT			None	R: 20/16 L: 20/16				30’	None	

			Near Cover test: 18-20 CAXT 6LHyperT								
53	008	30	Distance Cover test: 6CLET Near Cover test: 2-4CLET	None	R: 20/20 L: 20/25				140’	None	

Non-naïve subject. Did not perceive any difference between binocular and monocular-aperture viewing. Indicated depth perception to be better under binocular than monocular aperture viewing. Coding starting with “00” indicates participants tested in Florida, USA. Coding starting with “A” indicates participants tested in Abertay, Dundee. Subjects with TNO score “None test” are participants, who sow the stimuli in the first 3 pages (e.g. butterfly), but not the test stimuli measuring level of stereovision.

Stereo-normal subjects

Nr.	Code	Age	Disorder history	Onset	Deviation at time of testing	Correction	Visual acuity			Dom eye	Stereovision		Colour def
							Far	Near	Monitor		Fly	TNO/ RanDot	
1	CS1	23	Strabismus L eye	10-11	none	Vergence ex	R: 20/30 L: 20/30	R: 15J1 L: 20J2	---	Left	40’	240’	No
2	C1	21	none	--	--	--	R: 20/30 L: 20/30	R: 20 J2 L: 20 J2	---	Left	40’	60’	No
3	C2	20	none	--	--	--	R: 20/20 L: 20/26	R: 15 J1 L: 15 J1	---	Right	40’	60’	No
4	C3	28	none	--	--	--	R: 20/26 L: 20/20	R: 15 J1 L: 15 J1	---	Right	40’	60’	No
5	C4	28	none	--	--	--	R:20/20 L:20/30	R:15J1 L:20J2	R:20J2 L:20J2	Left	40’	30’	No
7	C6	20	none	--	--	--	R: 20/30 L: 20/30	R:15J1 L: 15J1	R:- L:-	Left	80’	120’	No
13	O1	20	Intermittent Strabismus?	--	Exo-deviation	Vergence exercises	R:20/20 L:20/20	R:20J2 L:15J1	R:20J2 L:20J2	Left	50’	120’	No
14	O2	22	Intermittent strabismus?	--	Exo-deviation	--	R:20/26 L:20/26	R:15J1 L:15J1	R:- L:-	Left	40’	120’	No

18	CS7	21	Strabismus R eye	Infantile	exophoria	Vergence exercises	R:20/26 L:20/40	R:15J1 L:15J1	R:20J2 L:20J2	Right	40'	120'	No
19	O4	21	Intermittent strabismus?	--	Eso-deviation	--	R:20/30 L:20/30	R:15J1 L:20J2	R:25J3 L:20J2	Right	50'	240'	No
30	C8	19	none	-	exophoria	-	R:20/13 L:20/15	R:15J1 L:15J1	R:20J2 L:20J2	right	40'	60' 20'	no
32	C10	19	none	-	-	-	R:20/15 L:20/15	R:15J1 L:20J2	R:25J3 L:25J3	right	40'	120' 70'	no
33	C11	23	none	-	-	-	R:20/13 L:20/13	R:15J1 L:15J1	R:20J2 L:20J2	right	40'	30' 20'	no
34	C12	18	none	-	-	-	R:20/15 L:20/20	R:20J2 L:15J1	R:30J3 L:30J3	right	50'	240' 30'	no
35	C13	23	none	-	-	-	R:20/13 L:20/13	R:15J1 L:15J1	R:20J2 L:20J2	right	40'	30' 40'	no
36	C15	26	none	-	-	-	R:20/20 L:20/20	R:15J1 L:15J1	R:20J2 L:20J2	right	40'	30' 50'	no
37	C16	20	none	-	-	-	R:20/13 L:20/13	R:15J1 L:15J1	R:25J3 L:20J2	right	40'	60' 20'	No
38	C7	18	none	-	-	-	R: 20/10 L: 20/10	R: 15J1 L: 15J1	R: 15J1 L: 15J1	right	40'	60' 40'	no
39	C14	21	none	-	-	-	R: 20/13 L: 20/13	R: 20J2 L: 20J2	R: 20J2 L: 20J2	right	40'	60' 30'	no
40	C17	22	none	-	-	-	R: 20/13 L: 20/15	R: 15J1 L: 20J2	R: 30J4 L: 25J3	right	50'	120' 40'	no

Did not perceive any difference between binocular and monocular-aperture viewing. Coding starting with “00” indicates participants tested in Florida, USA. Coding starting with “A” indicates participants tested in Abertay, Dundee.

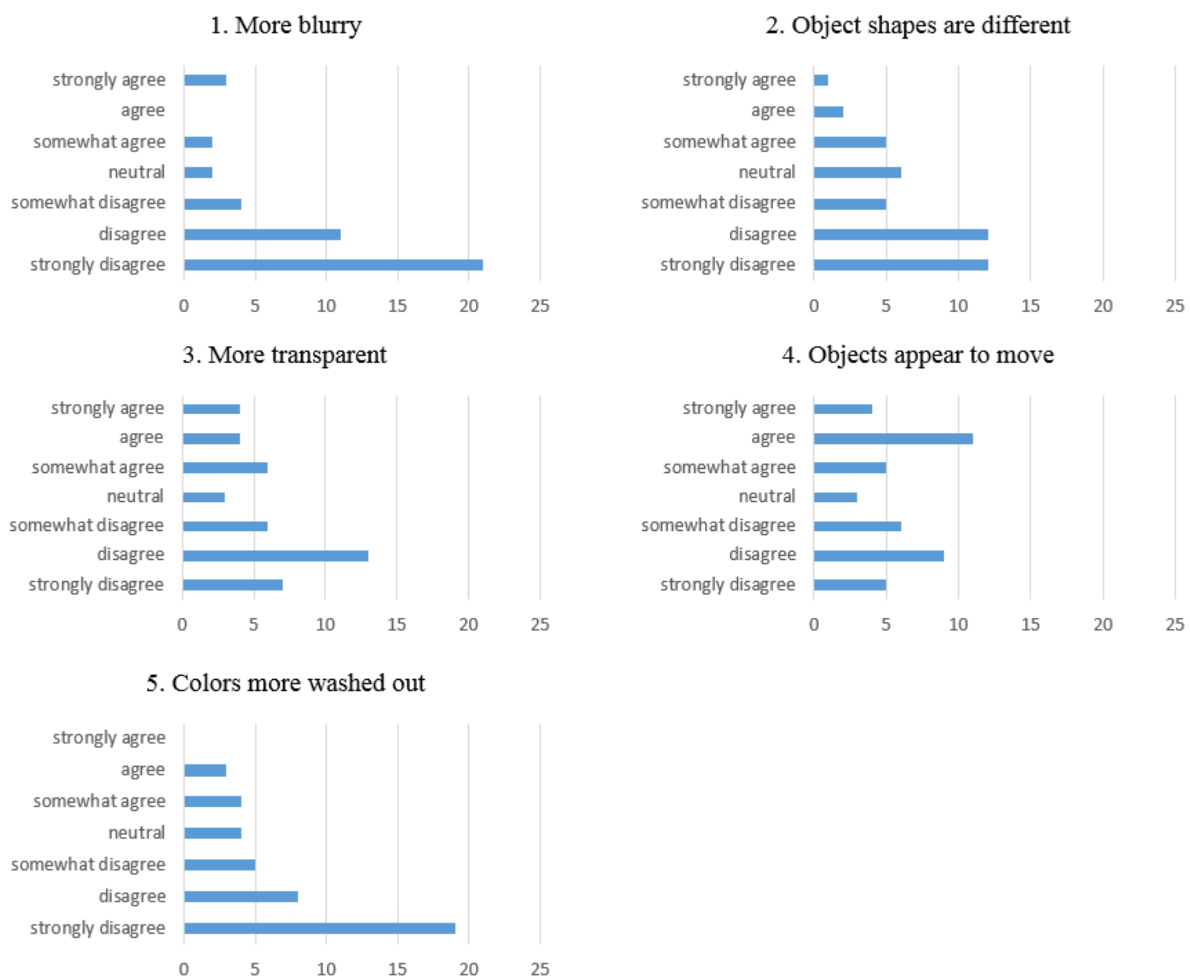
Anomalous stereovision subjects

Nr.	Code	Age	Disorder history	Onset	Deviation at time of testing	Correction	Visual acuity			Dom eye	Stereovision		Colour def
							Far	Near	Monitor		Fly	TNO/ RanDot	
6	C5	21	none	--	--	--	R:20/26 L:20/20	R:15J1 L:15J1	R:15J1 L:15J1	Right	200’	120’	no
11	MS2	19	Strabismus L eye	Infantile	L eye hypertropia	none	R:20/20 L:20/20	R:15J1 L:15J1	R:20J2 L:20J2	Right	50’	60’	No
15	CS5	19	Strabismus R exotropia	Infantile	none	Patching (4-10y), eye drops	R:20/26 L:20/26	R:15J1 L:15J1	R:20J2 L:20J2	Right	400’	60’	No
16	CS6	27	Strabismus L eye	Infantile	L eye exotropia	Surgery 10y	R:20/20 L:20/26	R:15J1 L:15J1	R:20J2 L:20J2	Right	140’	120’	No
31	C9	23	none	-	exophoria	-	R:20/20 L:20/25	R:20J2 L:15J1	R:20J2 L:20J2	left	400’	120’ 70’	no

Did not perceive any difference between binocular and monocular-aperture viewing. Indicated depth perception to be better under binocular than monocular aperture viewing. Coding starting with “00” indicates participants tested in Florida, USA. Coding starting with “A” indicates participants tested in Abertay, Dundee.

Appendix 3.3.

Bar graphs summarising frequencies for the 5 distractor statements from the experiment 3.1 Part 2 Likert scale questionnaire (Chapter 3). Statement 3 (“more transparent”) and statement 4 (“objects appear to move”) had higher means and medians than other distractor statements. Looking at the frequency bar charts it is evident that participants’ responses were more spread out for these two statements. However, for statement 3 (“more transparent”) largest number of subjects chose Disagree. For the statement 4 (“objects appear to move”) largest number of participants answered either Agree or Disagree. This, arguably, suggests that participants were attributing different precepts to this statement, i.e. subjects might have experienced change in focus whilst looking at the image binocularly and changing into monocular aperture viewing, and thus mistakenly attributed it to perception of the image quality rather than change in their vision.



Appendix 3.4.

Instruction given to participants in the experiment 3.2 Part 3A (experiment 2 chapter 3). First page was the top sheet, while second page was the back sheet.

Part 3A

In the main part of this experiment you will be asked to make judgments about whether the depth you experience in presentations of a 3D object appears more like depth you experience when viewing a real object or when viewing a picture of the object.

In order to be able to do this, we first ask you to view an actual real object and a picture of the object. Please look back and forth at them few times as instructed by the experimenter and make a mental note of any differences in way you perceive depth in the two cases.

Based on the way you experienced the real object and its picture displayed on a computer monitor, please rate realness of the following 8 presentations of a 3-D object. Please circle in your opinion the most suitable answer on the realness scale from the “Picture” to the “Real Object”.

Very Important!

Base your answers on what you actually perceive, not what you think you should perceive based on your knowledge, or what you think the experimenter wants you to perceive.

Appendix 3.5

Instruction given to participants in the experiment 3.2 Part 3B (experiment 2 chapter 3).

Part 3B

In this experiment you will be asked to view two images of a 3-D object and make a judgement about which one appears to have a better impression of depth. Then you have to rate how big the difference in perceived depth is between the two.

In order to do this, we ask you to first view a Reference comparison. Please make a mental note on the difference in the quality of depth you experience between these two sequential presentations of a 3-D object. You should attribute a value of '5' for this difference, which will be your Reference value while viewing other comparisons.

IMPORTANT

- **Make sure to take your time in viewing the two images**

- **Make sure your judgement is only on the difference in perceived depth, NOT any other attribute such as a difference in sharpness, or colour.**

Now you will be shown a pair of images to compare.

For each comparison please tick either “First” or “Second” box to indicate during which presentation of the 3-D object you perceived better quality depth.

Then rate that difference by writing down a value that indicates the magnitude of the difference your perceived

‘5’ means you perceived the same amount of difference as in the reference comparison, a value more than ‘5’ that the difference was greater than in the reference, and a value between ‘1’ and ‘4’ as perceiving a difference that was less than the reference.

If you perceive no noticeable difference in the quality of depth please circle ‘0’ for the “Difference” and do not tick any of the boxes.

The experimenter will show you the Reference comparison at the beginning and after certain number of trails. However, if you feel you need to remind yourself the Reference value and the difference in quality of depth you perceived in the Reference comparison, please ask the experimenter to show this comparison at any point.

IMPORTANT

Base your answers on what you actually perceive, not what you think you should perceive, or what you think the experimenter wants you to perceive.

- **Make sure your judgement is only on the difference in perceived depth, NOT any other attribute such as a difference in sharpness, or colour.**

Appendix 3.6.

The two final testing sequences for the experiment 3.2 Part 3B (experiment 2 chapter 3). Each comparison pair is coded by a different colour.

Part 3 B) Comparison task

Testing sequence A

Nr.	Comparison	I stimuli	Light	II stimuli	Light
R	Reference	B-P	1st	MA-P	1st
1	32	M-R	50	MA-R	25
2	22	B-R	25	MA-P	1st
3	34	MA-R	25	MA-P	1st
	Reference	B-P	1st	MA-P	1st
4	35	B-P	1st	BA-P	2nd
5	Non-ran 1	B-P	1st	M-P	2nd
6	6	M-R	25	MA-P	1st
7	3	B-R	25	B-P	1st
8	Non-ran 2	M-P	1st	MA-P	2nd
9	16	MA-R	25	MA-P	1st
	Reference	B-P	1st	MA-P	1st
10	11	B-R	50	M-R	25
11	30	B-R	25	B-P	1st
12	Non-ran 1	B-P	2nd	M-P	1st
13	33	M-R	25	MA-P	1st
14	7	MA-P	1st	MA-R	25
15	28	B-R	50	BA-R	25
	Reference	B-P	1st	MA-P	1st
16	17	B-P	2nd	BA-P	1st
17	Non-ran 2	M-P	2nd	MA-P	1st
18	14	M-R	25	MA-R	50
19	8	BA-P	2nd	B-P	1st
20	Non-rand 1	M-P	2nd	B-P	1st
21	5	MA-R	25	M-R	50
22	29	B-R	25	M-R	50

Nr.	Comparison	I stimuli	Light	II stimuli	Light
R	Reference	B-P	1st	MA-P	1st
23	21	B-P	1st	B-R	25
24	Non-ran 2	M-P	1st	MA-P	2nd
25	25	MA-P	1st	MA-R	25
	Reference	B-P	1st	MA-P	1st
26	31	B-R	25	MA-P	1st
27	27	MA-P	1st	BA-P	2nd
28	26	BA-P	1st	B-P	2nd
29	Non-ran 1	M-P	1st	B-P	2nd
30	19	B-R	25	BA-R	50
31	15	MA-P	1st	M-R	25
	Reference	B-P	1st	MA-P	1st
32	1	BA-R	25	B-R	50
33	36	MA-P	2nd	BA-P	1st
34	23	MA-R	50	M-R	25
35	2	M-R	25	B-R	50
36	4	MA-P	1st	B-R	25
37	18	BA-P	2nd	MA-P	1st
	Reference	B-P	1st	MA-P	1st
38	24	MA-P	1st	M-R	25
39	13	MA-P	1st	B-R	25
40	9	BA-P	1st	MA-P	2nd
41	20	M-R	50	B-R	25
42	10	BA-R	50	B-R	25
43	12	B-P	1st	B-R	25
44	Non-ran 2	M-P	2nd	MA-P	1st

Part 3 B) Comparison task

Testing sequence B

Nr.	Comparison	I stimuli	Light	II stimuli	Light
R	Reference	B-P	1st	MA-P	1st
1	4	B-R	25	MA-P	1st
2	19	B-R	50	BA-R	25
3	32	M-R	50	MA-R	25
	Reference	B-P	1st	MA-P	1st
4	33	M-R	25	MA-P	1st
5	18	MA-P	1st	BA-P	2nd
6	9	MA-P	2nd	BA-P	1st
7	24	M-R	25	MA-P	1st
8	36	BA-P	2nd	MA-P	1st
9	26	B-P	1st	BA-P	2nd
10	Non-ran 1	B-P	1st	M-P	2nd
	Reference	B-P	1st	MA-P	1st
11	34	MA-R	25	MA-P	1st
12	15	MA-P	1st	M-R	50
13	2	B-R	50	M-R	25
14	22	B-R	25	MA-P	1st
15	6	MA-P	1st	M-R	25
16	5	M-R	25	MA-R	50
	Reference	B-P	1st	MA-P	1st
17	11	B-R	25	M-R	50
18	10	B-R	25	BA-R	50
19	20	M-R	25	B-R	50
20	27	BA-P	1st	MA-P	2nd
21	31	MA-P	1st	B-R	25
22	23	MA-R	25	M-R	50

Nr.	Comparison	I stimuli	Light	II stimuli	Light
R	Reference	B-P	1st	MA-P	1st
23	12	B-R	25	B-P	1st
24	Non-ran 2	M-P	1st	MA-P	2nd
25	17	B-P	2nd	BA-P	1st
26	Non-ran 1	B-P	2nd	M-P	1st
	Reference	B-P	1st	MA-P	1st
27	16	MA-R	25	MA-P	1st
28	1	BA-R	25	B-R	50
29	28	BA-R	50	B-R	25
30	13	MA-P	1st	B-R	25
31	25	MA-P	1st	MA-R	25
32	14	MA-R	50	M-R	25
	Reference	B-P	1st	MA-P	1st
33	7	MA-P	1st	MA-R	25
34	8	BA-P	2nd	B-P	1st
35	Non ran 2	M-P	2nd	MA-P	1st
36	35	BA-P	1st	B-P	2nd
37	Non ran 1	M-P	2nd	B-P	1st
38	29	M-R	50	B-R	25
	Reference	B-P	1st	MA-P	1st
39	3	B-R	25	B-P	1st
40	Non ran 2	M-P	1st	MA-P	2nd
41	30	B-P	1st	B-R	25
42	Non ran 1	M-P	1st	B-P	2nd
43	21	B-P	1st	B-R	25
44	Non ran 2	M-P	2nd	MA-P	1st

Appendix 3.7.

Experiment 3.2 (experiment 2 chapter 3) participant vision information table.

No stereovision subjects

Nr.	Code	Age	Disorder history	Onset	Deviation at time of testing	Correction	Visual acuity			Dom eye	Stereovision		Colour def
							Far	Near	Monitor		Fly	TNO/ RanDot	
8	CS2	42	Strabismus R eye	Infantile	L eye hypertropia	Surgeries: 1-2, 11-12 years; patching & eye drops	R:20/30 L:20/26	R:20J2 L:20J2	R:20J2 L:20J2	Right	None	None	No
12	CS4	43	Strabismus R eye	Infantile	R eye esotropia	Surgery: ~1y; early patching	R: 20/30 L:20/20	R:50J8 L:15J1	R:50J8 L:20J2	Left	None	None None	No
21	CS8	54	Strabismus R amblyopia	Infantile	R esotropia	Surgery: 4y; early patching	R:no L:20/26	R:no L:20J2	R:no L:25J3	Left	None	None	No
41	A1 CS12	68	Strabismus R amblyopia	infantile	exophoria	Surgery20-30s vergence exercise	R: 20/25 L: 20/20	R: 20J2 L: 15J1	R: 50J8 L: 50J8	left	400'	None None	No
46	A6 CS14	43	Esotropia L eye	infantile	Esophoria	Surgery: 8y vergence ex, patching	R: 20/10 L: 20/13	R: 30J4 L: 25J3	R: 25J3 L: 25J3	right	800'	None None	No
47	A7 CS15	71	Esotropia	infantile	R exotropia exophoria	Surgery: 7-8y patching, vergence exercises	R: 20/100 L: 20/15	R: no L: 20J2	R: no L: 40J7	left	400'	None None	No

Coding starting with "00" indicates participants tested in Florida, USA. Coding starting with "A" indicates participants tested in Abertay, Dundee. All subjects were tested in both experiments 3.1 and 3.2.

Local stereovision subjects

Nr.	Code	Age	Disorder history	Onset	Deviation at time of testing	Correction	Visual acuity			Dom eye	Stereovision		Colour def
							Far	Near	Monitor		Fly	TNO/ RanDot	
20	O5	51	Amblyopia R eye	Infantile	none	none	R:20/200 L:20/30	R:no L:20J2	R:no L:20J2	Left	400’	None Test	No
22	O6	19	Amblyopia L eye	Infantile	exophoria	none	R:20/26 L:20/50	R:15J1 L:20J2	R:20J2 L:25J2	Right	400’	480’	No
28	O7	28	-	-	exophoria	-	R:20/30 L:20/30	R:15J1 L:20J2	R:20J2 L:25J3	Right	100’	None	No
29	SS2	30	Strabismus & farsighted	Infantile	exophoria L exotropia	Vergence exercises; childhood patching	R:20/10 L:20/15	R:15J1 L:20J2	R:20J2 L:30J4	right	140’	None 200’	No
44	A4 O9	21	Intermittent strabismus?	-	Exophoria	-	R: 20/13 L: 20/15	R: 15J1 L: 15J1	R: 20J2 L: 15J1	right	40’	480’ 400’	No

Coding starting with “00” indicates participants tested in Florida, USA. Coding starting with “A” indicates participants tested in Abertay, Dundee. All subjects were tested in both experiments 3.1 and 3.2.

Stereo-normal subjects

Nr.	Code	Age	Disorder history	Onset	Deviation at time of testing	Correction	Visual acuity			Dom eye	Stereovision		Colour def
							Far	Near	Monitor		Fly	TNO/ RanDot	
30	C8	19	none	-	exophoria	-	R:20/13 L:20/15	R:15J1 L:15J1	R:20J2 L:20J2	right	40’	60’ 20’	no
32	C10	19	none	-	-	-	R:20/15 L:20/15	R:15J1 L:20J2	R:25J3 L:25J3	right	40’	120’ 70’	no

33	C11	23	none	-	-	-	R:20/13 L:20/13	R:15J1 L:15J1	R:20J2 L:20J2	right	40’	30’ 20’	no
34	C12	18	none	-	-	-	R:20/15 L:20/20	R:20J2 L:15J1	R:30J3 L:30J3	right	50’	240’ 30’	no
35	C13	23	none	-	-	-	R:20/13 L:20/13	R:15J1 L:15J1	R:20J2 L:20J2	right	40’	30’ 40’	no
36	C15	26	none	-	-	-	R:20/20 L:20/20	R:15J1 L:15J1	R:20J2 L:20J2	right	40’	30’ 50’	no
37	C16	20	none	-	-	-	R:20/13 L:20/13	R:15J1 L:15J1	R:25J3 L:20J2	right	40’	60’ 20’	No

Coding starting with “00” indicates participants tested in Florida, USA. Coding starting with “A” indicates participants tested in Abertay, Dundee. All subjects were tested in both experiments 3.1 and 3.2.

Anomalous stereovision subjects

Nr.	Code	Age	Disorder history	Onset	Deviation at time of testing	Correction	Visual acuity			Dom eye	Stereovision		Colour def
							Far	Near	Monitor		Fly	TNO/ RanDot	
16	CS6	27	Strabismus L eye	Infantile	L eye exotropia	Surgery 10y	R:20/20 L:20/26	R:15J1 L:15J1	R:20J2 L:20J2	Right	140’	120’	No
31	C9	23	none	-	exophoria	-	R:20/20 L:20/25	R:20J2 L:15J1	R:20J2 L:20J2	left	400’	120’ 70’	no

Coding starting with “00” indicates participants tested in Florida, USA. Coding starting with “A” indicates participants tested in Abertay, Dundee. All subjects were tested in both experiments 3.1 and 3.2.

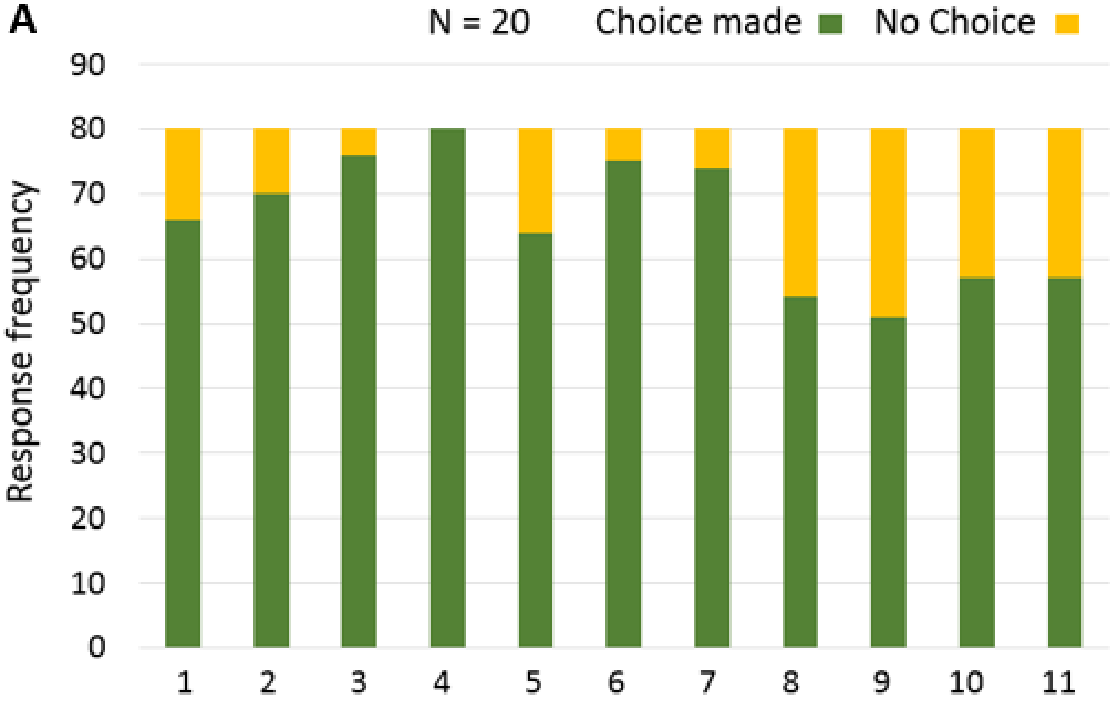
Appendix 3.8.

Supplementary data analysis for experiment 3.2 (experiment 2 chapter 3).

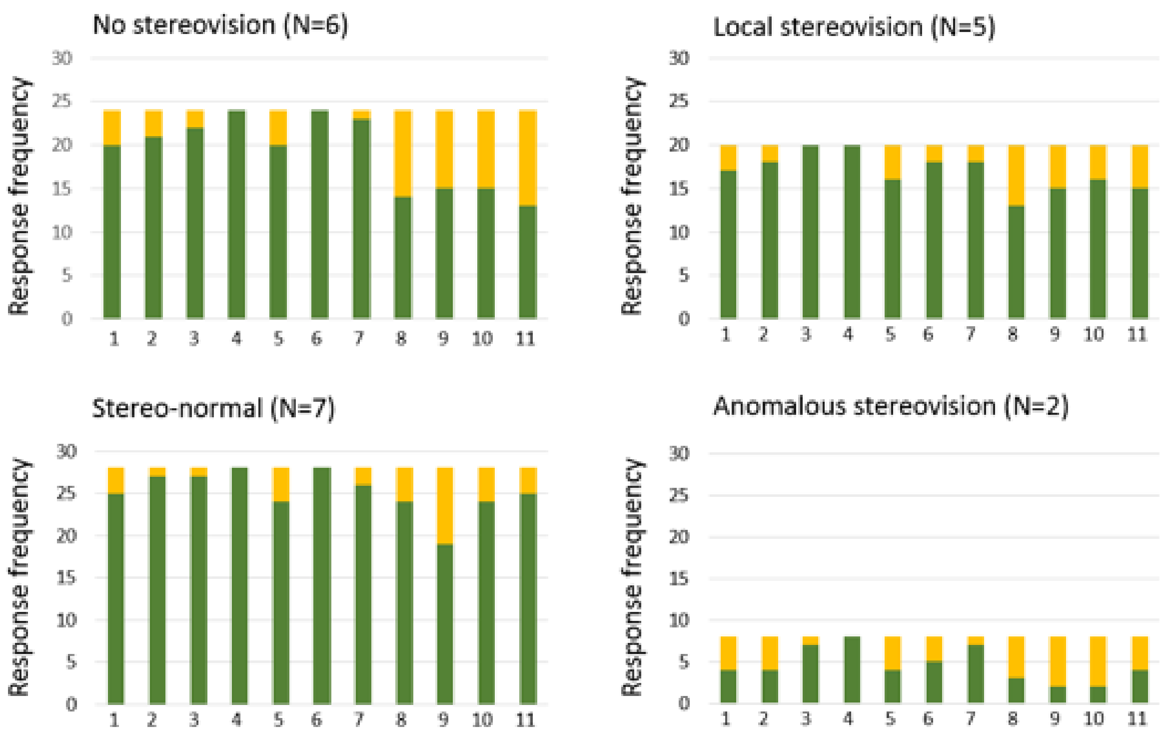
Summary of response frequencies for each of the 11 comparisons (panel C): choice was made (green) vs. no choice was made (yellow). A) Summarised for all participants, with the total possible response number 80. B) Summarised for each of the four participant classification groups, with the total possible response number varying according to the number of participants. The total number of possible choices for each of the 11 comparisons = 4 (number it was repeated for) * number of participants. C) Table with the corresponding comparisons and the percentage of trials in which choice was made (counted for all participants). Colour coding of the comparisons maintained in reference to prior tables in the main text.

No strong concerns raised, as in most cases percentage of responses in above 70%, with exception of comparison 8 and 9 (67.5% and 63.8%, respectively; see panel C). However, only comparison 4 had 100% of responses in all groups, whilst all over comparisons had trials in which the choice was not made. This is more prominent for comparisons involving only pictorial stimuli (comparisons 8, 9, 10, and 11), which indicates that participants experienced difficulty making their decision. On the other hand, even in comparison 3 - in which B-R viewing was always identified as providing better quality of depth by stereonormal, anomalous stereo, and local stereo subjects – stereonormal and anomalous stereovision subjects not always made a choice (27/28 and 7/8), which suggests that the task itself was quite challenging and may have allowed misperceptions due to a high number of consecutive trials requiring participants to remain highly sensitive.

A



B



C

	1	2	3	4	5	6	7	8	9	10	11
+	B-R	B-R	B-R	B-R	MA-R	M-R	MA-R	M-P	BA-P	MA-P	MA-P
-	BA-R	M-R	B-P	MA-P	M-R	MA-P	MA-P	B-P	B-P	M-P	BA-P
%	82.5	87.5	95.0	100	80	93.8	92.5	67.5	63.8	71.3	71.3

Appendix 4.1.

Matlab code for fitting psychometric function (based on the materials of the audited course PS4091 Computer-aided Research by Dr Dave Hunter):

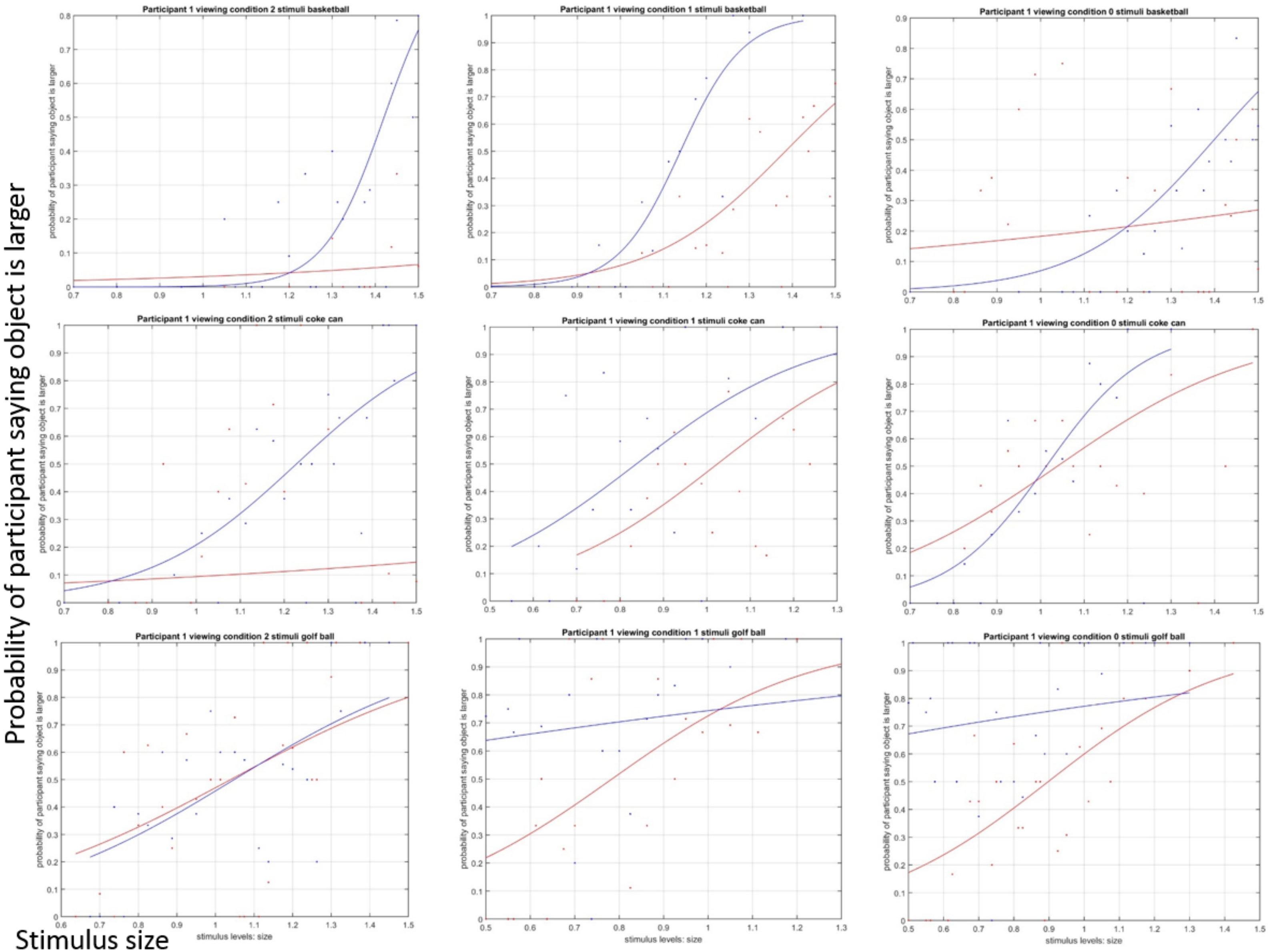
```
% Function equation

  ft=fittype('1./(1+exp(-(x-alpha)./beta))', 'independent', 'x', 'dependent', 'y');

    % Fitting funtion

    opts=fitoptions(ft);
    opts.Display='Off';
    opts.Lower=[-Inf 0 0 ];
    opts.Upper=[Inf 1 1];

    % Fit model to data

    [fitresult, gof] = fit(xData, yData, ft, opts);

% Results of function fitting
    F.threshold=fitresult.alpha;
    F.beta=fitresult.beta;
```

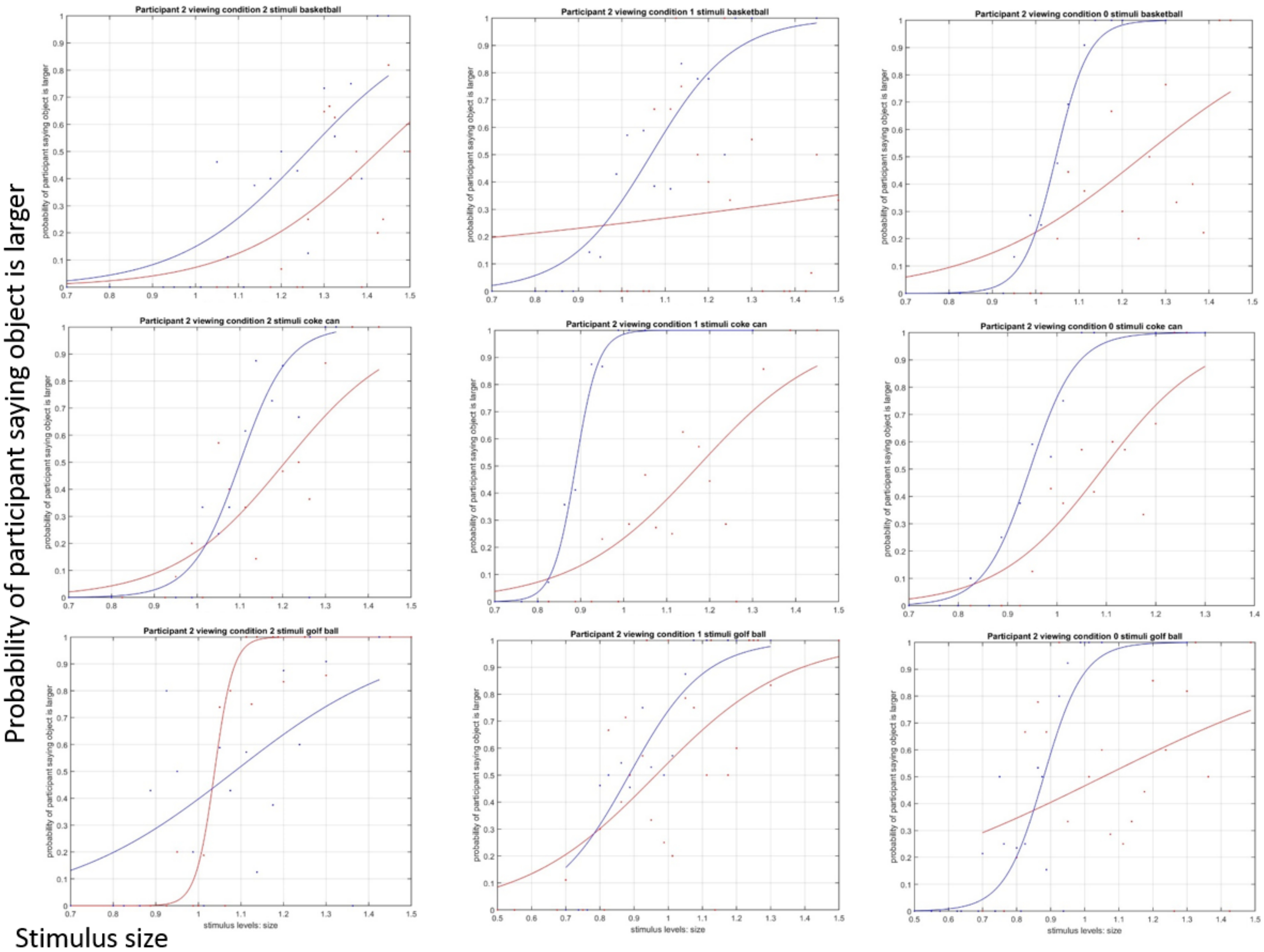
The obtained values were used to plot the following psychometric functions for all subjects.

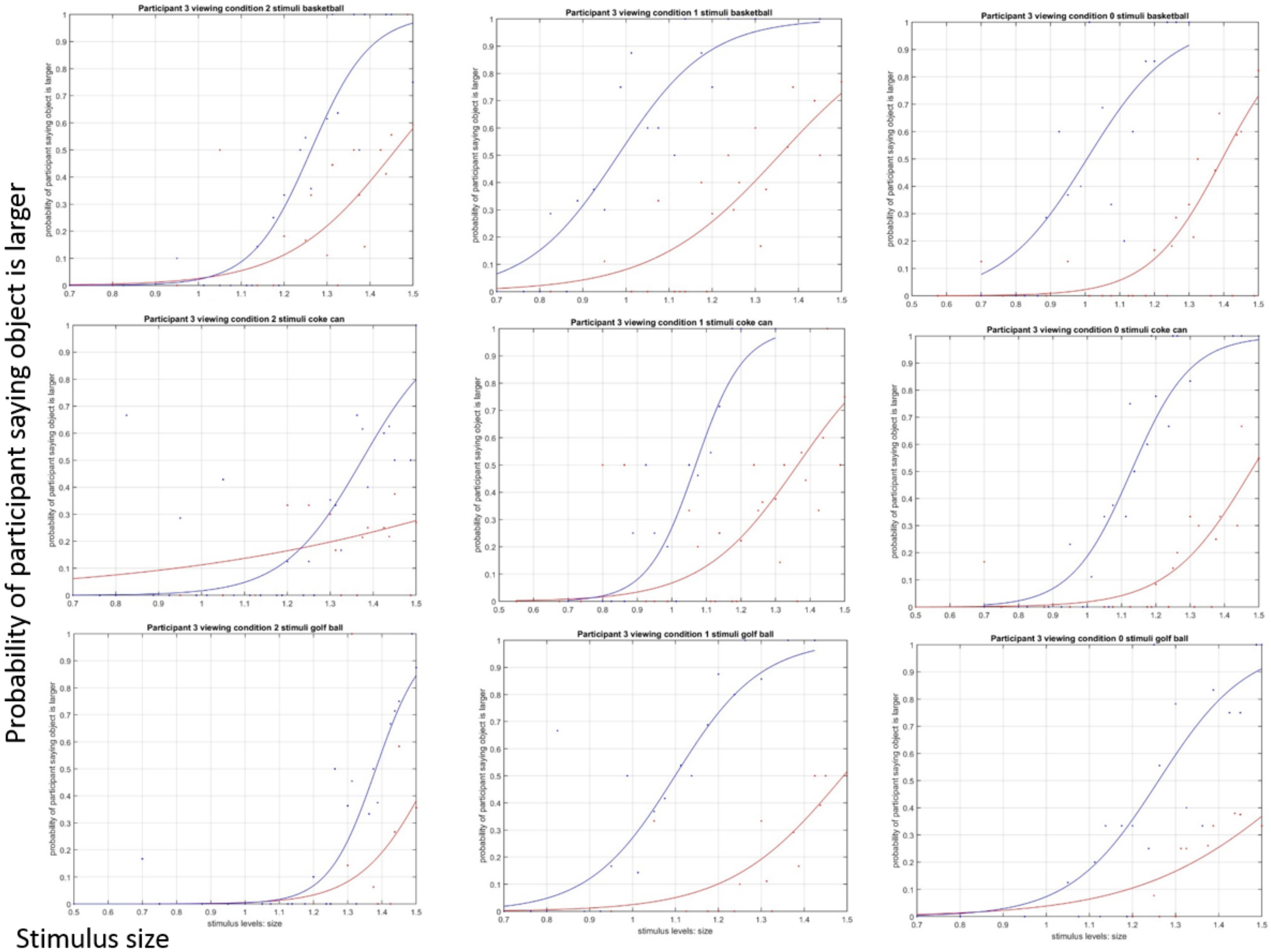
Subject numbers: 1-14, 19 – control stereonormal subjects; 15 and 17 – subjects with local binocular stereovision; 16, 20-23 – participants no measurable binocular stereovision.

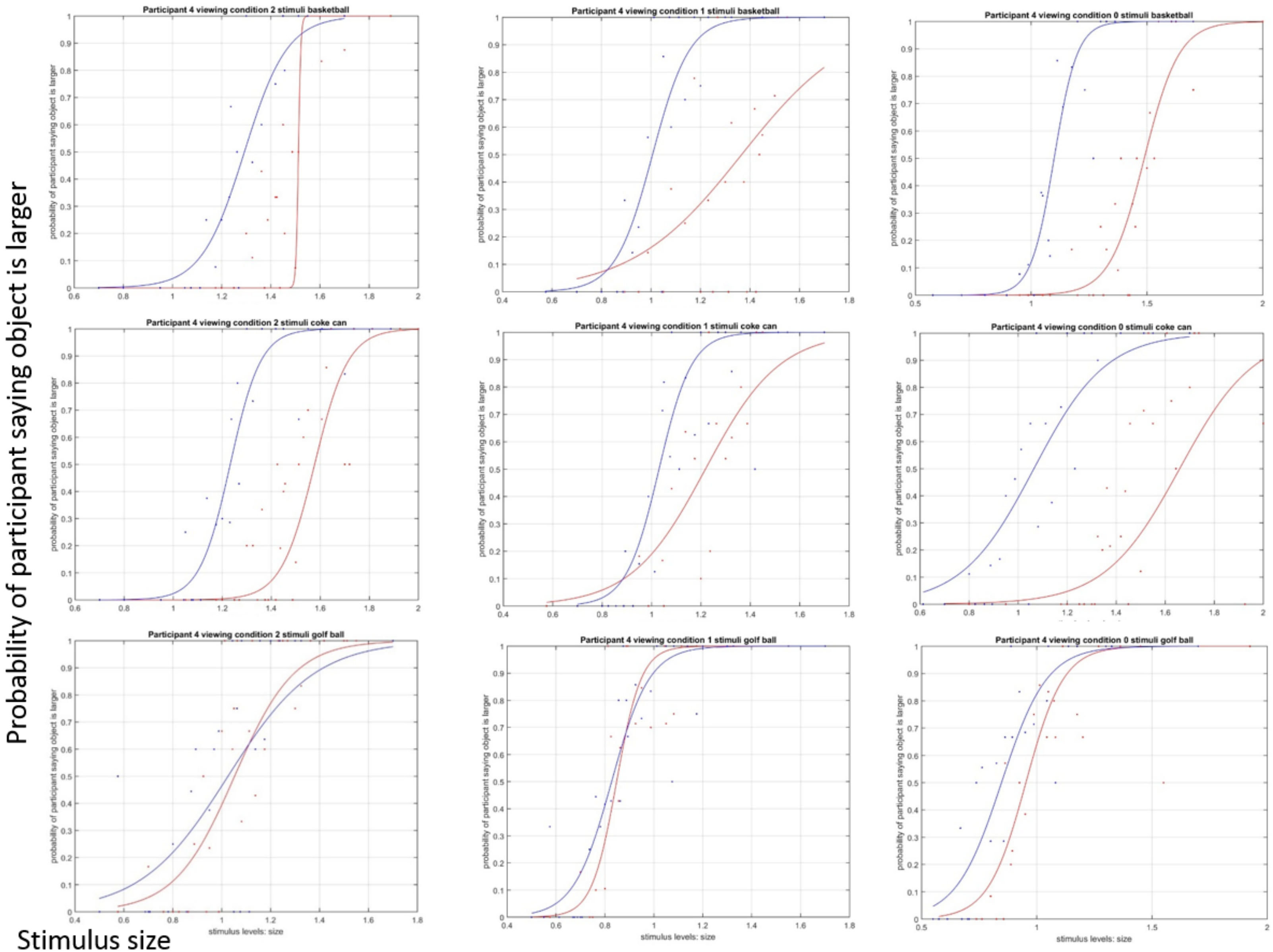
Viewing conditions: 2 – binocular-stereoscopic viewing; 1 – binocular-pictorial viewing; 0 – monocular pictorial viewing.

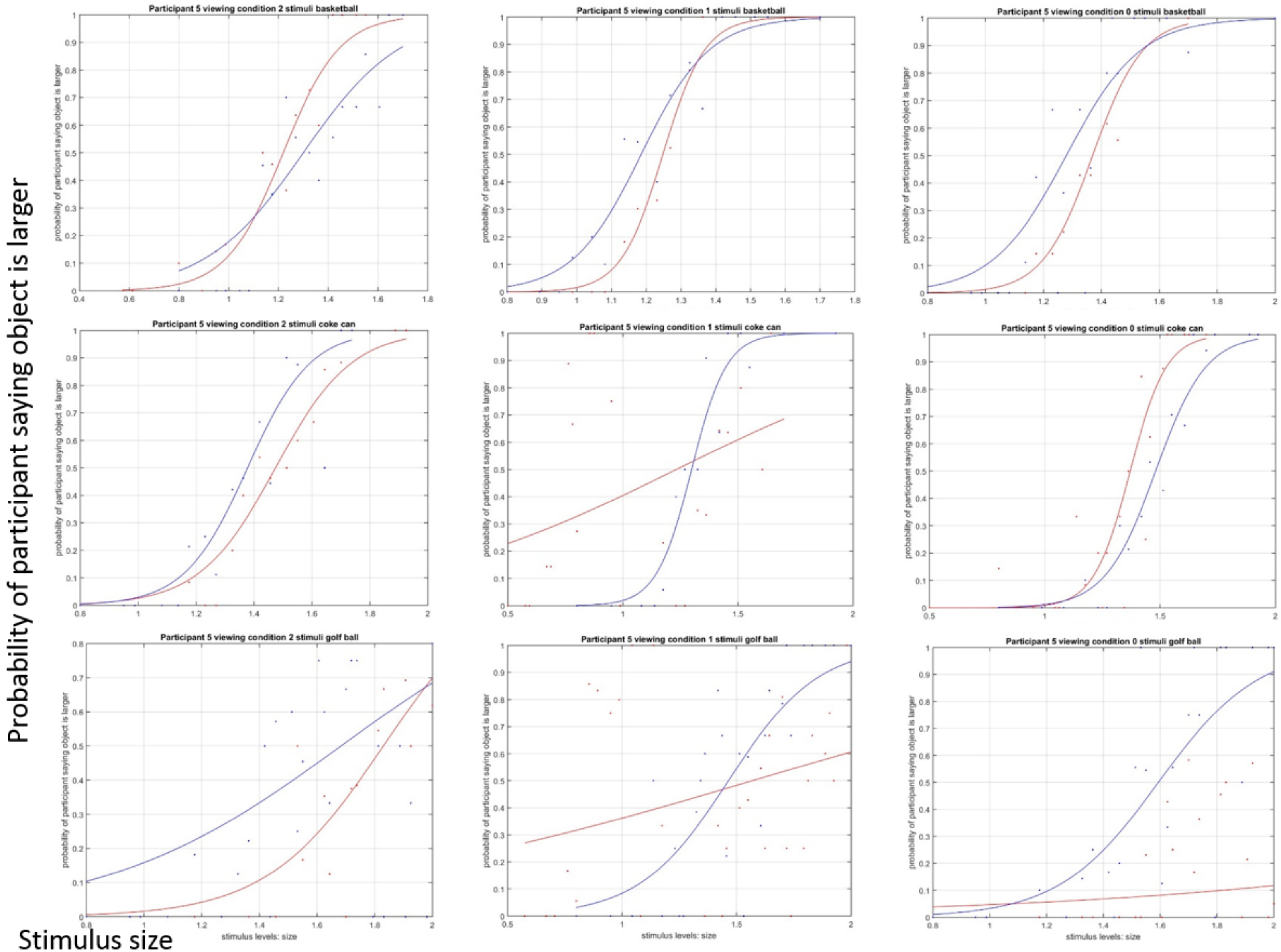
Blue function – 1.75m viewing distance. Red function – 3.5m viewing distance.

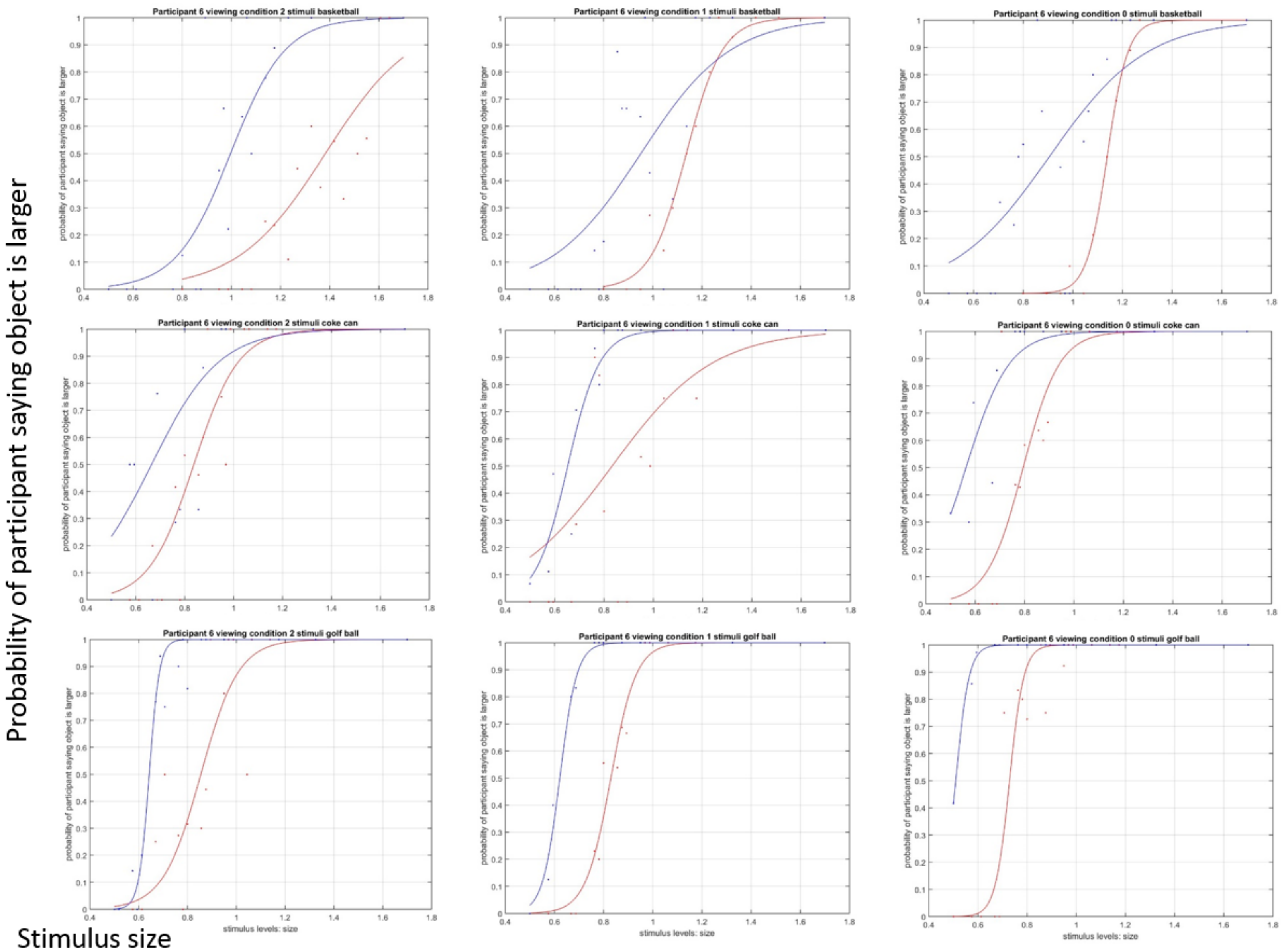

Participant 1 viewing condition 2 stimuli basketball
Participant 1 viewing condition 1 stimuli basketball
Participant 1 viewing condition 0 stimuli basketball
Participant 1 viewing condition 2 stimuli coke can
Participant 1 viewing condition 1 stimuli coke can
Participant 1 viewing condition 0 stimuli coke can
Participant 1 viewing condition 2 stimuli golf ball
Participant 1 viewing condition 1 stimuli golf ball
Participant 1 viewing condition 0 stimuli golf ball
probability of participant saying object is larger
stimulus levels: size
Probability of participant saying object is larger
Stimulus size

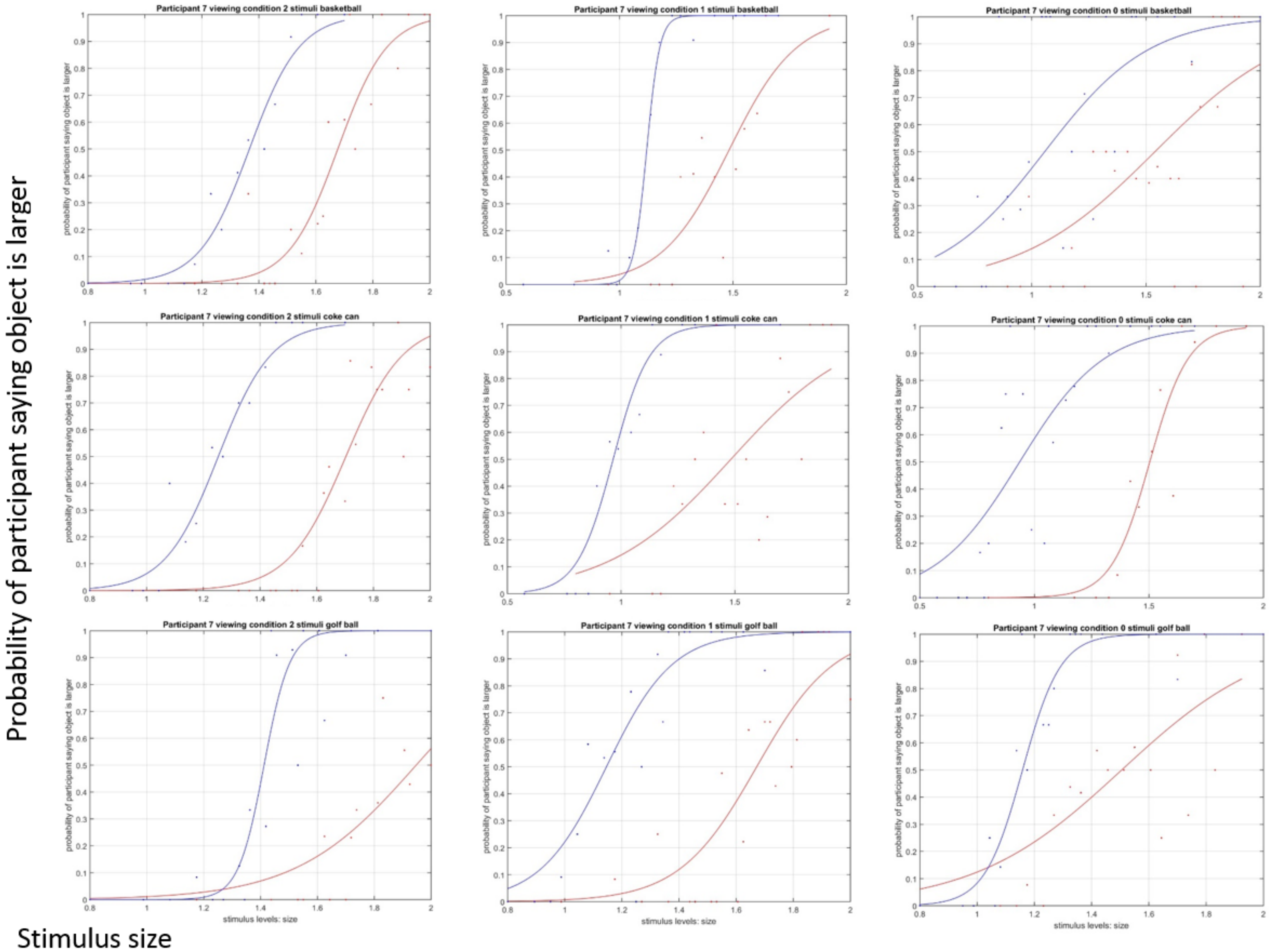

Probability of participant saying object is larger
Stimulus size
Participant 2 viewing condition 2 stimuli basketball
Participant 2 viewing condition 1 stimuli basketball
Participant 2 viewing condition 0 stimuli basketball
Participant 2 viewing condition 2 stimuli coke can
Participant 2 viewing condition 1 stimuli coke can
Participant 2 viewing condition 0 stimuli coke can
Participant 2 viewing condition 2 stimuli golf ball
Participant 2 viewing condition 1 stimuli golf ball
Participant 2 viewing condition 0 stimuli golf ball
probability of participant saying object is larger
stimulus levels: size

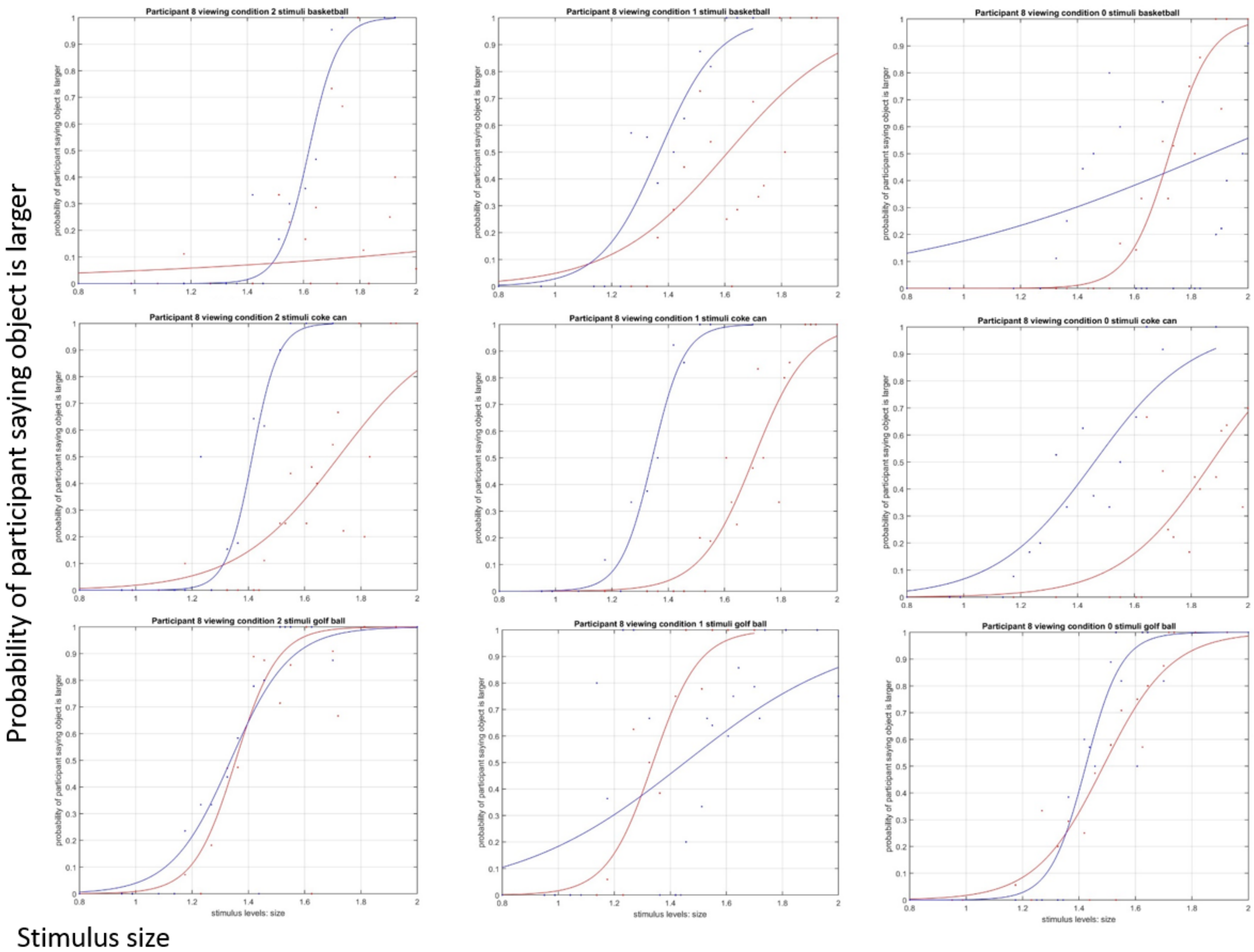

Participant 3 viewing condition 2 stimuli basketball
Participant 3 viewing condition 1 stimuli basketball
Participant 3 viewing condition 0 stimuli basketball
Participant 3 viewing condition 2 stimuli coke can
Participant 3 viewing condition 1 stimuli coke can
Participant 3 viewing condition 0 stimuli coke can
Participant 3 viewing condition 2 stimuli golf ball
Participant 3 viewing condition 1 stimuli golf ball
Participant 3 viewing condition 0 stimuli golf ball
probability of participant saying object is larger
stimulus levels: size
Probability of participant saying object is larger
Stimulus size

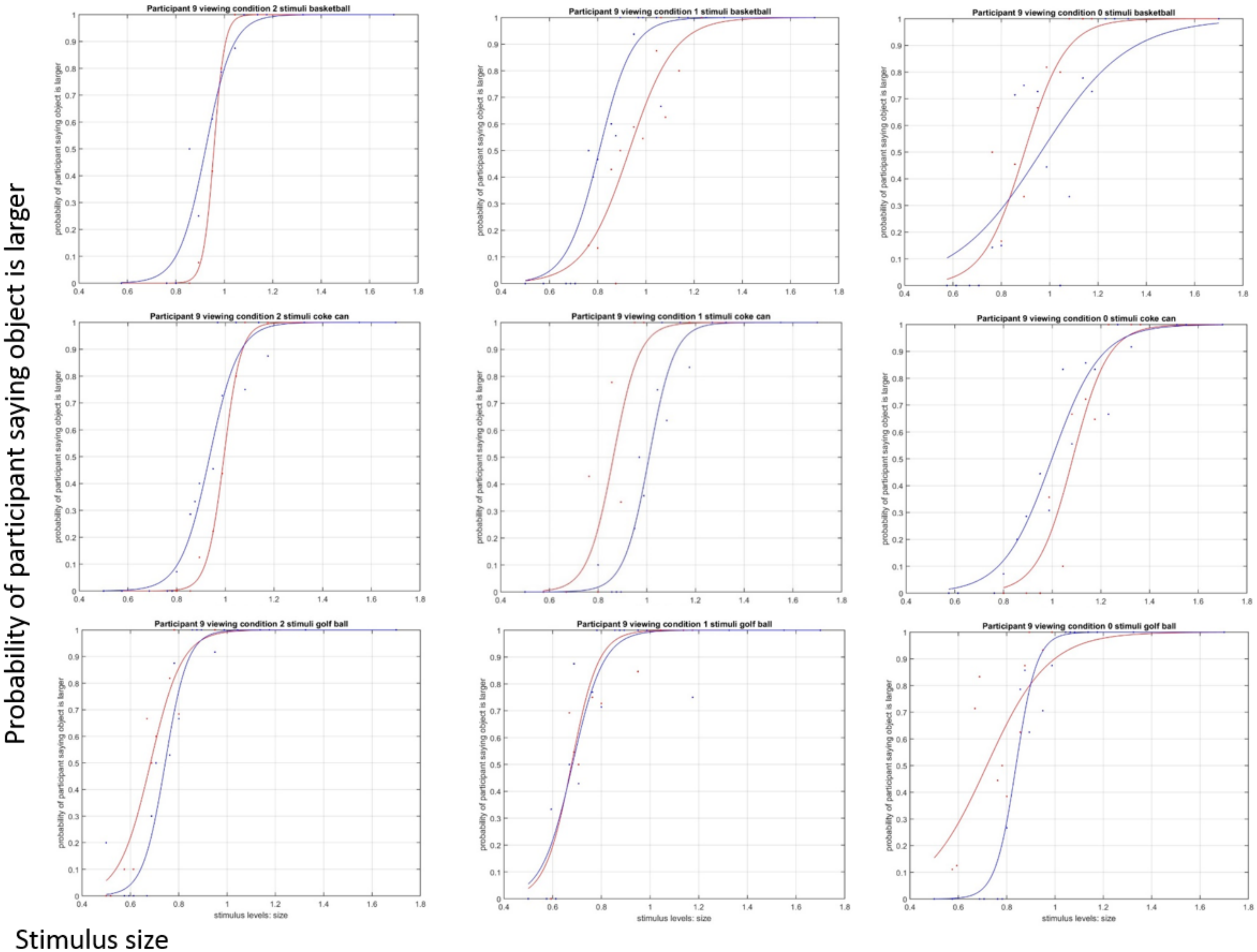

Participant 4 viewing condition 2 stimuli basketball
Participant 4 viewing condition 1 stimuli basketball
Participant 4 viewing condition 0 stimuli basketball
Participant 4 viewing condition 2 stimuli coke can
Participant 4 viewing condition 1 stimuli coke can
Participant 4 viewing condition 0 stimuli coke can
Participant 4 viewing condition 2 stimuli golf ball
Participant 4 viewing condition 1 stimuli golf ball
Participant 4 viewing condition 0 stimuli golf ball
probability of participant saying object is larger
stimulus levels: size
Probability of participant saying object is larger
Stimulus size

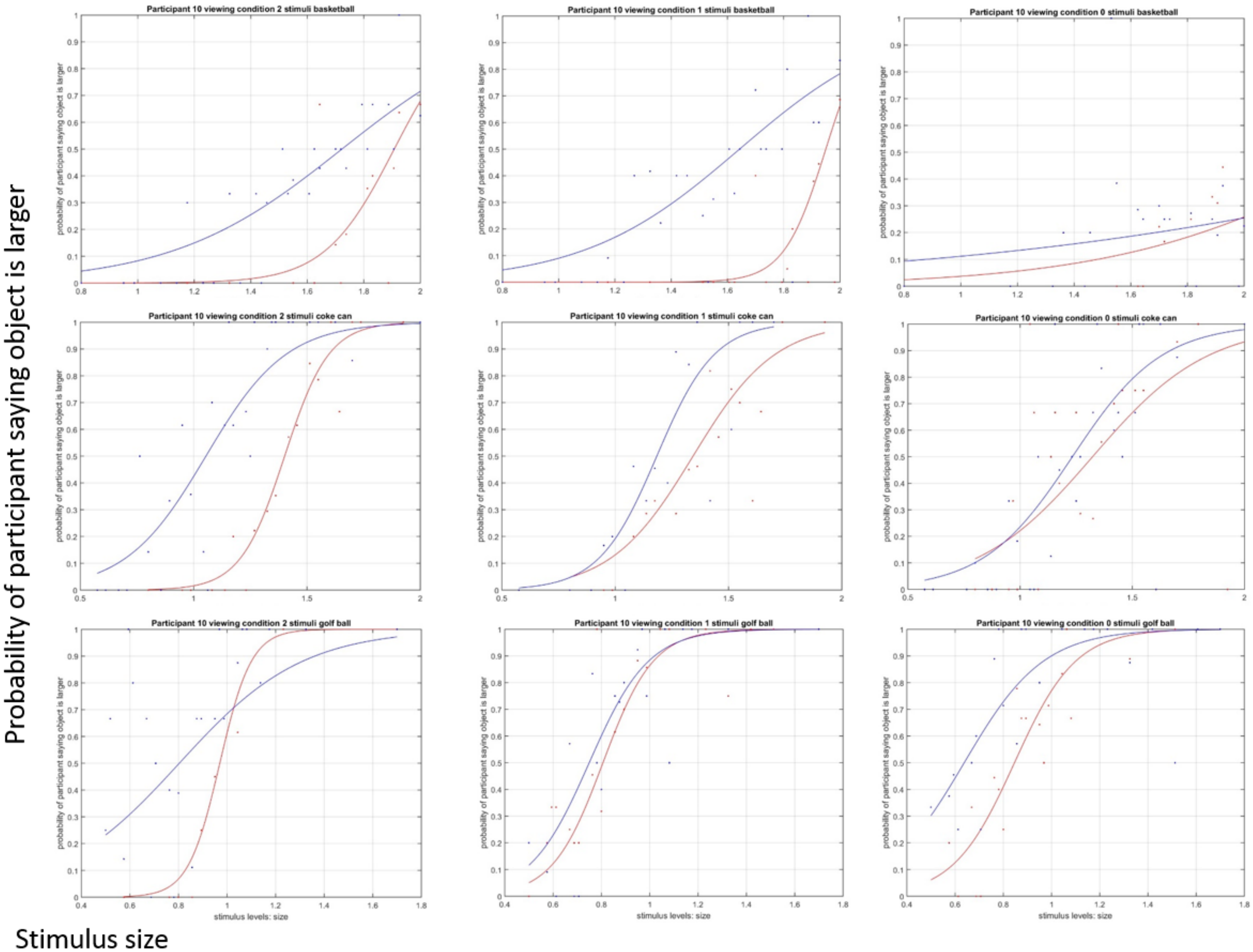

Probability of participant saying object is larger
Stimulus size
Participant 5 viewing condition 2 stimuli basketball
Participant 5 viewing condition 1 stimuli basketball
Participant 5 viewing condition 0 stimuli basketball
Participant 5 viewing condition 2 stimuli coke can
Participant 5 viewing condition 1 stimuli coke can
Participant 5 viewing condition 0 stimuli coke can
Participant 5 viewing condition 2 stimuli golf ball
Participant 5 viewing condition 1 stimuli golf ball
Participant 5 viewing condition 0 stimuli golf ball
probability of participant saying object is larger
stimulus levels: size

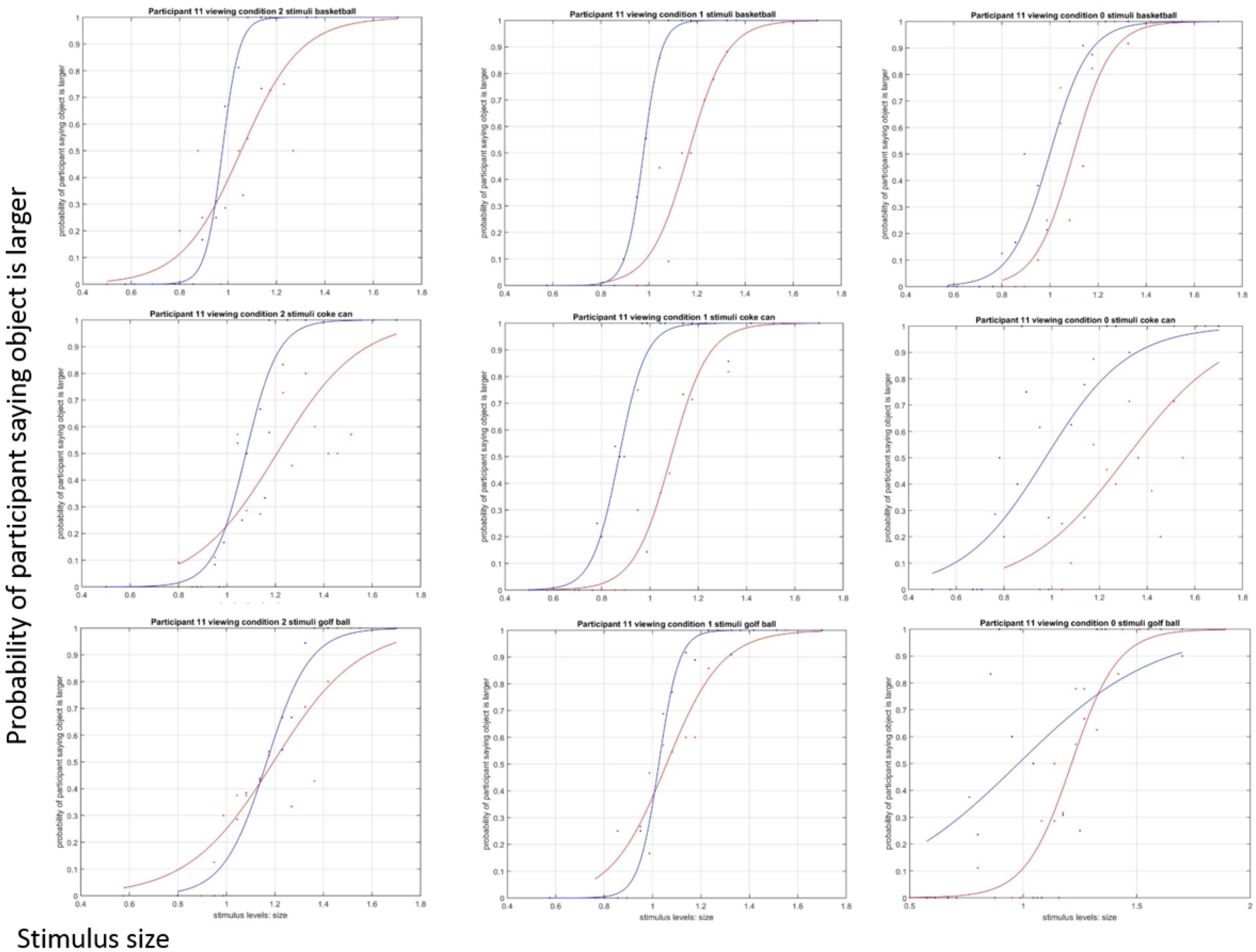

Probability of participant saying object is larger
Stimulus size
Participant 6 viewing condition 2 stimuli basketball
Participant 6 viewing condition 1 stimuli basketball
Participant 6 viewing condition 0 stimuli basketball
Participant 6 viewing condition 2 stimuli coke can
Participant 6 viewing condition 1 stimuli coke can
Participant 6 viewing condition 0 stimuli coke can
Participant 6 viewing condition 2 stimuli golf ball
Participant 6 viewing condition 1 stimuli golf ball
Participant 6 viewing condition 0 stimuli golf ball
probability of participant saying object is larger
stimulus levels: size

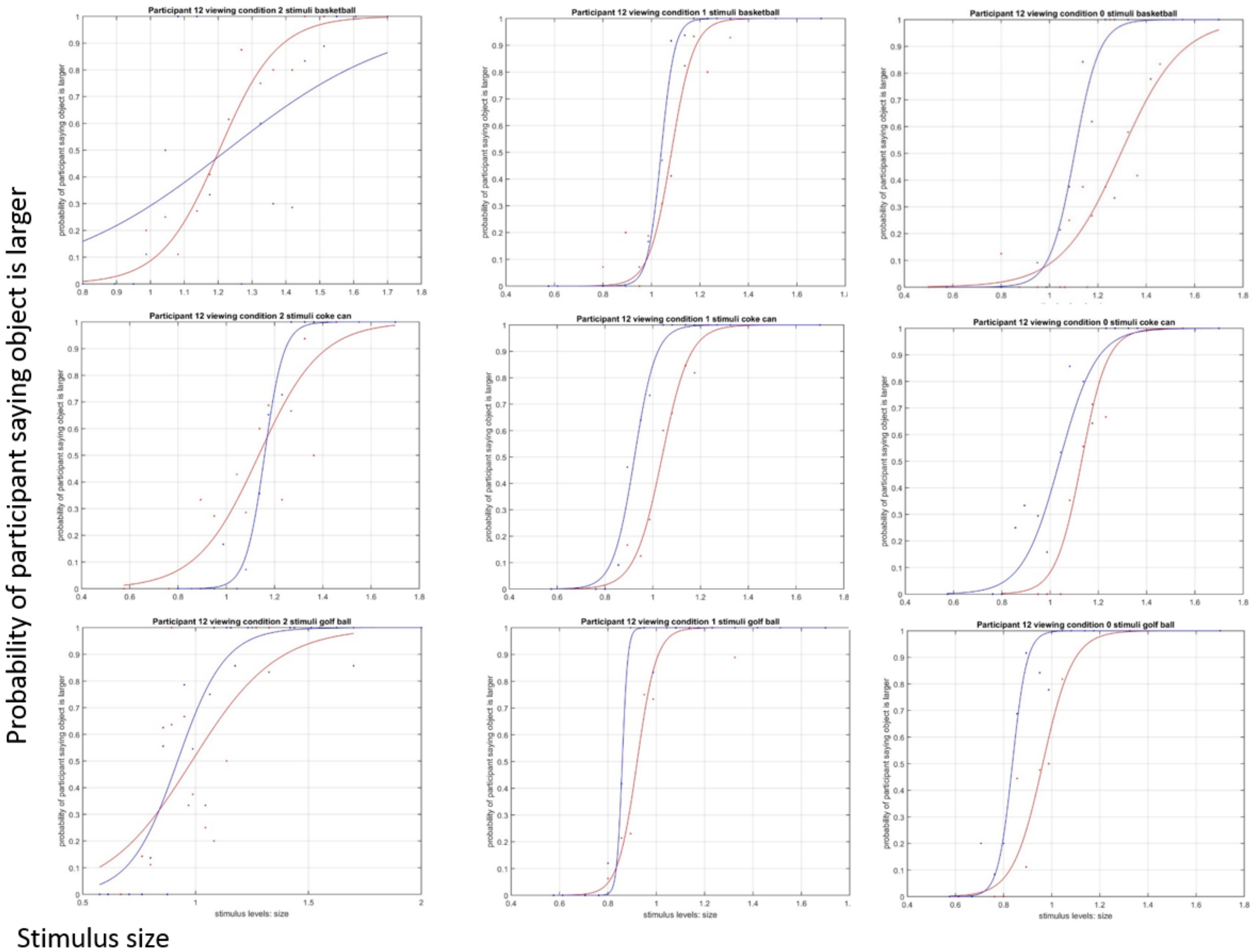

Probability of participant saying object is larger
Participant 7 viewing condition 2 stimuli basketball
Participant 7 viewing condition 1 stimuli basketball
Participant 7 viewing condition 0 stimuli basketball
Participant 7 viewing condition 2 stimuli coke can
Participant 7 viewing condition 1 stimuli coke can
Participant 7 viewing condition 0 stimuli coke can
Participant 7 viewing condition 2 stimuli golf ball
Participant 7 viewing condition 1 stimuli golf ball
Participant 7 viewing condition 0 stimuli golf ball
probability of participant saying object is larger
stimulus levels: size
Stimulus size

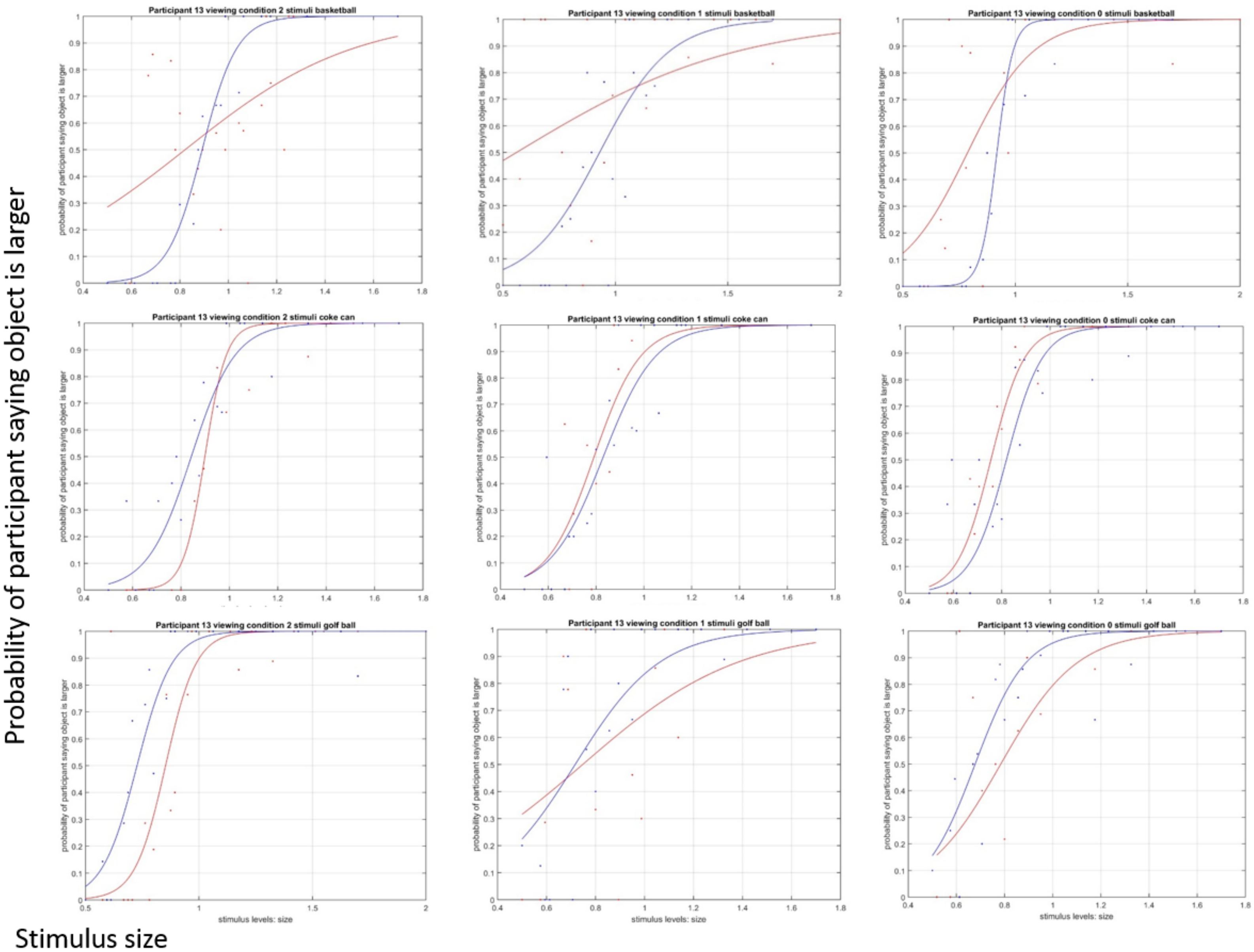

Participant 8 viewing condition 2 stimuli basketball
Participant 8 viewing condition 1 stimuli basketball
Participant 8 viewing condition 0 stimuli basketball
Participant 8 viewing condition 2 stimuli coke can
Participant 8 viewing condition 1 stimuli coke can
Participant 8 viewing condition 0 stimuli coke can
Participant 8 viewing condition 2 stimuli golf ball
Participant 8 viewing condition 1 stimuli golf ball
Participant 8 viewing condition 0 stimuli golf ball
probability of participant saying object is larger
stimulus levels: size
Probability of participant saying object is larger
Stimulus size

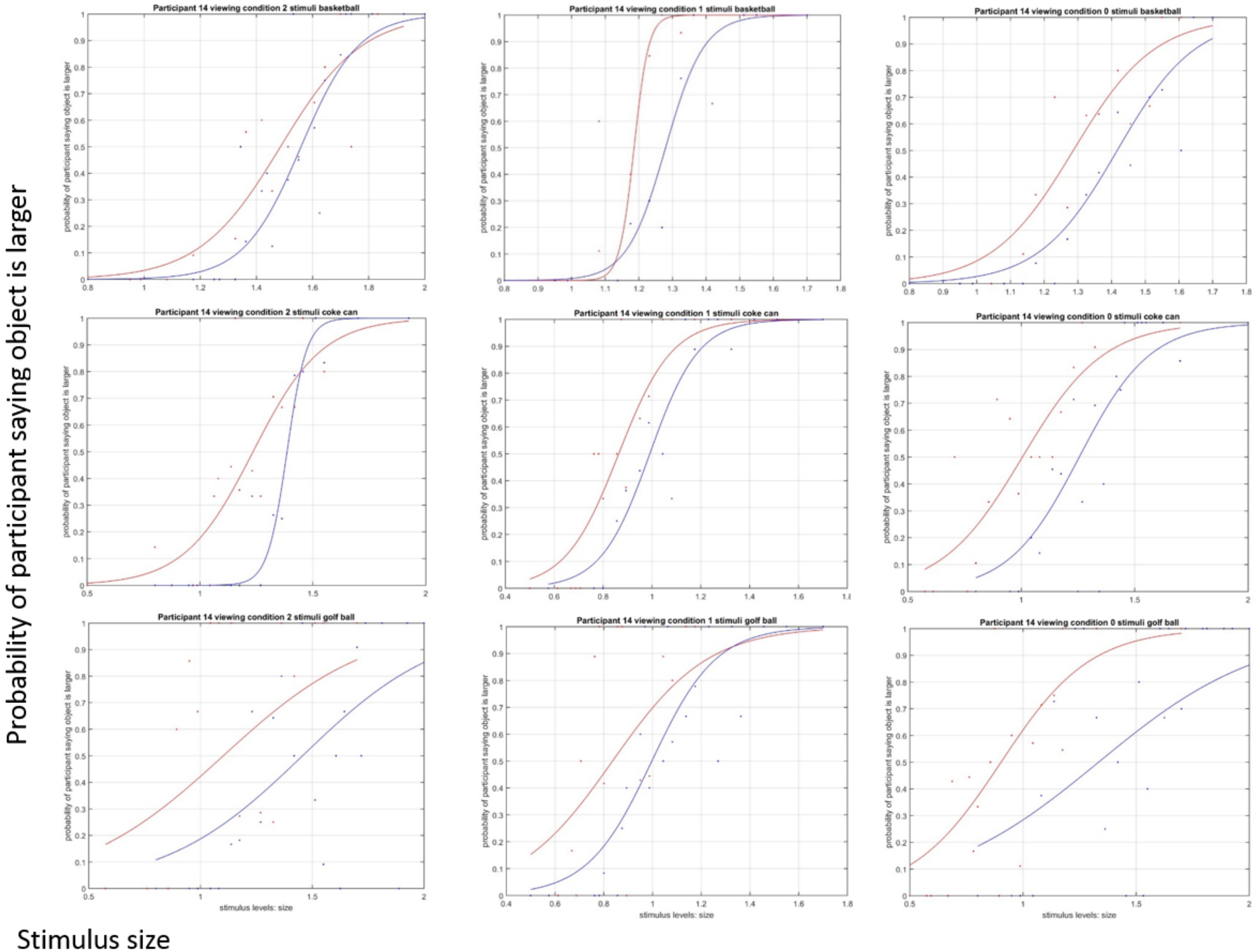

Participant 9 viewing condition 2 stimuli basketball
Participant 9 viewing condition 1 stimuli basketball
Participant 9 viewing condition 0 stimuli basketball
Participant 9 viewing condition 2 stimuli coke can
Participant 9 viewing condition 1 stimuli coke can
Participant 9 viewing condition 0 stimuli coke can
Participant 9 viewing condition 2 stimuli golf ball
Participant 9 viewing condition 1 stimuli golf ball
Participant 9 viewing condition 0 stimuli golf ball
probability of participant saying object is larger
stimulus levels: size
Probability of participant saying object is larger
Stimulus size

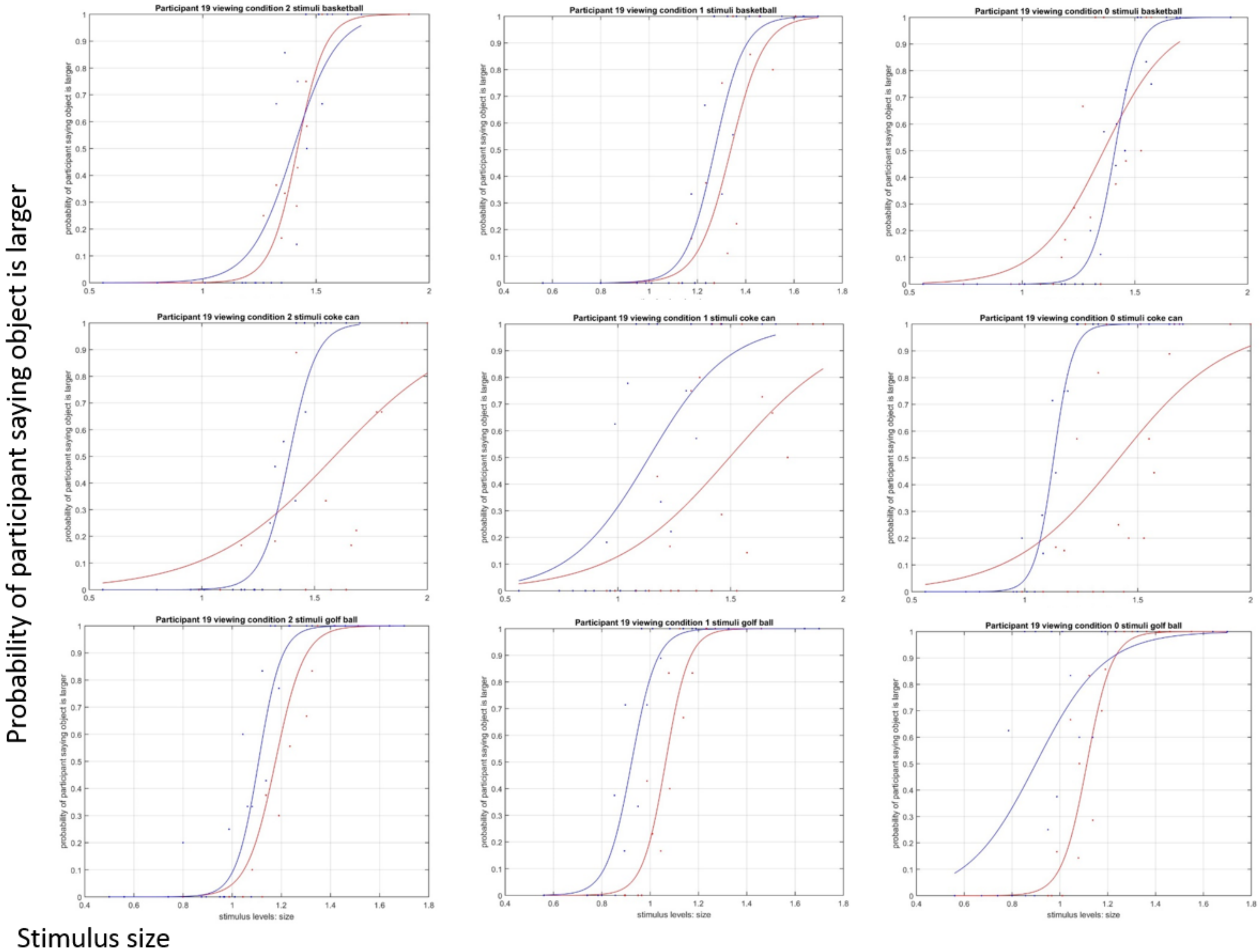

Probability of participant saying object is larger
Participant 10 viewing condition 2 stimuli basketball
Participant 10 viewing condition 1 stimuli basketball
Participant 10 viewing condition 0 stimuli basketball
Participant 10 viewing condition 2 stimuli coke can
Participant 10 viewing condition 1 stimuli coke can
Participant 10 viewing condition 0 stimuli coke can
Participant 10 viewing condition 2 stimuli golf ball
Participant 10 viewing condition 1 stimuli golf ball
Participant 10 viewing condition 0 stimuli golf ball
probability of participant saying object is larger
stimulus levels: size
Stimulus size

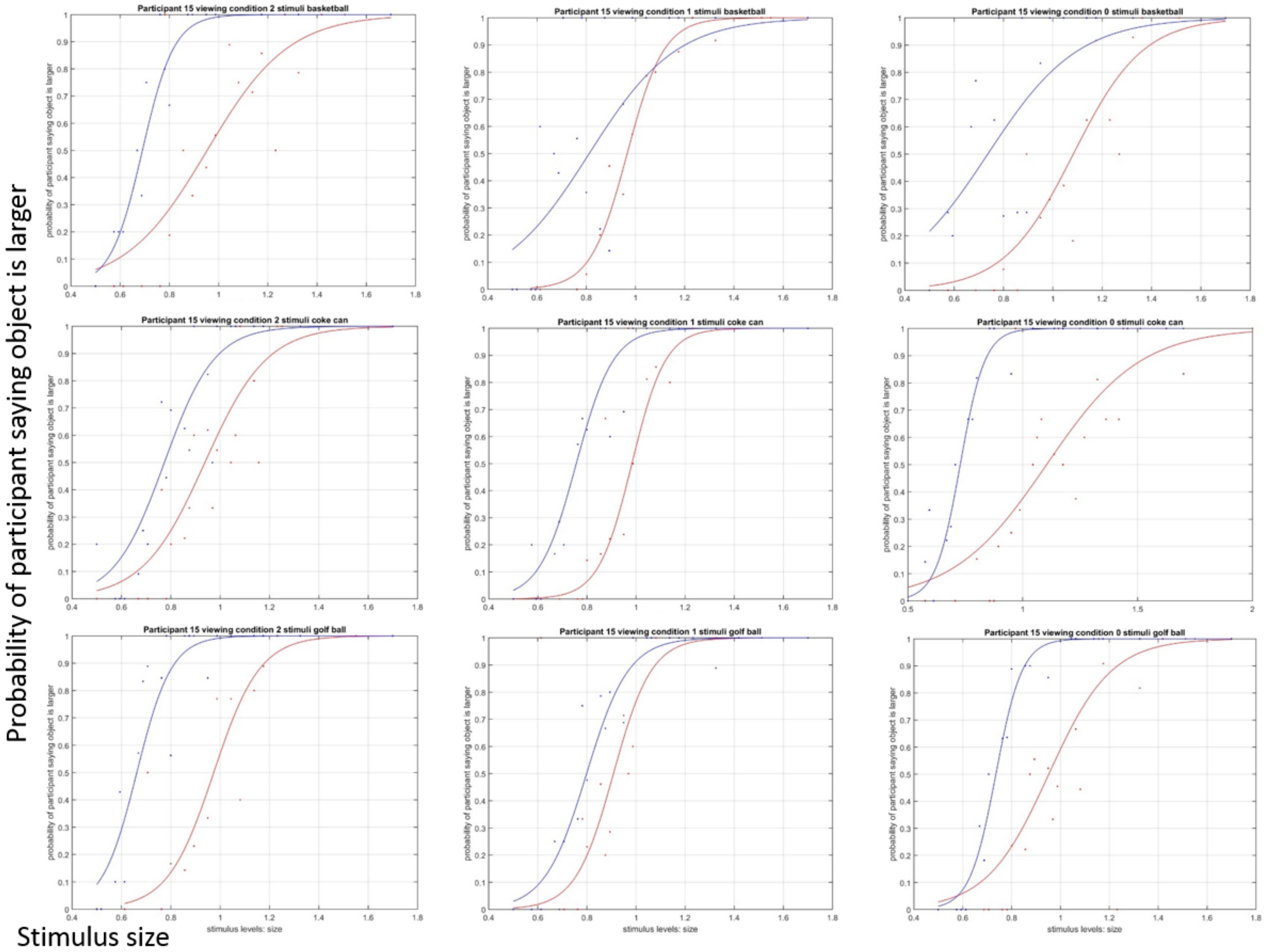

Probability of participant saying object is larger
Participant 11 viewing condition 2 stimuli basketball
Participant 11 viewing condition 1 stimuli basketball
Participant 11 viewing condition 0 stimuli basketball
Participant 11 viewing condition 2 stimuli coke can
Participant 11 viewing condition 1 stimuli coke can
Participant 11 viewing condition 0 stimuli coke can
Participant 11 viewing condition 2 stimuli golf ball
Participant 11 viewing condition 1 stimuli golf ball
Participant 11 viewing condition 0 stimuli golf ball
probability of participant saying object is larger
stimulus levels: size
Stimulus size


Participant 12 viewing condition 2 stimuli basketball
Participant 12 viewing condition 1 stimuli basketball
Participant 12 viewing condition 0 stimuli basketball
Participant 12 viewing condition 2 stimuli coke can
Participant 12 viewing condition 1 stimuli coke can
Participant 12 viewing condition 0 stimuli coke can
Participant 12 viewing condition 2 stimuli golf ball
Participant 12 viewing condition 1 stimuli golf ball
Participant 12 viewing condition 0 stimuli golf ball
probability of participant saying object is larger
stimulus levels: size
Probability of participant saying object is larger
Stimulus size

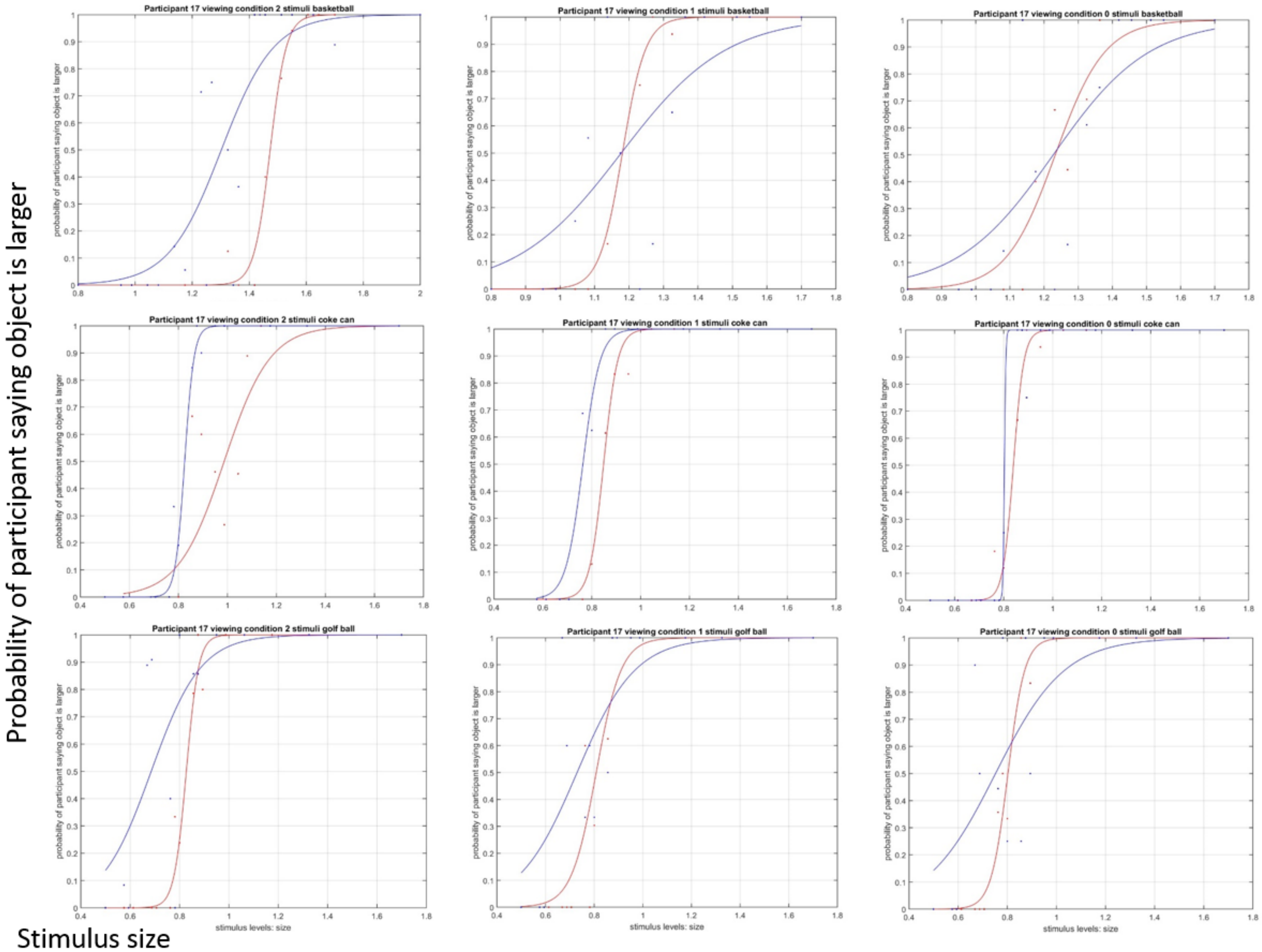

Probability of participant saying object is larger
Stimulus size
Participant 13 viewing condition 2 stimuli basketball
Participant 13 viewing condition 1 stimuli basketball
Participant 13 viewing condition 0 stimuli basketball
Participant 13 viewing condition 2 stimuli coke can
Participant 13 viewing condition 1 stimuli coke can
Participant 13 viewing condition 0 stimuli coke can
Participant 13 viewing condition 2 stimuli golf ball
Participant 13 viewing condition 1 stimuli golf ball
Participant 13 viewing condition 0 stimuli golf ball
probability of participant saying object is larger
stimulus levels: size


Participant 14 viewing condition 2 stimuli basketball
Participant 14 viewing condition 1 stimuli basketball
Participant 14 viewing condition 0 stimuli basketball
Participant 14 viewing condition 2 stimuli coke can
Participant 14 viewing condition 1 stimuli coke can
Participant 14 viewing condition 0 stimuli coke can
Participant 14 viewing condition 2 stimuli golf ball
Participant 14 viewing condition 1 stimuli golf ball
Participant 14 viewing condition 0 stimuli golf ball
probability of participant saying object is larger
stimulus levels: size
Probability of participant saying object is larger
Stimulus size

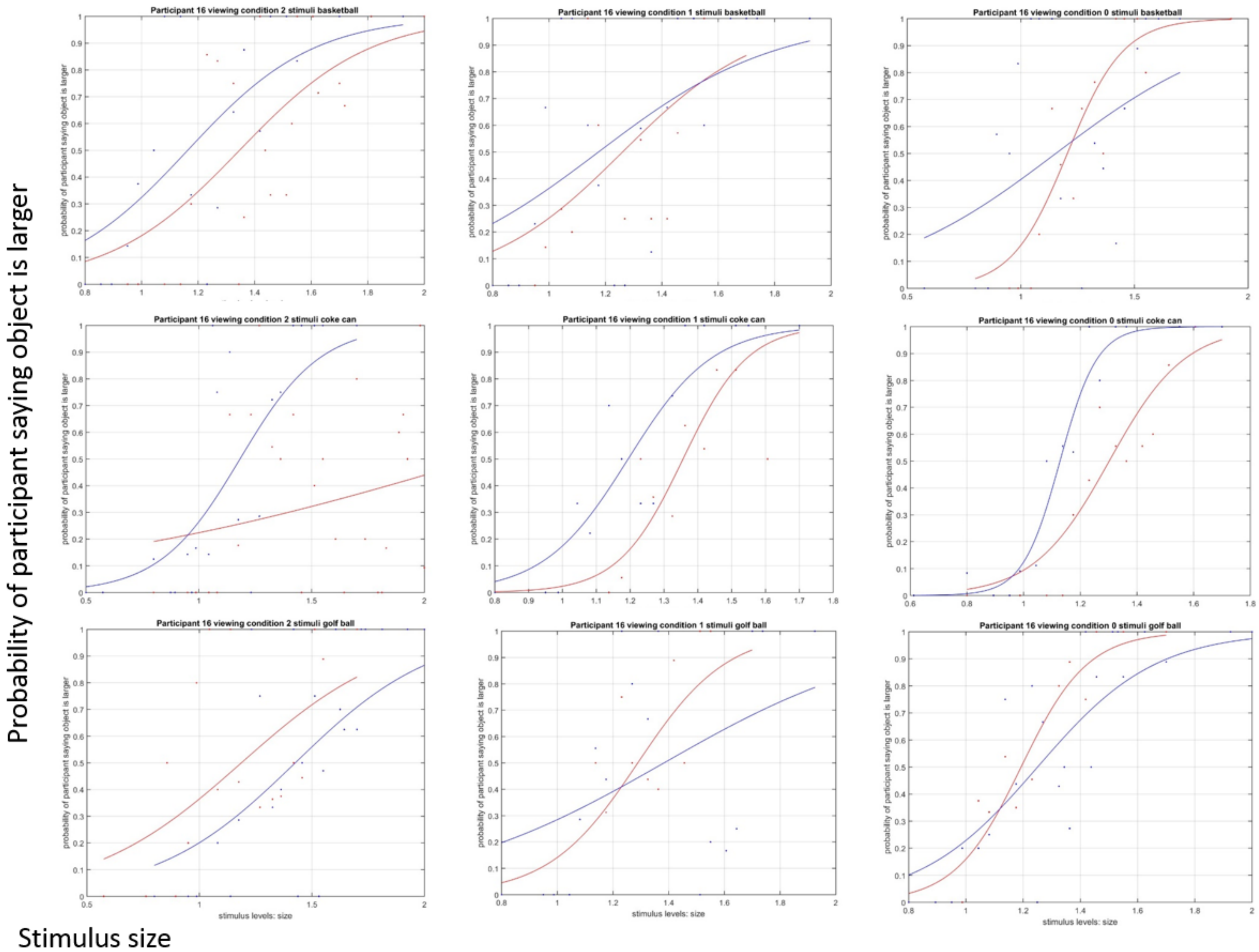

Probability of participant saying object is larger
Participant 19 viewing condition 2 stimuli basketball
Participant 19 viewing condition 1 stimuli basketball
Participant 19 viewing condition 0 stimuli basketball
Participant 19 viewing condition 2 stimuli coke can
Participant 19 viewing condition 1 stimuli coke can
Participant 19 viewing condition 0 stimuli coke can
Participant 19 viewing condition 2 stimuli golf ball
Participant 19 viewing condition 1 stimuli golf ball
Participant 19 viewing condition 0 stimuli golf ball
probability of participant saying object is larger
stimulus levels: size
Stimulus size

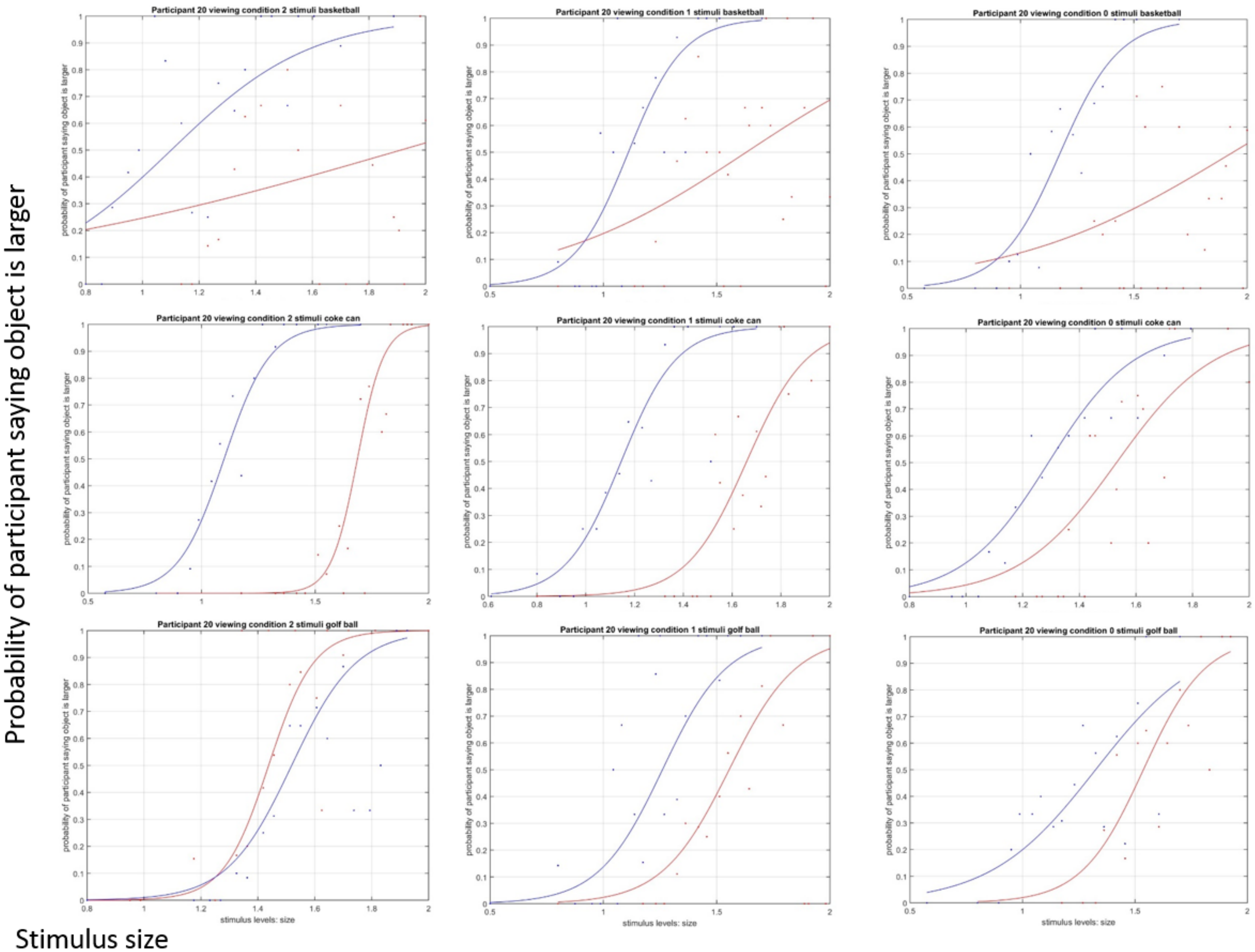


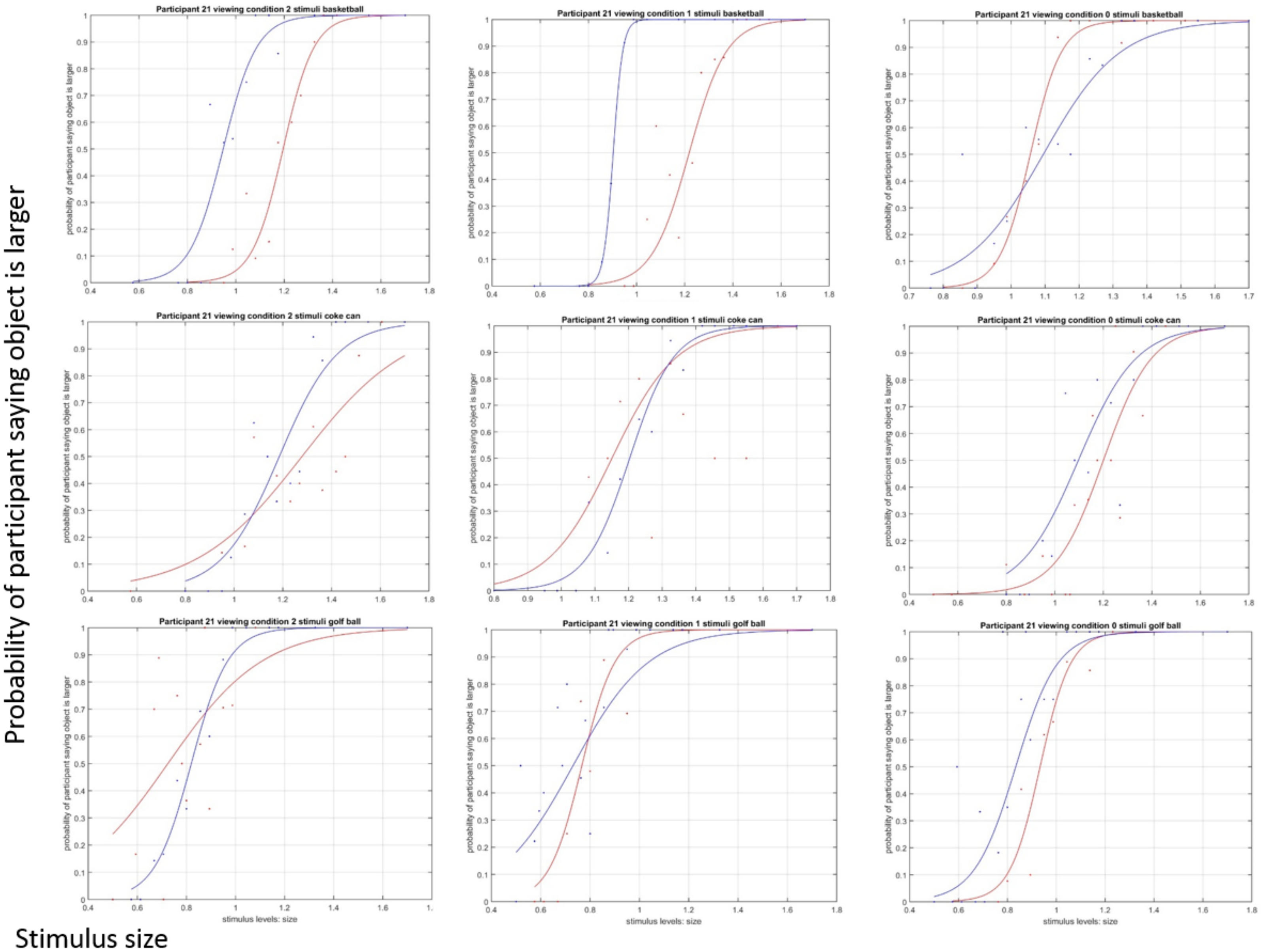
Probability of participant saying object is larger
Stimulus size
Participant 15 viewing condition 2 stimuli basketball
Participant 15 viewing condition 1 stimuli basketball
Participant 15 viewing condition 0 stimuli basketball
Participant 15 viewing condition 2 stimuli coke can
Participant 15 viewing condition 1 stimuli coke can
Participant 15 viewing condition 0 stimuli coke can
Participant 15 viewing condition 2 stimuli golf ball
Participant 15 viewing condition 1 stimuli golf ball
Participant 15 viewing condition 0 stimuli golf ball
probability of participant saying object is larger
stimulus levels: size

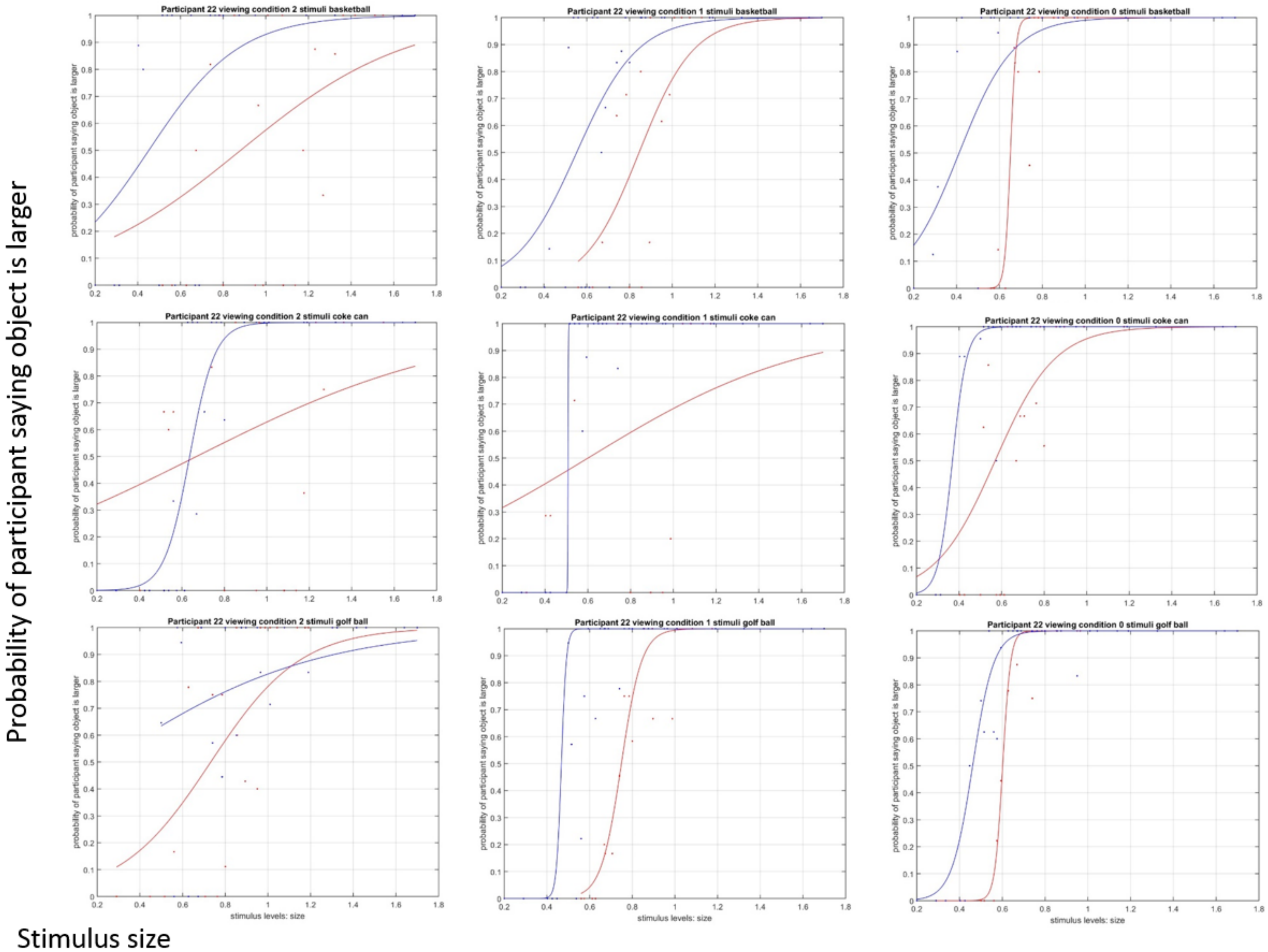


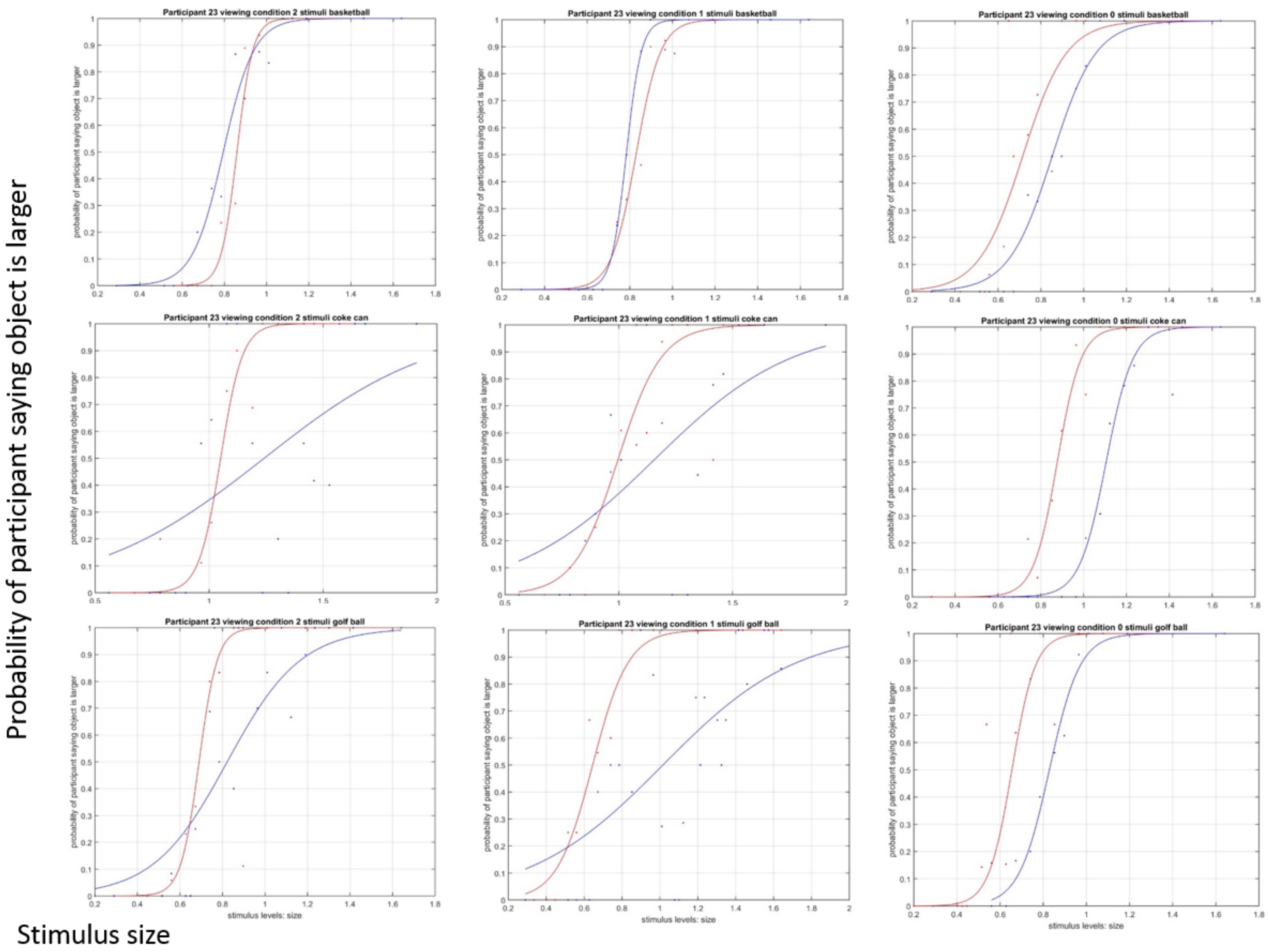
Probability of participant saying object is larger
Participant 17 viewing condition 2 stimuli basketball
Participant 17 viewing condition 1 stimuli basketball
Participant 17 viewing condition 0 stimuli basketball
Participant 17 viewing condition 2 stimuli coke can
Participant 17 viewing condition 1 stimuli coke can
Participant 17 viewing condition 0 stimuli coke can
Participant 17 viewing condition 2 stimuli golf ball
Participant 17 viewing condition 1 stimuli golf ball
Participant 17 viewing condition 0 stimuli golf ball
probability of participant saying object is larger
stimulus levels: size
Stimulus size


Probability of participant saying object is larger
Participant 16 viewing condition 2 stimuli basketball
Participant 16 viewing condition 1 stimuli basketball
Participant 16 viewing condition 0 stimuli basketball
Participant 16 viewing condition 2 stimuli coke can
Participant 16 viewing condition 1 stimuli coke can
Participant 16 viewing condition 0 stimuli coke can
Participant 16 viewing condition 2 stimuli golf ball
Participant 16 viewing condition 1 stimuli golf ball
Participant 16 viewing condition 0 stimuli golf ball
probability of participant saying object is larger
stimulus levels: size
Stimulus size


Probability of participant saying object is larger
Participant 20 viewing condition 2 stimuli basketball
Participant 20 viewing condition 1 stimuli basketball
Participant 20 viewing condition 0 stimuli basketball
Participant 20 viewing condition 2 stimuli coke can
Participant 20 viewing condition 1 stimuli coke can
Participant 20 viewing condition 0 stimuli coke can
Participant 20 viewing condition 2 stimuli golf ball
Participant 20 viewing condition 1 stimuli golf ball
Participant 20 viewing condition 0 stimuli golf ball
probability of participant saying object is larger
stimulus levels: size
Stimulus size


Participant 21 viewing condition 2 stimuli basketball
Participant 21 viewing condition 1 stimuli basketball
Participant 21 viewing condition 0 stimuli basketball
Participant 21 viewing condition 2 stimuli coke can
Participant 21 viewing condition 1 stimuli coke can
Participant 21 viewing condition 0 stimuli coke can
Participant 21 viewing condition 2 stimuli golf ball
Participant 21 viewing condition 1 stimuli golf ball
Participant 21 viewing condition 0 stimuli golf ball
probability of participant saying object is larger
stimulus levels: size
Probability of participant saying object is larger
Stimulus size


Participant 22 viewing condition 2 stimuli basketball
Participant 22 viewing condition 1 stimuli basketball
Participant 22 viewing condition 0 stimuli basketball
Participant 22 viewing condition 2 stimuli coke can
Participant 22 viewing condition 1 stimuli coke can
Participant 22 viewing condition 0 stimuli coke can
Participant 22 viewing condition 2 stimuli golf ball
Participant 22 viewing condition 1 stimuli golf ball
Participant 22 viewing condition 0 stimuli golf ball
probability of participant saying object is larger
stimulus levels: size
Probability of participant saying object is larger
Stimulus size


Participant 23 viewing condition 2 stimuli basketball
Participant 23 viewing condition 1 stimuli basketball
Participant 23 viewing condition 0 stimuli basketball
Participant 23 viewing condition 2 stimuli coke can
Participant 23 viewing condition 1 stimuli coke can
Participant 23 viewing condition 0 stimuli coke can
Participant 23 viewing condition 2 stimuli golf ball
Participant 23 viewing condition 1 stimuli golf ball
Participant 23 viewing condition 0 stimuli golf ball
probability of participant saying object is larger
stimulus levels: size
Probability of participant saying object is larger
Stimulus size

Appendix 4.2.

Experiment 4.1 (experiment 1 chapter 4) participant vision information table.

Control subjects

Nr.	Code	Age	Disorder history	Onset	Deviation at time of testing	Correction	Visual acuity			Dom eye	Stereovision		Colour def	IPD (cm)
							Far	Near	Monitor		Fly	TNO/ RanDot		
1.	P1	19	none	--	--	--	R: 20/10 L: 20/10	R: 15J1 L: 15J1	R:20 J2 L:20 J2	Right	40’	120’ 30’	No	5.8
2.	P2	22	none	--	--	--	R: 20/10 L: 20/10	R: 15 J1 L: 15 J1	R:20 J2 L:20 J2	Right	40’	60’ 25’	No	5.7
3.	P3	22	Short-sighted	--	--	Wore corrections	R: 20/10 L: 20/13	R: 15 J1 L: 15 J1	R:20 J2 L:20 J2	Right	60’	60’ 70’	No	6.1
4.	P4	21	none	--	--	--	R: 20/10 L: 20/10	R: 15 J1 L: 15 J1	R:20 J2 L:20 J2	Right	40’	60’ 20’	No	6.0
5.	P5	19	none	--	--	--	R:20/10 L:20/10	R:15 J1 L:15 J1	R:20J2 L:20J2	Right	40’	120’ 20’	No	5.5
6.	P6	20	none	--	--	--	R:20/10 L:20/10	R:15 J1 L:15 J1	R:15J1 L:15J1	Left	40’	60’ 30’	No	6.2
7.	P7	19	Short-sighted	--	--	Wore corrections	R:20/10 L:20/13	R:15 J1 L:15 J1	R:20J2 L:15J1	Right	40’	120’ 40’	No	5.5
8.	P8	19	Short-sighted	--	--	Wore corrections	R:20/13 L:20/15	R:20 J2 L:20 J2	R:20J2 L:25J3	Right	40’	240’ 200’	No	6.0
9.	P9	31	Short-sighted	--	--	Wore corrections	R:20/10 L:20/10	R:15J1 L:15J1	R:20J2 L:20J2	Right	40’	60’ 30’	No	6.0
10	P10	19	none	--	--	--	R:20/10 L:20/13	R:15J1 L:15J1	R:20J2 L:20J2	Right	40’	60’ 30’	No	5.5
11.	P11	19	none	--	--	--	R:20/10 L:20/10	R:15J1 L:15J1	R:20J2 L:20J2	Right	40’	15’ 25’	No	5.8

12.	P12	19	none	--	--	--	R:20/10 L:20/13	R:20J2 L:15J1	R:20J2 L:20J2	Right	40'	240' 70'	No	6.3
13.	P13	21	none	--	--	--	R:20/10 L:20/10	R:15J1 L:15J1	R:20J2 L:20J2	Left	40'	60' 20'	No	6.4
14.	P14	21	none	--	--	--	R:20/10 L:20/10	R:15J1 L:15J1	R:20J2 L:20J2	Left	40'	60' 20'	No	5.9
15.	P19	23	none	--	--	--	R:20/10 L:20/10	R:15J1 L:15J1	R:20J2 L:20J2	Right	40'	60' 25'	No	5.8

Subjects with no/limited binocular stereovision

Nr.	Code	Age	Disorder history	Onset	Deviation at time of testing	Correction	Visual acuity			Dom eye	Stereovision		Colour def	IPD (cm)
							Far	Near	Monitor		Fly	TNO/ RanDot		
1.	P15	21	Strabismus L esotropia	infantile	Exo/eso-phoria	Surgery 6y; patching, glasses	R: 20/15 L: 20/13	R: 20J2 L: 15J1	R:25J3 L:20J2	Right	40'	None none	No	5.8
2.	P16 CS4	43	Strabismus R eye	Infantile	R eye esotropia	Surgery: ~1y; early patching	R: 20/15 L:20/10	R:50J8 L:15J1	R:50J8 L:20J2	Left	none	None None	No	5.8
3.	P17 O10	48	Amblyopia R eye	-	exophoria	Patching, corrective lens	R: 20/15 L: 20/13	R:60J10 L: 20J1	R:60J10 L: 25J3	Left	200'	None 400'	No	6.7
4.	P20 CS8	54	Strabismus R amblyopia	Infantile	R esotropia	Surgery: 4y; early patching	R:no L:20/13	R:no L:20J2	R:no L:25J3	Left	none	None None	No	6.0
5.	P21 O8	30	Intermittent strabismus	--	exophoria	-	R: 20/13 L: 20/13	R: 20J2 L: 20J2	R: 25J3 L: 20J2	Right	none	None None	no	5.4
6.	P22 CS 15	71	Esotropia	infantile	R exotropia exophoria	Surgery: 7-8y patching, vergence exercise	R: 20/100 L: 20/15	R: no L: 20J2	R: no L: 40J7	Left	400'	None None	no	5.9
7.	P23 CS 18	20	Esotropia L eye	infantile	L eso-hypotropia	Surgery: ~2y patching ~1y	R:20/10 L: 20/15	R: 15J1 L:20J2	R: 20 J2 L: 25 J3	Right	none	None None	no	5.9

8.	P24 CS 14	43	H esotropia L; current intermitted	infantile	Esophoria	Surgery: 8y vergence ex, patching	R: 20/10 L: 20/13	R: 30J4 L: 25J3	R: 25J3 L: 25J3	right	800'	None 400'	No	5.8

Local stereovision. Outliers eliminated from the analysis. Tested in both experiments 4.1 and 4.2.

Appendix 4.3.

Experiment 4.2 (experiment 2 chapter 4) participant vision information table.

Control subjects

Nr.	Code	Age	Disorder history	Onset	Deviation at time of testing	Correction	Visual acuity			Dom eye	Stereovision		Colour def	IPD (cm)
							Far	Near	Monitor		Fly	TNO/ RanDot		
1.	P1	22	Short-sighted	--	--	Wore corrections	R: 20/15 L: 20/20	R: 15J1 L: 15J1	R:20 J2 L:20 J2	Right	40'	60' 20'	No	6.0
2.	P2	25	none	--	--	--	R: 20/20 L: 20/13	R: 20 J2 L: 15 J1	R:20 J2 L:20 J2	Right	40'	60' 30'	No	6.5
3.	P3	21	Short-sighted	--	--	Wore corrections	R: 20/13 L: 20/10	R: 15 J1 L: 15 J1	R:20 J2 L:20 J2	Right	40'	30' 20'	No	5.7
4.	P4	29	Short-sighted	--	--	Wore corrections	R: 20/15 L: 20/13	R: 15 J1 L: 15 J1	R:20 J2 L:20 J2	Left	40'	60' 20'	No	6.3
5.	P5	22	Short-sighted	--	--	Wore corrections	R:20/15 L:20/13	R:15 J1 L:15 J1	R:20J2 L:20J2	Left	40'	60' 20'	No	5.9
6.	P6	21	Far-sighted	--	--	Wore corrections	R:20/13 L:20/10	R:15 J1 L:15 J1	R:20 J2 L:20 J2	Left	40'	60' 30'	No	5.6
7.	P7	26	Short-sighted	--	--	Wore corrections	R:20/13 L:20/13	R:15 J1 L:15 J1	R:20 J2 L:20 J2	Right	40'	60' 20'	No	5.9
8.	P8	27	Short-sighted	--	--	Wore corrections	R:20/10 L:20/13	R:15 J1 L:15 J1	R:20 J2 L:20 J2	Right	40'	30' 20'	No	6.5

9.	P14	25	Short-sighted	--	--	Wore corrections	R:20/20 L:20/15	R:15J1 L:20J2	R:20J2 L:20J2	Left	40’	60’ 20’	No	6.4
10	P18	19	none	--	--	--	R:20/13 L:20/15	R:15J1 L:15J1	R:25J3 L:20J2	Right	40’	60’ 20’	No	6.0
11.	P20	21	Short-sighted	--	--	Wore corrections	R:20/13 L:20/13	R:15J1 L:15J1	R:20J2 L:20J2	Right	40’	60’ 20’	No	5.5
12.	P21	19	none	--	--	--	R:20/13 L:20/13	R:15J1 L:15J1	R:20J2 L:20J2	Right	40’	120’ 30’	No	6.3
13.	P22	20	Short-sighted	--	--	Wore corrections	R:20/10 L:20/10	R:15J1 L:15J1	R:20J2 L:20J2	Right	40’	60’ 20’	No	6.0
14.	P23	19	Short-sighted	--	--	Wore corrections	R:20/10 L:20/10	R:15J1 L:15J1	R:20J2 L:20J2	Right	40’	120’ 20’	No	5.6
15.	P24	25	none	--	--	--	R:20/13 L:20/10	R:15J1 L:15J1	R:20J2 L:20J2	Left	40’	60’ 20’	No	5.8

Tested in Study 3 experiment 2, as subject nr. 7 and nr.24, respectively.

Subjects with no/limited binocular stereovision

Nr.	Code	Age	Disorder history	Onset	Deviation at time of testing	Correction	Visual acuity			Dom eye	Stereovision		Colour def	IPD (cm)
							Far	Near	Monitor		Fly	TNO/ RanDot		
1.	P9 CS 19	23	Strabismus L esotropia	Infantile	esophoria	Surgery 4 & 15y	R: 20/10 L: 20/13	R: 15J1 L: 15J1	R:20J2 L:20J2	Right	200’	480’ 200’	No	5.5
2.	P10 O10	48	Amblyopia R eye	-	exophoria	Patching, corrective lens	R: 20/15 L: 20/13	R:60J10 L: 20J1	R:60J10 L: 25J3	Left	200’	None 400’	No	6.7
3.	P11 O8	30	Intermittent strabismus	--	exophoria	-	R: 20/13 L: 20/13	R: 20J2 L: 20J2	R: 25J3 L: 20J2	Right	none	None None	No	5.1
4.	P12 CS8	54	Strabismus R amblyopia	Infantile	R esotropia	Surgery: 4y; early patching	R:no L:20/13	R:no L:20J2	R:no L:25J3	Left	none	None None	No	6.0

5.	P13 CS4	43	Strabismus R eye	Infantile	R eye esotropia	Surgery: ~1y; early patching	R: 20/15 L:20/10	R:50J8 L:15J1	R:50J8 L:20J2	Left	none	None None	No	5.8
6.	P15 CS3	31	Strabismus R esotropia	14	None	Surgery: 21 years	R:20/20 L:20/13	R:20J2 L:15J1	R:25J3 L:20J2	Left	140'	480' 200'	No	5.5
7.	P16 CS 20	20	L & R esotropia	Infantile	L esotropia esophoria	surgery ~11y & ~13y; patching (R eye); drops	R: 20/10 L: 20/13	R: 15 J1 L: 20 J2	R: 20J2 L: 20J2	right	none	None None	No	5.5
8.	P17 O12	21	R amblyopia Short-sighted	-	-	Patching 4/5 to 9/10 y	R: 20/20 L: 20/13	R: 40J7 L: 15J1	R: 50J8 L: 20J2	left	140'	480' None	No	6.3
9.	P19 O14	19	L amblyopia Far-sighted	Infantile	L exotropia	Glasses 3-14y; patching	R:20/10 L:20/15	R:15 J1 L:20 J2	R:20 J2 L:25 J3	Right	50'	None 70'	No	5.9
10.	P25 CS 21	45	esophoria	2 y	R esotropia esophoria	Surgery ~3.5y; before patching	R: 20/30 L: 20/15	R: no L: 40 J7	R: no L: 40 J7	left	400'	None None	No	5.4
11.	P27 CS 23	19	L & R esotropia R amblyopia short-sighted	infantile	R exo-hypotropia exo-hypophoria	Surgeries <1y; patching (L) & eye drops <5y	R: 20/25 L: 20/10	R: 30 J4 L: 15 J1	R: 50 J8 L: 20 J2	left	200'	None None	No	6.3

Tested in both experiments 4.1 and 4.2.

Participant 26 was recruited as a control, but had really poor visual acuity due to short-sightedness and bad prescription, but no history of strabismus or amblyopia. Thus was not tested, and full vision info was not gathered. (Far distance R: 20/25; L: 20/20)

Appendix 5.1.

Experiment 5.1 (experiment 1 chapter 5) participant vision information table.

Control subjects

15 Control subjects were tested by a senior honours student as part of her undergraduate course completion. All 15 subjects had binocular stereoacuity of 20' according to the RanDot test. No other vision tests were used for these subjects. Subject number 2 was eliminated due to incomplete dataset. Subject number 3 and 15 were eliminated as outliers.

9 Additional control subjects were tested by the lead experimenter and the author of this thesis.

Nr.	Code	Age	Disorder history	Onset	Deviation at time of testing	Correction	Visual acuity			Dom eye	Stereovision		Colour def	IPD (cm)
							Far	Near	Monitor		Fly	TNO/ RanDot		
1.	P26	18	Short-sighted	--	--	Wore corrections	R: 20/13 L: 20/10	R:15 J1 L:15 J1	R:20 J2 L:20 J2	Right	40'	60' 20'	No	6.3
2.	P27	20	none	--	--	--	R: 20/15 L: 20/25	R:15 J1 L:15 J1	R:20 J2 L:20 J2	Right	40'	15' 20'	No	5.5
3.	P28	19	Short-sighted	--	--	Wore corrections	R: 20/25 L: 20/20	R:15 J1 L:15 J1	R:20 J2 L:20 J2	Right	60'	120' 20'	No	6.0
4.	P29	28	Short-sighted	--	--	Wore corrections	R: 20/13 L: 20/13	R:15 J1 L:15 J1	R:20 J2 L:20 J2	Right	40'	60' 20'	No	6.3
5.	P30	18	Short-sighted	--	--	Wore corrections	R:20/20 L:20/15	R:15 J1 L:15 J1	R:20 J2 L:20 J2	Right	40'	60' 25'	No	5.4
6.	P31	22	none	--	--	--	R:20/10 L:20/13	R:15 J1 L:15 J1	R:20 J2 L:20 J2	Left	40'	60' 20'	No	5.8
7.	P32	22	Short-sighted	--	--	Wore corrections	R:20/10 L:20/13	R:15 J1 L:15 J1	R:25 J3 L:20 J2	Right	40'	60' 20'	No	5.9

8.	P33	20	Short-sighted	--	--	Wore corrections	R:20/10 L:20/13	R:15 J1 L:15 J1	R:20 J2 L:20 J2	Left	40’	30’ 20’	No	4.9
9.	P34	22	none	--	--	--	R:20/10 L:20/10	R:15 J1 L:15 J1	R:20 J2 L:20 J2	Left	40’	60’ 20’	No	5.8

Outliers eliminated from the analysis.

Subjects with no/limited binocular stereovision

Nr.	Code	Age	Disorder history	Onset	Deviation at time of testing	Correction	Visual acuity			Dom eye	Stereovision		Colour def	IPD (cm)
							Far	Near	Monitor		Fly	TNO/ RanDot		
1.	**P9 O13**	27	L amblyopia Far-sighted	-	-	Patching 6/7 to 14	R: 20/10 L: 20/10	R: 15J1 L: 15J1	R: L:	right	200’	None None	no	5.8
2.	P11 O10	48	Amblyopia R eye	-	exophoria	Patching, corrective lens	R: 20/15 L: 20/13	R:60J10 L: 20J1	R:60J10 L: 25J3	left	200’	None None	No	
3.	P12 CS2	42	Strabismus R eye	Infantile	L eye hypertropia	Surgeries: 1-2, 11-12 years; patching & eye drops	R:20/15 L:20/13	R:20J2 L:20J2	R:20J2 L:20J2	Right	None	None None	No	
4.	P13 CS8	54	Strabismus R amblyopia	Infantile	R esotropia	Surgery: 4y; early patching	R:no L:20/13	R:no L:20J2	R:no L:25J3	Left	none	None None	No	6.0
5.	P14 CS4	43	Strabismus R eye	Infantile	R eye esotropia	Surgery: ~1y; early patching	R: 20/15 L:20/10	R:50J8 L:15J1	R:50J8 L:20J2	Left	none	None None	No	5.8
6.	P20 CS 18	20	Esotropia L eye	infantile	L eso- hypotropia	Surgery: ~2y patching ~1y	R:20/10 L: 20/15	R: 15J1 L:20J2	R: 20 J2 L: 25 J3	Right	none	None None	no	5.9
7.	P23 O11	18	Short-sighted	-	-	-	R: 20/15 L: 20/15	R: 30J4 L: 25J3	R: 40J7 L: 30J4	left	400’	240’ 100’	no	6.8
8.	P24 O12	21	R amblyopia Short-sighted	-	-	Patching 4/5 to 9/10 y	R: 20/20 L: 20/13	R: 40J7 L: 15J1	R: 50J8 L: 20J2	left	140’	480’ None	no	6.3

Limited binocular stereovision. **Non-naïve subject**. Tested in both experiments 5.1 and 5.2.

Appendix 5.2.

Experiment 5.2 (experiment 2 chapter 5) participant vision information table.

Control subjects

Nr.	Code	Age	Disorder history	Onset	Deviation at time of testing	Correction	Visual acuity			Dom eye	Stereovision		Colour def	IPD (cm)
							Far	Near	Monitor		Fly	TNO/ RanDot		
1.	P2	29	Short-sighted	--	--	Wore corrections	R: 20/15 L: 20/13	R:15 J1 L:15 J1	R:20 J2 L:20 J2	Left	40’	60’ 20’	No	6.0
2.	P3	19	Short-sighted	--	--	Wore corrections	R: 20/13 L: 20/13	R:15 J1 L:15 J1	R:20 J2 L:20 J2	Right	40’	60’ 20’	No	
3.	P7	27	Short-sighted	--	--	Wore corrections	R: 20/10 L: 20/13	R:15 J1 L:15 J1	R:20 J2 L:20 J2	Right	40’	30’ 20’	No	6.5
4.	P8	19	Short-sighted	--	--	Wore corrections	R: 20/13 L: 20/15	R:15 J1 L:15 J1	R:20 J2 L:20 J2	Left	40’	120’ 40’	No	
5.	P10	35	none	--	--	--	R:20/10 L:20/10	R:15 J1 L:15 J1	R:20 J2 L:20 J2	Right	40’	60’ 20’	No	
6.	P12	27	none	--	--	--	R:20/10 L:20/10	R:15 J1 L:15 J1	R:20 J2 L:20 J2	Right	40’	60’ 20’	No	
7.	P13	29	none	--	--	--	R:20/13 L:20/13	R:15 J1 L:15 J1	R:20 J2 L:20 J2	Right	40’	60’ 20’	No	5.3
8.	P15	28	Short-sighted	--	--	Wore corrections	R:20/13 L:20/13	R:15 J1 L:15 J1	R:20 J2 L:20 J2	Right	40’	60’ 20’	No	
9.	P16	25	Short-sighted	--	--	Wore corrections	R:20/20 L:20/15	R:15 J1 L:20 J2	R:20 J2 L:20 J2	Left	40’	60’ 20’	No	6.4
10	P23	24	Short-sighted	--	--	Wore corrections	R:20/10 L:20/10	R:15 J1 L:15 J1	R:20 J2 L:20 J2	Left	40’	60’ 20’	No	5.5
11.	P24	19	none	--	--	--	R:20/13 L:20/15	R:15 J1 L:15 J1	R:25 J3 L:20 J2	Right	40’	60’ 20’	No	6.0

12.	P25	19	Short-sighted	--	--	Wore corrections	R:20/10 L:20/10	R:15 J1 L:15 J1	R:20 J2 L:20 J2	Right	40’	30’ 20’	No

Incomplete dataset - eliminated from the analysis.

Subjects with no/limited binocular stereovision

Nr.	Code	Age	Disorder history	Onset	Deviation at time of testing	Correction	Visual acuity			Dom eye	Stereovision		Colo ur def	IPD (cm)
							Far	Near	Monitor		Fly	TNO/ RanDot		
1.	P9 O13	27	L amblyopia Far-sighted	-	-	Patching 6/7 to 14	R: 20/10 L: 20/10	R: 15J1 L: 15J1	R: L:	right	200’	None None	no	5.8
2.	P4 O12	21	R amblyopia Short-sighted	-	-	Patching 4/5 to 9/10 y	R: 20/20 L: 20/13	R: 40J7 L: 15J1	R: 50J8 L: 20J2	left	140’	480’ None	No	6.3
3.	P5 O8	30	Intermittent strabismus	--	exophoria	-	R: 20/13 L: 20/13	R: 20J2 L: 20J2	R: 25J3 L: 20J2	Right	none	None None	No	5.1
4.	P6 CS 19	23	Strabismus L esotropia	Infantile	esophoria	Surgery 4 & 15y	R: 20/10 L: 20/13	R: 15J1 L: 15J1	R:20J2 L:20J2	Right	200’	480’ 200’	No	5.5
5.	P9 CS3	31	Strabismus R esotropia	14	None	Surgery: 21 years	R:20/20 L:20/13	R:20J2 L:15J1	R:25J3 L:20J2	Left	140’	480’ 100’	No	5.5
6.	P11 O10	48	Amblyopia R eye	-	exophoria	Patching, corrective lens	R: 20/15 L: 20/13	R:60J10 L: 20J1	R:60J10 L: 25J3	Left	200’	None None	No	6.7
7.	P14 CS8	54	Strabismus R amblyopia	Infantile	R esotropia	Surgery: 4y; early patching	R:no L:20/13	R:no L:20J2	R:no L:25J3	Left	none	None None	No	6.0
8.	P17 CS2	42	Strabismus R eye	Infantile	L eye hypertropia	Surgeries: 1-2, 11-12 years; patching & eye drops	R:20/15 L:20/13	R:20J2 L:20J2	R:20J2 L:20J2	Right	None	None None	No	

9.	P18 MS3	24	L eye hypertropia	infantile	R eye hypertropia	Surgery 2y Patching 2-5y	R: 20/13 L: 20/15	R: 15J1 L: 15J1	R:20J2 L:20J2	Right	800'	None None	no	5.8
10.	P19 CS 20	20	L & R esotropia	Infantile	L esotropia esophoria	surgery ~11y & ~13y; patching (R eye); drops	R: 20/10 L: 20/13	R: 15 J1 L: 20 J2	R: 20J2 L: 20J2	right	none	None None	No	5.5
11.	P20 CS 21	45	esophoria	2 y	R esotropia esophoria	Surgery ~3.5y; before patching	R: 20/30 L: 20/15	R: no L: 40 J7	R: no L: 40 J7	left	400'	None None	No	5.4
12.	P21 CS 22	48	Esotropia R eye	Infantile	none	Surgery ~4y; patching & vergence ex	R: 20/20 L: 20/15	R: 20J2 L: 15J1	R: 40J7 L: 30J4	left	200'	480' 140'	no	
13.	P22 CS4	43	Strabismus R eye	Infantile	R eye esotropia	Surgery: ~1y; early patching	R: 20/15 L:20/10	R:50J8 L:15J1	R:50J8 L:20J2	Left	none	None None	No	5.8
14.	P26 CS 23	19	L & R esotropia R amblyopia short-sighted	infantile	R exo-hypotropia exo-hypophoria	Surgeries <1y; patching (L) & eye drops <5y	R: 20/25 L: 20/10	R: 30 J4 L: 15 J1	R: 50 J8 L: 20 J2	left	200'	None None	No	6.3

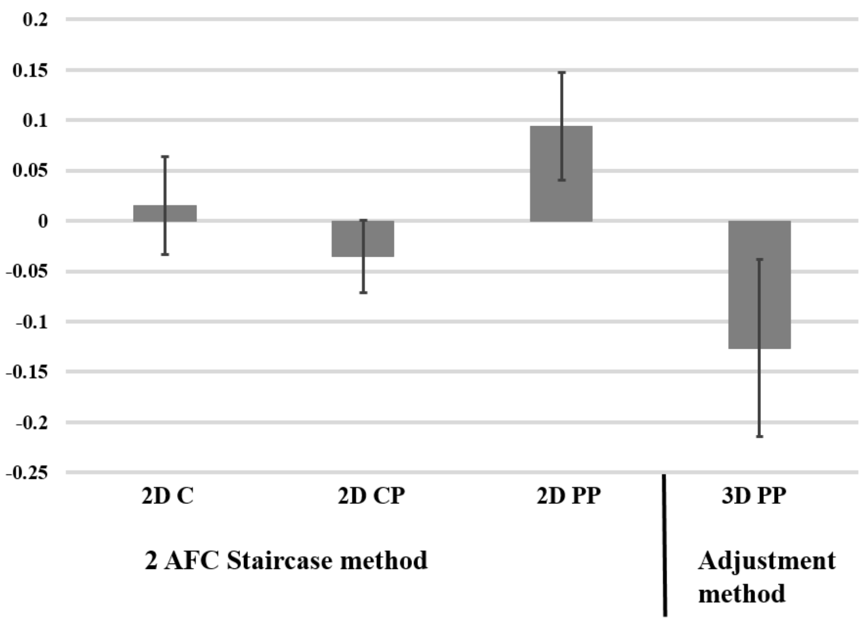
Limited binocular stereovision. Tested in both experiments 5.1 and 5.2. Outliers eliminated from the analysis. Non-naïve subject eliminated from analysis.

Appendix 5.3.

Supplementary data analysis for experiment 5.2 (experiment 2 chapter 5).

Average difference (average rations of experiment 5.2 – experiment 5.1) for the 5 participants who took part in both experiments. Only corresponding tasks and viewing conditions (binocular) were used from the experiment 5.2. Error bars indicate standard deviation of the mean.

The comparison of participants' data show that while performance in 2D C and CP staircase method tasks was similar between experiment 5.1 and 5.2, there were notable changes in participants' 2D and 3D interval equidistance judgments in Pictorial Perspective (PP) stimuli tasks. This establish that it was the changes in testing order and more explicit explanation of the tasks that crystallised the differences between the 2D PP and 3D PP conditions in experiment 5.2.



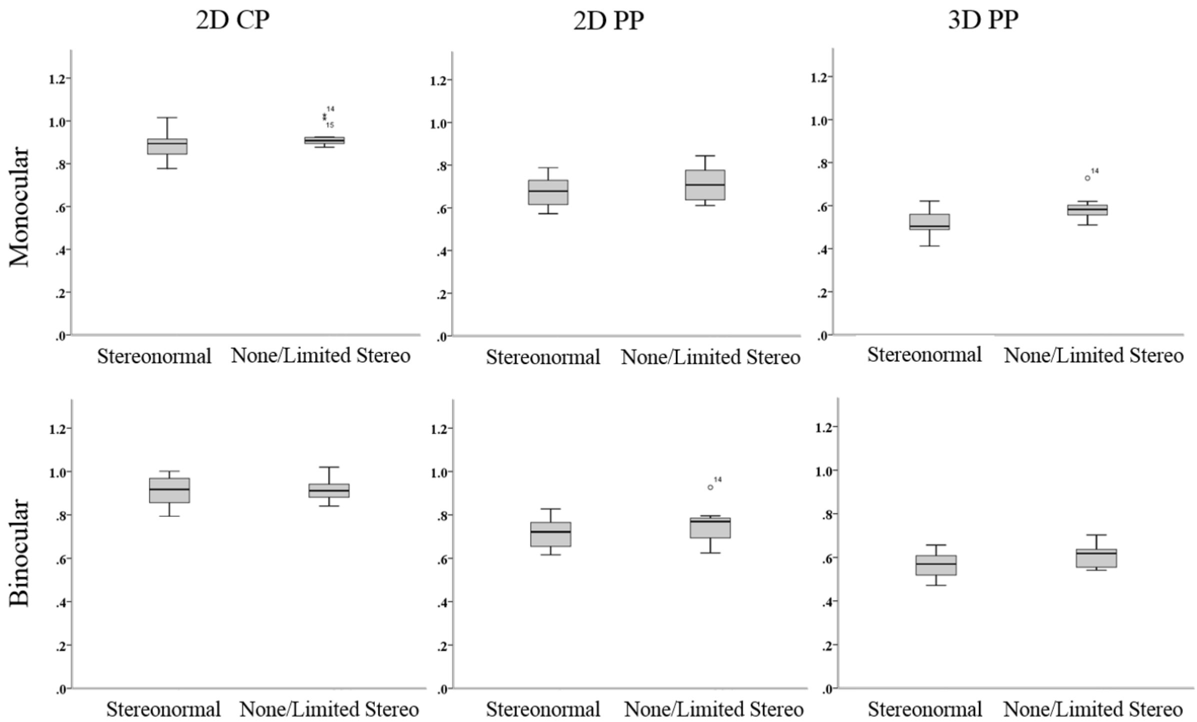
Appendix 5.4.

Supplementary data analysis for experiment 5.2 (experiment 2 chapter 5).

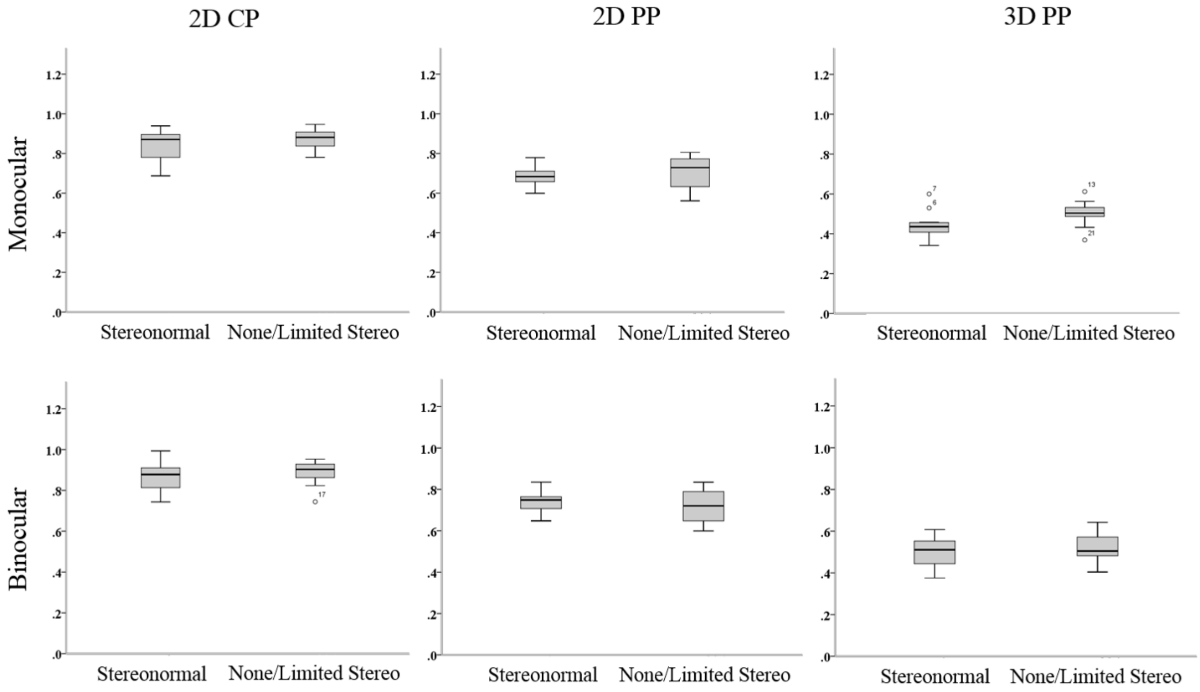
Whisker box plots summarising the data for the three experimental conditions (2D CP, 2D PP, 3D PP) under monocular and binocular viewing for stereonormal subjects and subjects with none/limited stereovision. Panel A – 2 AFC Staircase method. Panel B - Method of Adjustment. Circles mark the outliers, while starts indicate the extreme cases.

The comparison of the two participants groups does not reveal major notable patterns, even though in some cases it seems that strabismic individuals overall showed less variability than controls. Outliers, for instance subject 14 in 2 AFC Staircase method task, highlight that there were individual differences which had created high data variability within conditions, but throughout the conditions participants consistently were affected by the perspective information in the stimuli. Additionally, higher number of outliers in Adjustment method task 3D PP task does not seem surprising considering that participants were asked to imagine intervals to be equidistant within the depicted pictorial space and had unlimited time to make their adjustments, which would have increased variability within individuals.

Panel A: 2 AFC Staircase Method



Panel B: Method of Adjustment



Ethical approval letters for the carried out research

University of St Andrews
from first to foremost

600 YEARS
1413 – 2013

Project Title	Depth perception in strabismus
Researchers' Names	Dr Dhanraj Vishwanath and Giedre Zlatkute
Supervisor	Dr Dhanraj Vishwanath
Department/Unit	School of Psychology & Neuroscience
Ethical Approval Code (Approval allocated to Original Application)	PS10556
Original Application Approval Date	12 November 2013
Amendment Application Approval	04 March 2015

Ethical Amendment Approval

Thank you for submitting your amendment application which was considered by the Psychology & Neuroscience School Ethics Committee on the 3rd March 2015. The following documents were reviewed:

1. Ethical Amendment Application Form 04/03/2015
2. Advertisement 04/03/2015
3. Questionnaire 04/03/2015

The University Teaching and Research Ethics Committee (UTREC) approves this study from an ethical point of view. Please note that where approval is given by a School Ethics Committee that committee is part of UTREC and is delegated to act for UTREC.

Approval is given for three years from the original application only. Ethical Amendments do not extend this period but give permission to an amendment to the original approval research proposal only. If you are unable to complete your research within the original 3 three year validation period, you will be required to write to your School Ethics Committee and to UTREC (where approval was given by UTREC) to request an extension or you will need to re-apply. You must inform your School Ethics Committee when the research has been completed.

Any serious adverse events or significant change which occurs in connection with this study and/or which may alter its ethical consideration, must be reported immediately to the School Ethics Committee, and an Ethical Amendment Form submitted where appropriate.

Approval is given on the understanding that the 'Guidelines for Ethical Research Practice' (http://www.st-andrews.ac.uk/media/UTRECguidelines%20Feb%2008.pdf) are adhered to.

Yours sincerely

Convenor of the School Ethics Committee

Cc School Ethics Committee

School of Psychology & Neuroscience, St Mary's Quad, South Street, St Andrews, Fife KY16 9JP
Email: psyethics@st-andrews.ac.uk Tel: 01334 462071

University of St Andrews | FOUNDED 1413

University Teaching and Research Ethics Committee

04 December 2015

Dear Giedre

Thank you for submitting your ethical application which was considered at the School of Psychology & Neuroscience Ethics Committee meeting on 3rd October 2015; the following documents were reviewed:

1. Ethical Application Form
2. Advertisements
3. Participant Information Sheets
4. Consent Form
5. Debriefing Form
6. Data Management Plan

The School of Psychology & Neuroscience Ethics Committee has been delegated to act on behalf of the University Teaching and Research Ethics Committee (UTREC) and has granted this application ethical approval. The particulars relating to the approved project are as follows -

Approval Code:	PS11855	**Approved on:**	02/12/2015	**Approval Expiry:**	02/12/2018
Project Title:	Quantifying depth perception in strabismus (squint)				
Researcher:	Giedre Zlatkute				
Supervisor:	Dr Dhanraj Vishwanath				

Approval is awarded for three years. Projects which have not commenced within two years of approval must be re-submitted for review by your School Ethics Committee. If you are unable to complete your research within the 3 three year approval period, you are required to write to your School Ethics Committee Convener to request a discretionary extension of no greater than 6 months or to re-apply if directed to do so, and you should inform your School Ethics Committee when your project reaches completion.

If you make any changes to the project outlined in your approved ethical application form, you should inform your supervisor and seek advice on the ethical implications of those changes from the School Ethics Convener who may advise you to complete and submit an ethical amendment form for review.

Any adverse incident which occurs during the course of conducting your research must be reported immediately to the School Ethics Committee who will advise you on the appropriate action to be taken.

Approval is given on the understanding that you conduct your research as outlined in your application and in compliance with UTREC Guidelines and Policies (http://www.st-andrews.ac.uk/utrec/guidelinespolicies/). You are also advised to ensure that you procure and handle your research data within the provisions of the Data Provision Act 1998 and in accordance with any conditions of funding incumbent upon you.

Yours sincerely

Convener of the School Ethics Committee

cc Dr Dhanraj Vishwanath (Supervisor)

School of Psychology & Neuroscience, St Mary's Quad, South Street, St Andrews, Fife KY16 9JP
Email: psyethics@st-andrews.ac.uk Tel: 01334 462071

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University Teaching and Research Ethics Committee

27 January 2016

Dear Dhanraj and Giedre

Thank you for submitting your amendment application which comprised the following documents:

1. Ethical Amendment Application Form
2. Advertisement
3. Participant Information Sheet
4. Participant Consent Form
5. Participant Debriefing Form

The School of Psychology & Neuroscience Ethics Committee is delegated to act on behalf of the University Teaching and Research Ethics Committee (UTREC) and has approved this ethical amendment application. The particulars of this approval are as follows –

Original Approval Code:	PS10556	**Approved on:**	12/11/2013
Amendment Approval Date:	27/01/2016	**Approval Expiry Date:**	12/11/2018
Project Title:	Depth perception in strabismus		
Researchers:	Dr Dhanraj Vishwanath, Giedre Zlatkute and Dr Kenneth Scott-Brown		
Supervisor:	N/a		

Ethical amendment approval does not extend the originally granted approval period of five years, rather it validates the changes you have made to the originally approved ethical application. If you are unable to complete your research within the original five year validation period, you are required to write to your School Ethics Committee Convener to request a discretionary extension of no greater than 6 months or to re-apply if directed to do so, and you should inform your School Ethics Committee when your project reaches completion.

Any serious adverse events or significant change which occurs in connection with this study and/or which may alter its ethical consideration, must be reported immediately to the School Ethics Committee, and an Ethical Amendment Form submitted where appropriate.

Approval is given on the understanding that you adhere to the 'Guidelines for Ethical Research Practice' (http://www.st-andrews.ac.uk/media/UTRECguidelines%20Feb%2008.pdf).

Yours sincerely

Convener of the School Ethics Committee

School of Psychology & Neuroscience, St Mary's Quad, South Street, St Andrews, Fife KY16 9JP
Email: psyethics@st-andrews.ac.uk Tel: 01334 462071

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University Teaching and Research Ethics Committee

27 October 2016

Dear Charlotte

Thank you for submitting your amendment application which comprised the following documents:

1. Ethical Amendment Application Form
2. Advertisement
3. Participant Information Sheet
4. Participant Consent Form
5. Participant Debriefing Form

The School of Psychology & Neuroscience Ethics Committee is delegated to act on behalf of the University Teaching and Research Ethics Committee (UTREC) and has approved this ethical amendment application. The particulars of this approval are as follows –

Original Approval Code:	PS11855	**Approved on:**	02/12/2015
Amendment Approval Date:	26/10/2016	**Approval Expiry Date:**	02/12/2020
Project Title:	Quantifying depth perception in strabismus (squint)		
Researchers:	Giedre Zlatkute and Charlotte Sagnay de la Bastida		
Supervisor:	Dr Dhanraj Vishwanath		

Ethical amendment approval does not extend the originally granted approval period of five years, rather it validates the changes you have made to the originally approved ethical application. If you are unable to complete your research within the original five year validation period, you are required to write to your School Ethics Committee Convener to request a discretionary extension of no greater than 6 months or to re-apply if directed to do so, and you should inform your School Ethics Committee when your project reaches completion.

Any serious adverse events or significant change which occurs in connection with this study and/or which may alter its ethical consideration, must be reported immediately to the School Ethics Committee, and an Ethical Amendment Form submitted where appropriate.

Approval is given on the understanding that you adhere to the 'Guidelines for Ethical Research Practice' (http://www.st-andrews.ac.uk/media/UTRECguidelines%20Feb%2008.pdf).

Yours sincerely

pp

Convener of the School Ethics Committee

cc Dr Dhanraj Vishwanath (Supervisor)

School of Psychology & Neuroscience, St Mary's Quad, South Street, St Andrews, Fife KY16 9JP
Email: psyethics@st-andrews.ac.uk Tel: 01334 462071