Exploration of the Underlying Visual Perceptual and Cognitive Mechanisms of Dynamic Visual Acuity

by

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Author's Declaration

This thesis consists of material all of which I authored or co-authored: see Statement of Contributions included in the thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Statement of Contributions

Heather Hudecki was the sole author of the initial drafts of the chapters and appendices within this thesis, which were written under the supervision of Dr. Kristine Dalton.

Four chapters are included in this thesis describing the previous research performed in this area of vision science and our study researching the underlying mechanisms of dynamic VA. Acknowledgments of those who contributed to the success of this project, this thesis, and my degree are described below.

Contributors	Concept, design, and creation	Data collection	Data analysis	Thesis Writing	Thesis Editing
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The study was designed by Dr. Kristine Dalton and Heather Hudecki, with contributions from Dr. Dania Abuleil, Dr. Elizabeth Irving, and Dr. Ewa Niechwiej-Szwedo, the latter two being members of Heather Hudecki's MSc committee. The data were collected by Heather Hudecki, Yiran Ge, and Karen Fan all under the supervision of Dr. Kristine Dalton. Data analysis was conducted by Heather Hudecki, under the supervision of Dr. Kristine Dalton, with substantial contributions from Dr. Natalie Hutchings, and valuable input from Dr. Elizabeth Irving. Heather Hudecki drafted this thesis manuscript, with valuable input from Dr. Ewa Niechwiej-Szwedo, Dr. Elizabeth Irving, Dr. Natalie Hutchings, and Dr. Kristine Dalton, with

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Conflict of interest: Dr. Kristine Dalton is the co-inventor of the dynamic VA task (moV&, V&mp Vision Suite) used in this study and is currently exploring commercialization options for this task.

Abstract

Purpose:

Dynamic visual acuity (dynamic VA) is a complex, perceptual ability of the visual system that involves determining fine details of objects as they move across one's field of view (1–4). Over the years, there has been increasing interest in dynamic VA because of its apparent relevance to everyday life, and its ability to account for motion, which static VA is unable to do. Dynamic VA has a crucial role in a variety of real-world situations and daily tasks that involve functioning in a dynamic environment, such as driving, piloting, crossing a busy intersection, and many ball sports (5–8). In addition, dynamic VA is an essential element involved in one's ability to adapt to moving and changing environments (1). Although various research has been performed, dynamic VA as a visual function is not very well understood. This study was designed to investigate the potential underlying neurophysiological mechanisms that may be associated with dynamic VA.

Methods:

This study was an observational analysis of visual and cognitive function data collected from 130 participants. Participants were members of the University of Waterloo Department of Psychology Research Experiences Group (i.e., SONA), the University of Waterloo undergraduate and graduate community, the University of Waterloo Optometry Program, and the Kitchener-Waterloo Community. Five visual function tasks were studied including static visual acuity (static VA), horizontal and random dynamic VA, global motion (GM), global form (GF), and local motion (LM), along with two cognitive tasks, multiple object tracking (MOT) and the Stroop task. Static VA was measured first at each study visit to confirm participant eligibility, followed by horizontal and random motion dynamic VA (randomized order). After dynamic VA, the remaining visual and cognitive function tasks were measured in a randomized order. Static VA (LogMAR) was tested with an Early Treatment Diabetic Retinopathy Study (ETDRS) chart. Binocular dynamic VA (LogMAR; moV&, V&mp Vision Suite) was assessed using tumbling E optotypes moving in a horizontal (left to right) or unpredictable random motion. GM perception, and LM perception were assessed using random dot kinematograms (RDKs), GF perception was tested using Glass patterns, Stroop was assessed using word stimuli, and MOT was tested using

randomly moving ball stimuli. Experimental effects, including the effects of participant age, participant gender, and testing order were examined for each task independently using one-way independent measures ANOVAs (age and visual function task order), and two-sample t-tests (gender and dynamic VA task order). Tukey post-hoc test was used to further evaluate any significant order effects found with the one-way independent measures ANOVAs. Correlation plots, matrices, and tables including Pearson correlation coefficients were calculated to examine the relationships between dynamic VA performance and the visual function tasks. Backwards stepwise regression analyses were conducted to determine which visual or cognitive function tasks were most predictive of dynamic VA performance. The correlation and regression analyses were performed separately for horizontal and random dynamic VA.

Results:

Highly significant correlations were found between horizontal dynamic VA and random dynamic VA ($r = 0.49$, $p = 4.84e\text{-}9$), static VA ($r = 0.48$, $p = 6.35e\text{-}9$), and LM ($r = 0.32$, $p = 2.47e\text{-}4$); a weak, significant correlation also noted with GM ($r = 0.23$, $p = 9.16e\text{-}3$). Highly significant correlations with random dynamic VA were found with static VA ($r = 0.46$, $p = 4.39e\text{-}8$) and horizontal dynamic VA ($r = 0.49$, $p = 4.84e\text{-}9$); weak, significant correlations were found with LM ($r = 0.16$, $p = 6.43e\text{-}2$), and GF ($r = 0.15$, $p = 9.89e\text{-}2$). Statistically significant predictors for horizontal dynamic VA were static VA ($p = 6.09e\text{-}4$), LM ($p = 3.96e\text{-}2$), and random dynamic VA ($p = 1.20e\text{-}4$) . GM ($p = 0.139$) was not a significant predictor of horizontal dynamic VA but still had a trend towards a positive relationship with the task. Static VA ($p = 7.85e\text{-}4$) and horizontal dynamic VA ($p = 8.14e\text{-}5$) were the only statically significant predictors of random dynamic VA, but there were also trends towards positive relationships between random dynamic VA and LM ($p = 8.70e\text{-}2$), and GF ($p = 0.135$). Additional analyses determined there to be no age or gender effects on any of the visual function tasks. A statistically significant order effect was present for GF ($F(2, 127) = [4.92]$, $p = 1.02e\text{-}3$), but no other tasks.

Conclusion:

Horizontal dynamic VA appears to be most closely related to random dynamic VA, static VA, GM, and LM, suggesting the dorsal stream and V1 pathway may be the underlying neurophysiological pathways associated with processing horizontal dynamic VA. This is in comparison to random dynamic VA, which was most closely connected with horizontal dynamic

VA, static VA, GF, and LM, suggesting the neuro pathways involved with random dynamic VA could be the ventral stream and V1 pathway. Further research is required to confirm and validate such neurophysiological mechanisms are associated with both horizontal and random dynamic VA.

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Dedication

I lovingly dedicate this thesis to my mom, whose unwavering love and boundless support has helped me succeed and become the person I am today.

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Chapter 1

Literature review

1.1 Visual Acuity

Visual acuity (VA) is the most frequently used visual function in everyday life and the most common method for determining how well the visual system is performing (9). Many researchers and clinicians often exclusively measure VA to assess vision and to define impairment in vision (10). There are many forms of acuity related to vision including static VA, dynamic VA, low contrast acuity, hyper acuity (Vernier acuity), and stereo acuity.

Static VA is the visual function most individuals are likely to know and understand, as this task is routinely measured in an optometric clinical practice. Dynamic VA is a visual acuity measure that incorporates motion. Although dynamic VA has not yet been implemented as a routine clinical measure, it has now become more important to learn about, as research is beginning to demonstrate its significance in everyday life (1,5–8,11–25).

Hyperacuity describes how one can discern spatial position information with great precision (26). It refers to the visual systems ability to perceive fine details and discriminate between small differences or misalignments in the positioning of objects or targets (26,27). Compared to static VA, hyperacuity is often associated with exceptionally low thresholds, even smaller than a foveal cone's receptor size (28,29).

Vernier acuity is a form of hyperacuity that describes one's ability to identify small changes in the alignment of objects, such as between two vertical lines (28). Its thresholds are also smaller than a foveal cone receptor's size (28). Vernier acuity can be used as a measure of cortical visual function because optical media factors negligibly affect it (28), however it is not normally measured in a clinical setting as much like dynamic VA, the Vernier acuity task itself is not well understood (28).

Low contrast acuity is an assessment of how well one can see details in reduced contrast situations. Low contrast assessments are not routinely measured clinically and are often only incorporated into an eye examination if there are signs of decreased performance associated with low contrast or if an individual mentions issues with contrast sensitivity (30).

Stereopsis-is the ability of the visual system to perceive the relative distance of objects when there is a horizontal disparity of the retinal images between eyes (31,32). Stereoacuity is a threshold measure associated with the sharpness or precision of the depth perception (31). It also provides details about an individual's ability to integrate visual information from each eye into a binocular 3-D percept. (31,32). Stereoacuity is frequently tested in clinical settings to screen for deficits in binocular visual function (31,32).

1.2 Why Static VA and Dynamic VA are of Particular Interest

Although it is notable that all the types of visual acuity mentioned above are crucial to one's visual function, it is static VA and dynamic VA that are of particular interest to this thesis because of their fundamental roles in many human activities. These activities may include occupational demands, such as in policing or piloting, where certain visual standards must be met; spatial awareness for safety with vehicle and equipment operation or crossing a busy intersection; and healthcare where the tasks are used for diagnosing of conditions or diseases. Understanding these two visual functions is essential if one is attempting to improve various aspects of, or optimize performance on, daily life activities, such as with reading, learning, work and productivity, driving, sports and physical activities, social interactions, hazard recognition, and health and well-being.

1.3 Static VA

1.3.1 Definition

Static visual acuity (Static VA) is the ability to distinguish and discriminate spatial detail of targets and objects, when both the image and individual are stationary (1,33). Static VA describes one's visual sharpness and is measured using high contrast, stationary targets. Many researchers have described it as the most common and frequently evaluated clinical test for visual function (1,5). Static VA has been mentioned to be the basis for many, if not all, visual skills, and is a good measurement for determining one's visual system integrity (34,35). As a result, visual acuity is a highly studied attribute of vision (34). However, it is important to note that while, visual function has often been equated with static VA (36), the measurement of static VA alone ignores many other important aspects of visual function, including contrast, colour, and motion perception (36).

The measuring of static VA is both useful and necessary in an eye examination to screen for, detect, or examine ocular pathology that affects central vision, including media opacities and eye diseases; for refractive error assessment and to establish ideal refractive corrections; and for prescribing aids needed for those who are visually impaired (36,37). It is also useful when determining how effective a medical and/or surgical treatment may have been, and when determining vision standards required for driving and/or employment (36).

For static VA to be within the range of what is considered normal, the cornea and lens must properly refract light, so the light is focused on the retina's foveal region to be transferred to the occipital cortex (35). This means that if the eye's optical properties are altered in a way that distorts light onto the retina, if the retina is diseased, or if the neural pathways are defective, there will be an issue with static VA (35). As a result, static VA has a high level of clinical utility and provides a great deal of information about the visual status of the eye. Static VA is also a relatively easy, low-cost task to perform (35), as it can be performed easily and efficiently with an examiner that has little training and presents minimal risks for patient (35).

1.3.2 Measurement

The current clinical gold standard for measuring static VA is the Early Treatment Diabetic Retinopathy Study (ETDRS) chart (36). The ETDRS charts are based on the Bailey-Lovie chart (38) principles and use a logMAR scale to measure distance VA (5). LogMAR allows for higher measurement repeatability and greater measurement accuracy compared to other visual acuity measurement methods, as it has a per letter acuity score (5). Snellen letters and Landolt's C or ring are two of the most common optotypes used for Static VA measurements (1). Luminance, contrast, refractive error, and the individual's age (anatomical and physiological changes) are some of the factors that affect static VA (1). These factors must then be considered when measuring an individual's static VA to ensure a proper and accurate result has been recorded.

1.3.3 Relevance to Life

Static VA is an important aspect of one's overall visual function. It is essential for various endeavours in individual's daily lives that require clear and detailed vision. Some endeavours include sports and recreational activities, driving, reading and writing (education), and recognizing distant objects and/or people (23,37,39,40). For example, researchers have stated

that static VA is a fundamental part of one's visual performance in sports (23). Static VA is at the base of the vision pyramid used for sports training, meaning it is one of the most crucial visual functions used to enhance on-field performance (23).

As static VA is thought to be important for driving performance, it is always measured before an individual can acquire driver's license (39). Over the years, there has been much discussion about the vision testing requirements involved in obtaining a driver's license, specifically related to the suitability of one's fitness to drive being tested by static VA (40–45). Many researchers have stated there may be more relevant visual functions to measure for driving, such as contrast sensitivity and visual field, however static VA has still been the primary vision criteria used for licensing purposes due to its ease of measurement (40).

Static VA has also been mentioned to be imperative in a child's social and academic development, where research has suggested that poor visual acuity can lead to a hindered development (46–48). Previous research has also shown static VA testing results to be related to children's daily interactions and activities (47,49). This means early identification of visual issues in children can help the adults around them, whether it be parents, teachers, or eye care practitioners, make the required modifications to assist the children in educational and social environments (46,47,50,51).

Finally, as static VA is involved in many activities in one's daily life, it also is involved in determining whether an individual is suited for a specific occupation, such as policing or piloting (37). Static VA is frequently used to determine whether a person meets the visual requirements of such occupations (37), however the validity of many of the current standards for these professions are still being investigated.

1.3.4 Neurophysiological Mechanisms

Visual acuity in vertebrates is the result of an image's optical quality produced by the ocular system, and the retina's anatomical and physiological abilities to analyze the image (52). The diffraction effects that occur at the entrance point of the image into the eye help determine the quality of the image seen (52). However, the image detail to be analyzed is established by the density, slenderness, and quantity of visual cells associated with each optic nerve fibre (52).

How is one able to see this so-called image? Light passes through the cornea, where the cornea bends the light, helping the eye focus. The light then travels through the pupil, with the amount of light coming in being controlled by the iris. From there, the light passes through the lens, where the lens and cornea work together to focus the light onto the retina. It is at this point, where the light is turned into electrical signals/ neural impulses by photoreceptor cells (rods and cones) in the retina (35). These signals travel through the optic nerve via lateral geniculate bodies to the occipital cortex within the brain (35). The cortex then interprets and integrates the signals into the images individuals see (35).

With an increase in light intensity, also comes an increase in visual acuity, due to the central area of the retina being used (52). There are two types of photoreceptor cells in the eyes: rods and cones. In the peripheral areas of the retina, there is a higher rod to cone ratio, meaning there are more rod photoreceptors, which are more sensitive to detecting light and motion but have poorer spatial resolution and poorer visual acuity (52). However, the retina's central areas have a greater proportion of cones, compared to rods, and have a greater visual acuity accuracy (35,52). Particularly, in the very center of the retina, in the foveal region, is an area that contains purely cones, with no rods present, and these cones tend to be more slender than those in other regions (35,52). This slenderness allows for an increased density of cones in the fovea compared to other areas of the retina. In turn, the higher density of cones in the fovea increases its spatial resolution, which means the fovea can detect smaller details than any other area of the retina (52). The eye's static VA is ultimately determined by the delicacy of the cone mosaic in the fovea (52). Mammals, along with birds, are two additional groups of vertebrates in which certain areas of the retina provide especially high visual acuities due to specialized arrangements of the photoreceptor cells (52).

1.3.5 The Effect of Age on Static VA

Previous studies have found static VA to decrease with age (3,53,54). Static VA gradually develops until the age of about 5 years, where it has just about reached the static VA performance level of that of an adult (54–56). It is at this stage, where findings across studies have not been consistent. Pitts (1982) stated from the age of 5 to about 40, static VA remains relatively constant, then from age 40 and onwards, static VA gradually decreases (56). However, other researchers mention static VA to begin declining at the age of 50 (57), 65 (58) or even

above 70 (58). It appears static VA remains relatively constant for a number of years before beginning to decline. Potential reasoning for the decline in static VA with aging individuals without ocular disease, is the result of neural cell loss occurring, such that there is a decrease in the quantity of retinal ganglion and bipolar cells, and the connections between the cells, leading to reduced abilities to transmit visual information effectively (57). As well, there is a decrease in the density of photoreceptor cells, with rods being more greatly affected than cones, reducing an individual's ability to perceive fine details and compromising their vision in low-light conditions (59).

1.3.6 The Effect of Gender on Static VA

When reading this section and all following sections about the gender effect on each visual function task, it is important to note that many studies have investigated sex rather than gender or used the term "gender" and "sex" synonymously. In the sections about gender effect, we have used the terminology in the cited literature as it was reported.

In 1996, Long et al. reported there to be no differences in static VA amongst genders (60). This finding is contrary to the findings of many other researchers, reporting males to have better static VA than females amongst a variety of different age groups (61–63). Each of these studies appeared to have different methods of studying static visual acuity, including a Titmus II vision Test with Landolt-C targets (60), a Frieburg visual acuity test (63), and standard letter charts with Snellen optotypes (63). It is possible that the differences seen between the genders is the result of biological differences (e.g., hormonal influences), cognitive and perceptual processing (e.g., attention and focus), and educational and occupational activities (e.g., sports). It is also possible the differences could be the result of evolutionary adaptations, although more unlikely, where males and females previously often had distinct roles, such as with hunter-gatherer roles, where the males were involved with hunting and required acute distance vision, and females were engaged with gathering activities and required more close-range vision. Examining biological differences that may be influenced by social constructs poses a challenge as it is difficult to differentiate the impact of biology from cultural and societal factors. The challenge lies in discerning whether these differences are inherent biological variations, potentially shaped by evolutionary adaptations, or if they are influenced by societal roles and cultural expectations. Societal roles may contribute to the development of certain cognitive skills or visual processing

preferences based on the roles individuals traditionally assume within a given culture, thus potentially influencing evolution. While evolutionary adaptations could shape biological differences over time in response to environmental demands and subsequently influence the roles that individuals traditionally assume in a given culture. The interplay between biology and culture makes it challenging to attribute observed differences solely to one factor.

1.3.7 Limitations of Static VA

Static VA is a frequently evaluated visual task, though it has some limitations when it is the only measurement used to assess visual system function. The letters or symbols used in a static VA test are most often presented with maximum contrast (black letters/symbols on a white background), even though this level of contrast rarely is presented in one's daily life (1). Furthermore, static VA does not assess depth perception, crucial for evaluating one's environment. It is also a primarily central vision task thus, it does not provide any insight into the quality of individual's peripheral vision. As well, individuals encounter many different, moving stimuli in their daily life that static VA does not account for, however, dynamic VA does (1).

1.4 Dynamic VA

1.4.1 Definition

One of the limitations with static VA is its inability to account for the motion of objects that occurs in an individual's daily life, as previously stated. Dynamic VA has the potential to provide this additional information. The term dynamic VA was originally created by Ludvigh and Miller in 1949 (4). Since this time, dynamic VA has been defined as a complex, perceptual ability of the visual system that involves determining fine details of objects as they move across one's field of view (1–4). Dynamic VA also involves oculomotor functioning, peripheral awareness, target detection, and information processing (64).

1.4.2 Measurement Methods

There are several different ways dynamic VA can be measured, many of which seem to be relatively inconsistent with each other. As well, there is currently no standardized and validated dynamic VA test that is commercially available. Dynamic VA has previously been measured using projected letters or targets with rotating mirrors or discs, or targets on a screen that have

horizontal or rotating movements (5,7,23). Dynamic VA has also been measured by having participants stare at a stationary target while they move their head in a side-to-side motion or through examiner guided head rotations (5,7,65). In addition to the variety of tests used to measure dynamic VA, the target parameters used in dynamic VA testing, including target trajectory, target speed, type of target, target size, target contrast, and target colour also vary widely (4,23,66–68). Landolt C rings and Tumbling Es, are the most common optotypes used in dynamic VA tasks (5,20,69–73). Both of these optotypes are typically presented as four-way forced choice identification tasks. The Landolt C is shaped like a C (a circle with a gap), and the gap is typically pointed up, down, left, or right (20). When using this optotype, the individual's task is to determine which way the gap is oriented (20). The Tumbling E is a capital letter E positioned in one of four orientations for each trial (i.e., the legs will be pointed left, right, up, or down), and the goal with this optotype is to determine which way the legs of the E are pointed.

1.4.3 The Effect of Age on Dynamic VA

Previous studies with a variety of different age ranges amongst participants (5 to 92 (53), 8 to 17 (54), 6 to 60 (74)) have found that once participants reach the age of peak dynamic VA performance, the tasks performance then appears to decline (53,54,74). However, the age period when peak performance occurs tends to vary. One study states peak performance occurs at age 15 (53), another at age 17 (54), and a third study mentions between the ages of 20 and 39 (74). After this age period of peak performance, dynamic VA performance decreases, with researchers finding that there is a constant decline, with no plateau until the age of 80 (53). However, there is a quick increase that occurs in individuals from the ages of about 5 to 15 (53) or 17 (54). It has been speculated the reason for the decline that occurs as one ages is the result of decreased illumination of the retina (74), and aging of the central nervous system, as dynamic VA relies on the feedback mechanisms that interconnect the sensory and motor aspects of the visual response in addition to those aspects themselves, much like static VA (53).

1.4.4 The Effect of Gender on Dynamic VA

Various research has been performed investigating the effect of gender on dynamic VA. One previous study found there to be no difference in the results of the varying genders of participants (75). This finding of no gender effect, however, is contrary to many other studies

performed, that have found males to have the superior dynamic VA performance compared to females at most, if not all, ages (3,53,54,60,74,76–78).

The difference occurring between male and female sexes has been seen as early as 5 years old and has stayed relatively consistent until about age 20 (53). Ishigaki et al. (1994) stated that males likely inherently have a superior dynamic VA, due to there likely being a factor appearing from birth to age 5 that would cause a sex difference in dynamic VA (53). Ishigaki et al. (1994) mentioned a possible difference in the morphology of parts of the central nervous system associated with identifying moving objects to be the reasoning for sex differences in dynamic VA (53).

Although some researchers have believed social and cultural differences may cause the sex or gender differences that occur in dynamic VA (53,76), other researchers have accommodated for such differences and did not find an effect (75). It is possible that impact of sex and gender on dynamic VA is more complicated than effects that can be attributed to sex or gender alone. For example, Gale et al. (1978) suggested differential EEG activation occurs in the different sexes when viewing a moving object, potentially due to the sexes concentrating on different features of the moving target, and thus causing there to be a sex-effect on dynamic VA (79), however the features of moving targets that individuals of different sexes attend to could also be driven by social and cultural constructs.

1.4.5 Relevance to Life

Dynamic VA evaluates a visual system's spatial resolution when moving stimuli are present (1). Over the years, there has been increasing interest in dynamic VA because of its apparent relevance to everyday life, and its ability to account for motion, which static VA is unable to do. There have been many previous studies that have assessed the relationship between dynamic VA and static VA. Multiple studies have found some correlation between the two visual functions (2,3,77,80–82). However, other studies have found minimal, or no relationship at all between the two tasks (4,8,33,83,84).

Dynamic VA has a crucial role in a variety of real-world situations and daily tasks that involve functioning in a dynamic environment, such as driving, piloting, crossing a busy intersection, and many ball sports (5–8). In addition, dynamic VA is a crucial element involved in one's ability to adapt to moving and changing environments (1). Dynamic VA can be helpful

in predicting how one will perform in the execution of certain daily tasks and predicting the future location of a moving stimulus (1). Being able to predict such elements is essential when intercepting moving objects (such as a ball), and when predicting item's spatial locations (1).

Multiple researchers have studied the relationship between dynamic VA and driving, finding there to be a significant relationship between the two (1,11,12). There has also been a negative correlation found between dynamic VA and accident rates that have occurred in traffic scenarios, where there are fewer accident rates with better dynamic VA (1). Other research has been performed studying the relationship between truck and bus accidents and the drivers' dynamic VA, again finding there to be a negative correlation between them (1,11,12). In studies that have researched various visual abilities and driving, dynamic VA has been proven to be the best predictor of driving success, which was defined as fewer traffic accidents (11,12). Thus, it appears that there is a relationship between dynamic VA and driving such that drivers with good dynamic VA, appear to have fewer accidents.

Over the years, researchers have also performed studies involving the relationship between dynamic VA and pilots (13,14). They have found there to be a significant relationship between flying aircrafts and dynamic VA, with pilots having better dynamic VA than non-pilots (13–15). Other research indicated pilots with better dynamic VA made fewer errors (16–19).

Furthermore, dynamic VA and its association with sport and athlete performance has also been a highly studied topic. Many clinicians and researchers have been interested in research involving dynamic VA and athletic performance, hypothesizing the two are related (20–22). Researchers have even stated the most essential determinant of an athlete's visual system, as it relates to sports performance, may be dynamic VA (23). In many sports, there are quickly moving objects and people, and an athlete must be able to detect the objects or people and subtle differences that occur within their visual field (23). In fast-ball type sports (e.g., badminton, baseball, tennis), the ball or shuttlecock is moving at a very fast pace, and athletes must be able to track the fast-moving targets repeatedly within their training (20). Researchers have mentioned one of the best success indicators for certain sports (e.g., baseball, table tennis) is dynamic VA (1) . Several studies have also found dynamic VA to have a significant relationship with throwing and catching a ball (21,24,25) and baseball batting (25), where those that had good dynamic VA also performed well with such tasks.

Additionally, in multiple studies, dynamic VA has been positively influenced by sports experience, with more experienced athletes typically performing better on dynamic VA tasks (34,71,75,85,86). Furthermore, dynamic VA in athletes is typically better than nonathletes (23). Studies comparing college or university athletes, or professional athletes to nonathletes have found athletes to have a better dynamic VA in basketball (24), volleyball (87), tennis (20), water polo (75), football (34), baseball (1,20,71,85,86), martial arts (karate and judo) (1), and table tennis (1).

Researchers have not only studied the effects of dynamic VA in athletes, but also in video game players (7,88). Yee et al. investigated dynamic VA in athletes, action video game players, and non-athletes/video game players, concluding that there was no difference in the dynamic VA of video game players verses the controls, but athletes had superior dynamic VA compared to the other groups (7). Yee et al. determined that the difference in dynamic VA performance of the athletes was not related to refractive error, static VA, or smooth pursuit gain, as these parameters were all similar between groups (7). These results led the researchers to suggest the differences in dynamic VA were likely driven by other aspects such as visual perception and cognition (7).

Interestingly, in a recent study performed by Argiles et al. (2023), involving action video game players, non-action video game players, and non-experienced video game players, action video game players who mostly played first-person shooter games and more than 5 hours per week were found to have better dynamic VA than others tested (88). Their preliminary results also showed people who play first-person shooter games may have a greater improvement on dynamic VA than those who play other types of video games (88).

Other researchers have also shown training to improve dynamic VA (23,66,72). One specific study by researchers Long and Riggs in 1991 compared college athletes (soccer, baseball, tennis, and hockey players) to non-athletes (72). They found college athletes had slightly better dynamic VAs than the normal group, but once training of dynamic VA was involved for the normal group, the normal group performed better than the college athletes (72). Dynamic VA in all individuals was improved with training, but the greatest training effect occurred in those who initially performed the poorest (the normal students) (72).

Recent research by Redondo et al. further supports the hypothesis that dynamic VA can be trained or learned. Certain cognitive processes such as those used in driving and ball sports are sensitive to various external factors including psychostimulants like caffeine (6). Due to the

association of caffeine ingestion with improvements in cognitive performance and visual functioning, Redondo et al. believed caffeine ingestion may have an impact on the detection of moving objects and thus on the results of dynamic VA (6). In their study, Redondo et al. found that caffeine ingestion improved the accuracy of participant's responses on both horizontal and random dynamic VA tasks (6). These results may be explained by the positive influence caffeine has on the cognitive processes of decision-making and stimulus processing (6). Redondo et al.'s research demonstrated that dynamic VA performance can be improved following acute caffeine consumption, thus suggesting that there is a cognitive component to dynamic VA tasks which has the potential to be trainable. If it is trainable, the improved dynamic VA task performance could translate into improved performance on daily life activities, such as sports or driving.

1.5 Cognitive vs Visual Perception

1.5.1 Perception

Perception, as outlined by Qiong (2017), involves sensory observation (using senses to gather information) and conceptual interpretation (abstract understandings) (89). Perception is the way an individual thinks about and understands something, and it is shaped by their thought processes and sensory experiences (89), including how sensory information is processed (90). When referring to perception in psychology, philosophy, or cognitive science, it involves gaining awareness about sensory information and understanding this information, and then integrating sensory and intuitive elements to construct an individual's holistic understanding of the environment (89).

Visual perception has been defined as the combined process of receiving and interpreting visual stimuli (91). The visual receptive component (sensory function) retrieves and organizes information within the environment an individual is a part of (91). However, it is the visual cognitive component involving particular mental functions that assists one in organizing and interpreting stimuli, helping make sense of what a person is seeing (91). Visual perceptual skills involving shape, colour, and object recognition are fundamental in understanding the visual environment (91).

1.5.2 Cognition

Cognition encompasses the processes involved in transforming, simplifying, enhancing, storing, retrieving, and utilizing sensory input (92). Cognition has been defined through the lens of information processing and behaviour (92), elaborating on how an individual comprehends, retains, acquires, and processes information for problem solving and functioning in everyday life (90). Cognition involves mental processes building on one another; the progression of cognitive activity is characterized by a cause-and-effect relationship, where each step in the cognitive process triggers the subsequent step, emphasizing the interconnected nature of cognitive functioning (92). Researchers have stated there are three primary stages for informational flow involved with cognition including decision making, perceptual processes, and the selection and execution of responses (90). Sub areas of cognition include attention, memory, language (e.g., comprehension, writing), problem solving (using attention and perception), decision making and reasoning, and sensation and perception, among others (90).

Visual cognition is a complex mental process that involves an individual's previous knowledge, visual stimuli received by the retina (sensory input from the eye), and decision-making to create a meaningful representation of the visual world (93). This cognitive process is continuously updated as new visual data is acquired, providing individuals with a functional simulation of the visual world (93). Visual attention, discrimination, memory, and imagery are all elements of visual cognition (91).

1.5.3 The Intermixing of Perception and Cognition

As can be seen through the description of cognition, and what is involved in such processing, the worlds of cognition and perception intertwine, often making it difficult for researchers to define the difference between the two. I have come to understand perception and cognition as the following: Perception involves organizing and interpreting sensory information from the environment to give such information meaning. Visual perception involves the interpretation of visual stimuli received from an individual's eyes. Perception is primarily concerned with the early stages of visual processing, where the brain extracts basic features such as colours, shapes, and spatial relationships. Cognition seems to involve higher-order mental processes such as attention, memory, problem-solving and decision-making. Cognition includes more complex functions that influences how one interprets and interacts with visual information. This mental

process extends beyond the basic perceptual processes and involves the integration of visual information, along with other functions, assisting an individual with more complex analysis and understanding. Thus, for the purposes of this thesis, tasks that involve extracting basic features from visual information will be called perceptual tasks, and those that involve higher-order mental processes will be called cognitive tasks.

1.5.4 Perceptual Learning and Visual Training

Perceptual learning involves acquiring knowledge and information from one's surroundings to improve performance and increase our perceptual understanding of the world around us. Our perception understanding grows through perceptual learning with increased experience, practice, and exposure to environmental stimuli (91).

When researching visual function tasks, it is often questioned whether an individual can be trained to improve ones' performance on such task and subsequently improve their visual function. Visual perceptual learning is the process through which visual task performance can be improved by training (94). Thorough research has been performed regarding whether cortical mean neural activity could be regulated by perceptual learning (94–98). An increased amount of relevant neural detectors, or their improved sensitivity could explain why there was an increase in the mean neural activity of individuals who were trained with a visual detection task (94–98).

Research performed by Chen et al. showed there was an improvement in behavioural performance associated with motion direction discrimination training, where the improvement was direction specific to the one that had been trained (94). As well, this improvement was persistent for a minimum of two weeks (94).

As a result of this work, Chen et al. suggested long-term learning associated with motion perception involves refining neural mechanisms, and that this refinement is achieved by sharpening the brain's sensitivity (tuning) in the cortex at the sensory processing stage. Chen et al. suggested that over time, the brain becomes more proficient at processing and recognizing trained motion stimuli (94), and that further improvement in the long-term learning could occur if there were greater connections between the sensory and decision-making brain areas (94). According to the hypothesis of the reweighting models, the improvement in long-term learning would be due to the strengthening connections amongst the most sensitive neurons in the sensory areas and the decision areas (94).

Although not much research has been performed involving dynamic VA and its potential training capabilities, other research involved with visual training, such as the study by Chen et al. (94) mentioned above, has led us to believe that if dynamic VA can be trained, it is possible that it may be trained through visual perceptual learning processes such as repetition and exposure, adaptation to motion patterns, feedback and error correction, and task specific training. Understanding what neurophysiological mechanisms are associated with dynamic VA, could help guide training and determine what methods of training may be best.

1.6 Visual Perception

1.6.1 Dual Stream Hypothesis of Vision (Dorsal vs Ventral)

According to the dual-stream theory of vision, higher level processing of visual information occurs within the cortical area and involves both the dorsal and ventral streams (99–101). The dorsal stream extends from the striate cortex to the posterior parietal region and is involved with visually guided sensorimotor behaviours, while the ventral stream extends from the striate cortex to the inferotemporal cortex and is associated with object identification (101,102).

1.6.2 Ventral Stream

The ventral pathway, otherwise known as the "vision for recognition" pathway, is involved in cortical visual processing (99,101,103,104). Previous research led many to believe the ventral pathway was specialized for form processing and object recognition (99,101,103). An example of such research involved monkeys. These animals were found to have issues with discrimination and recognition of visual patterns when they had lesions in their inferotemporal cortex, but there was little to no issue with 'landmark' tasks, where one of two alternative locations was rewarded based on a visual cue's location (101,105). An example of a landmark tasks is randomly placing a striped cylinder between two covered foodwells, with the goal of the task for the monkey being to determine which foodwell is closest to the cylinder (106). The finding that the monkeys with the inferotemporal cortex lesions had little to no issues with the landmark task led researchers to believe the ventral pathway was associated with visual recognition (101,105).

Other research involved a patient known as DF that suffered from irreversible brain damage due to carbon monoxide poisoning (107–109). Focal lesions were found in the lateral occipital cortex of DF's brain, an area of the ventral stream pathway (109,110). As a result of these

lesions, DF was not able to recognize relatives' or friends' faces, identify common objects visual forms, or differentiate common geometric shapes, however the lesions did not diminish her motor control ability and she was still able to reach out and grasp objects normally (107,109). DF's ability to normally grasp objects while having ventral stream damage suggests that other brain areas are processing information such as orientation, size, and shape of the object for motor control abilities (109). Another patient, labelled SB, who experienced bilateral ventral stream damage in his early life had decreased ability to identify objects, colours, faces, and words but still demonstrated good visuomotor skills (motorcycle riding and tennis playing) (109,111,112). Research was also performed on an individual (JS) who suffered bilateral ventral stream damage from a stroke (109,113). Although he was not able to identify the orientation and shape of the objects, he was able to properly conduct the movement associated with grasping of these same objects (109,113). Thus, all this biological evidence supports the theory that the ventral pathway is used for form processing and object recognition.

The ventral pathway contains the occipital and temporal lobes' ventral regions (103,104), projecting from the striate to inferotemporal cortex (101). This pathway involves the movement of information from the retina to the dorsal part of the lateral geniculate nucleus, projecting information to the primary visual cortex (V1), then to secondary visual cortex (V2), V4, and finally the inferotemporal cortex (109,114,115). Neurons involved in the pathway from V1 to the inferior temporal cortex analyze form information (i.e., object shape and structure) (106,116–118).

V1 begins object processing, where the speed, direction, spatial and temporal frequency, orientation, and colour of objects are beginning to be processed (114). Orientation information, pertaining to local form, is first gathered from V1 cells, before these cells' outputs are integrated into higher cortical areas such as V4 (99,118–122). The cortical areas past V1 have larger receptive fields that are associated with the extra-striate areas involved with global processing (103). These areas combine the signals from earlier areas of the visual pathway, allowing them to take part in segregating signal and noise information (103).

V2 then continues with object integration and intermediate object representation, analyzing edges, borders, and colours (114). Research involving animal electrophysiology and human fMRI have both found that V2 and V4 are involved with local form cue integration and V4 neurons are also involved with signaling form information involving shapes (120,123–129). V4

is an area sensitive to form that is a part of the lateral geniculate nucleus parvocellular layers and that extends to the inferior temporal lobe (99). In V4, the integrated information from V1 and V2 supports object integration and representation, analysis of angles, curvature, perceived colour, kinetic contours, and motion (114) that help an individual determine forms (shapes and structures) (99,118–122). Finally, in the inferotemporal cortex, all the previous information is processed and brought together to help understand object recognition such with simple and complex shapes and body parts (114) (Figure 1.1).

Figure 1.1: The Ventral Pathway.

1.6.2.1 Global Form Perception

Global form (GF) perception is the ability of one to determine the overall shape or structure of an object or multiple objects within a visual scene (118,122,130) and is important in object identification and object shape recognition (118,122,130). Otherwise known as orientation discrimination, GF perception measures one's ability to identify objects from light patterns being projected onto our retinas based on distinguishing neural signals generated from the object's particular characteristics, such as contrast, shape, and size (131,132). GF is processed along the ventral pathway and is associated with ventral stream function (133), as the ventral pathway contains neurons that are selective for GF (99,103,104), that help with processing various shapes, including concentric and radial structures (99,118–122).

Glass Patterns (134) are a common task used to measure GF perception (99). They consist of many randomly distributed dots that can be arranged in such a way that they create the perception of a coherent pattern (99,118,135). Mathematically, a geometric transform determines the orientation of these dots and presents the global form percept to the observer (135). The individual dots in each Glass pattern are often referred to as dipoles, which are pairs of dots consisting of the same polarity (118). Some dipoles are grouped together to form coherent patterns (signal dipoles), the remaining dipoles are grouped and are randomly oriented (noise

dipoles) (103). A threshold for Glass patterns is obtained by adjusting the proportion of signal (dots contributing to the coherent pattern) to noise (dots of random orientations) dipoles (103).

Glass patterns are especially useful in examining how the human visual system processes information regarding an image's shape or structure. At least two stages occur in the visual system to create GF perception from Glass patterns: (1) an assessment of the local dipoles orientations that occurs in early areas of the visual pathway (i.e., V1) and (2) local dipole integration for GF occurring in higher extrastriate areas (i.e., V4) (122,135). Dot pairs are associated into dipoles by a local process, then dipoles are grouped into a GF structure by a global process (135). When dipoles orientation becomes consistent enough, a signal occurs demonstrating the orientation of the pattern created (122).

The above information about Glass patterns has led many researchers to believe that Glass patterns are the ideal stimuli for studying GF perception because the method directly investigates the underlying mechanisms involved in integrating visual forms and pulls information from both local and global levels (118).

The effect of age on GF perception has previously been studied, with one study performed by Norman et al. (2020) finding age to produce a significant, although very small, effect on a shape discrimination task used for measuring GF (136). From these results, Norman et al. (2020) concluded that as one ages, they practically retain their ability to perceive shapes, even those embedded in noise (136). However, this is contrary to the results of many other studies. Multiple researchers have found there to be increased form coherence thresholds, or worse performance, when studying older adults versus younger adults (137,138). This elevated coherence threshold occurred for both the concentric and radial patterns of the Glass pattern task, indicating there was consistent performance for individuals within the task (137). Changes in form perception that occur as one ages involve decreases in the ability to easily determine shapes when the shapes are presented amongst noise (137,138). Furthermore, when operating at the same level of difficulty in a GF task, older adults require there to be less noise amongst the form when attempting to determine the difference between concentric and radial structures (136,138). Weymouth et al. (2012) believe the increased coherence thresholds that occur with older age are the result of the alteration (due to healthy aging) of intermediate-level processes that assist with the functioning of such higher-level tasks (138).

Although the effect of gender on GF has not been studied yet, there is still reason to believe a gender effect may occur as hormonal influences, cognitive strategies, neurological and morphological brain differences, and attentional differences that occur between the genders may influence their performance on GF.

GF perception is crucial for developing the ability to perceive and interpret the visual world, as it assists individuals with quick and efficient object, shape, and pattern recognition. Previous research performed comparing GF to visual acuity and stereopsis found that both tasks are related to GF perception (132). Although this research has only previously been performed with static VA, some form patterns used while deciphering different GF patterns could potentially be used during dynamic VA tasks that involve resolving the shape and fine details of objects moving in one's visual field (1–4). Maintaining visual clarity when objects or scenes are in motion (i.e., dynamic VA) may require GF perception to be able to determine the form of objects or scenes that occur. Thus, it is possible that GF and dynamic VA are connected, and that GF perception may be an important fundamental component contributing to the visual processes driving dynamic visual acuity.

1.6.3 Dorsal Stream

The dorsal stream, also known as the "vision for action" stream, is involved with visuomotor control and coordination through identifying the motion of objects, their locations, and their positions relative to one another (99,103,139,140). This stream also assists with visually guided actions towards objects through mediating sensorimotor changes (101). More specifically, researchers believe the early dorsal stream is associated with motion processing, and the later dorsal stream with visuomotor control (114,141,142).

There has been ample research performed investigating the function of the dorsal stream. Monkeys that had posterior parietal lesions performed poorly on 'landmark' tasks (see 1.6.2 for detailed task description) (101,106,143–145). However, these monkeys did not seem to have issues with recognizing and discriminating patterns, tasks that are associated with the inferotemporal cortex and ventral stream (101,144). Other research involving individuals with optic ataxia as a result of posterior parietal damage demonstrated the individuals' inability to accurately reach for targets they recognized (101,146). These individuals demonstrated issues in their finger position and hand orientation when reaching toward the object, in addition to the

difficulty in reaching for the object (101,146). These findings provide support for the posterior parietal area within the dorsal stream being involved with spatial vision rather than object vision (101,146). In another patient suffering from bilateral parietal damage, the patient was found to have issues with gaze, spatial attention, reaching towards an object, and picking up an object (101,147). However, this patient did not have any issues identifying common objects presented as line drawings (101,147). This patient demonstrates that the ability to use the objects information for grasping and movement towards the object can by impaired by parietal lobe damage (101,147).

The dorsal stream runs from the striate cortex to the posterior parietal region (101). Although originally thought to consist of only one pathway, the dorsal stream now appears to consist of two pathways with supportive functions (Figure 1.2) (148,149). Each stream projects from the retina to the lateral geniculate nucleus, to V1, V2, and V3, however it is after this point where the two pathways diverge (148). The pathway that most frequently appears in research has been the ventro-dorsal stream. This stream projects from V1, V2, and V3 to the middle temporal area (V5), then to the medial superior temporal area and finally to the posterior parietal cortex (114,148,150–153). Assuming that macaques are neurologically similar to humans, studies have found that there is a direct connection between V1 and the middle temporal area (150–152). However, the middle temporal area is also receiving indirect input from V2 and V3 (150–152). The second dorsal stream pathway is known as the dorso-dorsal stream that projects from V2 and V3 to V6, then to the posterior parietal cortex (148,152,154–156). It is still being debated as to whether V1 projects directly to V6 (152).

Dorsal pathway neurons exhibit a high level of selectivity for motion direction (104,157). The integration of diverse visual information from one's visual field, specifically many small receptive fields, is required to accurately represent an object's true motion that one sees (103). The first visual region that contains direction-sensitive neurons is V1, and these neurons have small receptive fields (152) that contain information about individual dot's motion information (103). The feature processing that occurs in V1 of the dorsal pathway is similar to that of the ventral pathway (114) and V1 cells are associated with incoherent or local motion (99,103,118–122).

Although V2 is part of both the dorsal and ventral pathway, it has different functions. In the dorsal pathway, V2 along with V3 analyze local (1D or one-dimensional) motion with such

information as speed, spatial and temporal frequency, and direction (114). It is worth noting that only a minority of neurons in V2 and V3 are direction sensitive (152). Information from the V1, V2, and V3 cells is then amalgamated specifically within the middle temporal area, to recreate the pattern or global (2D) motion associated with the moving objects one was seeing (103,114,158–160), as the majority of MT neurons are direction sensitive (152).

V6 is involved with unidirectional motion, speed preference, direction selectivity, and object and self-motion recognition (156,161). Within V6, there are certain motion sensitive neurons, known as "real motion cells" (156,161). These neurons have also been found in V1 (162), V2 (163), and V3/V3A (164), although in smaller quantities (156). Research performed on monkeys demonstrated, that when they fixate on a point, the real motion cells will react when stimuli is moving in a specific direction (156), thus V6 is an area that has been demonstrated in macaques to be involved with motion analysis (156).

The major regions of the dorsal stream associated with motion processing are the middle temporal area (MT) and the medial superior temporal area (MST) (156). These regions are selective for direction (165–169), and speed (158,170–173), and are highly responsive to motion (156). MT cells have unique characteristics and greater receptive field sizes compared to V1 cells. It is the middle temporal area that integrates the information from the V1 cells to determine the global motion of the object or target (103). The larger receptive fields of the MT cells help individuals separate different moving objects from one another and determine the different motion directions of many moving dots within the same target (114). Thus, MT cells facilitate local (incoherent or component) and global (pattern/ RDKs) motion processing (114,174,175) in the dorsal pathway.

The MST area is involved with the processing of complex 3D (three-dimensional) motion and intermediate object representation, where movements such as contractions, translations, expansions, rotations, spirals, and optic flow are analyzed (114). Finally, in the posterior parietal complex, optic flow and intermediate object representation are processed, and self-motion and multi-model integration analysis occurs (114).

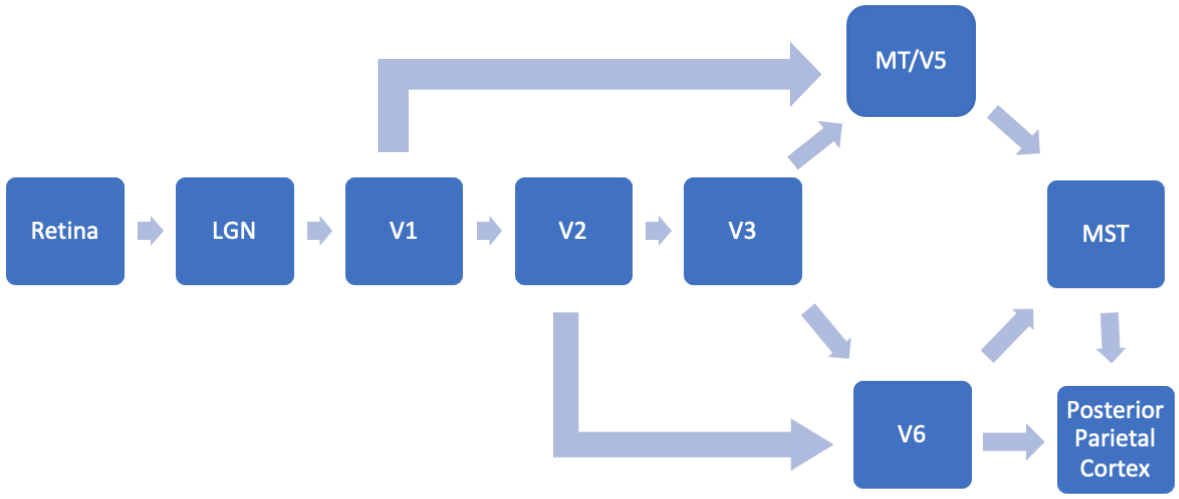

Figure 1.2: The Dorsal Stream.

1.6.3.1 Global Motion

Dorsal stream function can be measured by psychophysical tasks, such as global motion (GM) perception tasks that target such areas as the middle temporal area (99,119,159). GM perception refers to the ability of one's visual system being able to detect and perceive the overall motion direction of objects or patterns and recognize coherent motion within a noisy motion stimulus (176–179). GM involves the integration and analysis of separate local motion signals from multiple local motion detectors in the visual cortex into a coherent perception of motion (104,178–180).

Visual areas including V2 and V3 are highly sensitive to GM (152). The main function of the V2 and V3 visual areas is GM processing, with V3 being stronger than V2 (152). Additionally, extrastriate areas involved in GM processing include V3/V3A, V6, and areas in the intraparietal sulcus of the posterior parietal cortex (178). Thus, the entirety of the dorsal stream is involved in some way with GM perception and GM perception relies on the dorsal stream neural pathway to be processed properly (104,181).

Random dot kinematograms (RDKs) have been a common format used to measure GM perception (99,133). Early cortical areas (e.g., V1, V2) are involved in the initial processing of motion of the individual dots in the RDK (133). The gathering, consolidation, and spatial integration of local motion information occurs afterwards in the extrastriate cortex's neural networks of higher cortical areas (e.g., MT) and assists with the perception of the overall

direction of the RDK pattern created (111,113,152,154–156,158). Specifically, this network is thought to primarily involve a complex within the temporo-parieto-occipital junction known as the middle temporal area/medial superior temporal area complex (133,152,178).

Multiple researchers conducted studies involving macaques with lesions in their middle temporal area and found their GM to be impaired (104,152,159,182). Other researchers performed microstimulation to the middle temporal area and found one's judgement about GM direction to be impaired (152,160). The middle temporal area was further investigated using moving sine wave gratings and plaids. Sine-wave gratings consist of alternating light and dark stripes, with the alternation being described by a sine wave. The sine wave plaids occur when two moving sine wave gratings are crossed. Through using psychophysical and electrophysiological experiments involving the sine wave gratings and plaids, Movshaun et al., identified the middle temporal area as the location of cells involved in GM processing (179,183).

Parameters involved in a GM task, such as dot density and speed, contribute to an adult's GM sensitivity (178). Positional changes and the speed of an object are other factors that contribute to how one perceives directional movements (132,161). Furthermore, when a participant is performing a GM task involving RDKs, the researcher will often limit the dot lifetimes to ensure a participant is not able to track individual dots (178). By eliminating tracking strategies, it is easier to determine if an individual is measuring GM integration rather than local motion sensitivity (178).

Multiple studies have investigated the effect of age on GM perception, finding a decrease in GM to occur in older adults (184,185), where healthy aging leads to a decline in motion perception (186,187), shown by the increase in motion direction discrimination thresholds (186). This decline that occurs in older adults varies with the different speeds involved in GM tasks (184,188). Although the motion thresholds at both slow and fast speeds of GM were worse for older than younger adults, slow GM began to decline but fast GM was about normal at the age of 60 and fast GM showed no decline with age (184,189). Some researchers have associated the decline of GM in older adults with age-related structural changes of the visual cortex (184,185). Furthermore, atrophy of the dorsal stream (due to aging) worsens the results of both fast and slow GM, but ventral stream atrophy only worsens slow GM (184). Other researchers have also blamed additional resource and brain region recruitment, spontaneous noise increase, sensitivity

loss, and increased neuron excitability within the early visual areas for the decline in GM as one ages (186).

Many studies have also investigated the effect of gender on GM perception. Of these studies, Tran et al. (1998) did not find a gender effect associated with GM (190), however many other researchers did find males had lower thresholds than females, and thus, better GM at practically all ages (189,191–193). However, in the study performed by Arena et al. (2012) that included individuals aged 20 to 79, the gender effect was not found in individuals aged 20 to 59, it was only present from ages 60 to 79 (192). It appears that women are more prone to a functional decline in GM than their male counterparts, as they lose their motion sensitivity to a greater extent as they age (194–197). A recent study by Shaqiri et al. (2018) also found males to have better performance than females in GM tasks (62). The females involved with the Shaqiri et al. (2018) study had slower reaction times and needed a higher number of signal dots to be able to determine the motion (62). Some researchers believed females performed worse on motion detection tasks than males due to not being able to extract the signal dots from the noise dots as efficiently as males (194,198,199). However, this theory was disproven by Conlen et al. (2017), who suggested the gender difference was the result of females not being able to integrate motion signals as easily, rather than due to lower motion sensitivity (194,195).

Previous research has been performed comparing GM to other visual tasks with results finding that GM has been associated with both visual acuity and stereopsis (132). The visual information necessary for stereopsis, known as retinal disparity, uses the dorsal stream (181). Notably, in these specific research findings, the correlation between GM and VA was with static VA and not dynamic VA. However, some of the motion patterns present in GM are similar to those used within dynamic VA, therefore prompting further research in this area.

It is possible GM perception and dynamic VA are related as both these visual functions involve integrating motion information to be able to determine the fine details of objects moving in one's visual field and they are both involved in one's understanding of dynamic scenes in a visual environment. GM perception involves determining the overall motion or direction of objects or patterns within a scene (179), while dynamic VA helps determine fine details of objects in motion (1–4). To determine the overall motion of objects (GM), one must be able to see these moving objects clearly (dynamic VA), and to detect detail in moving objects (dynamic

VA), one must first be able to determine the overall motion of the object (GM). Thus, the neuromechanisms underlying GM may also play an important role in driving dynamic VA.

1.6.4 Local Motion

Local Motion (LM) is a perceptual task that assesses individuals' sensitivity to motion direction and perceptual knowledge about object motion in an image (176–178,200). Direction, speed, and motion coherence are three characteristics interpreted by an individual using LM (178,200). This further allows the interpretation of individual object's or pattern's movements within a larger scene (178,200). LM has been labelled as perceptual because LM involves the early cortical visual areas, along with multiple other brain areas and systems interacting with one another to integrate and process LM information (201–204).

LM processing begins in the retina, where a potential higher sensitivity to LM has been found in the neural circuits associated with the peripheral retina, compared to that of the central retina (204–206). From the retina, LM travels to V1. V1 is an area of the cerebral cortex with motion direction sensitivity and contains cells that extract LM information (118,207). Research involving damage in the V1 area, or magnocellular retino-geniculate pathway, has further proven an association with V1 and LM processing, as results demonstrated there to be subsequent impairment of LM processing when V1 was damaged (99). Usually, the outputs from V1 will travel and combine with one another in higher cortical areas such as V4 for GM perception, as previously stated (118). It is the LM signal extraction that generally begins the process of motion analysis (201); motion integration only happens once the processing of LM has occurred (208).

In addition to V1, another area of the brain that has been associated with LM is the middle temporal area. It has already been noted that the middle temporal area has an important role in visual motion analysis, especially GM perception (133,152,178,179). However, other researchers have found the middle temporal area to have some LM sensitivity (204,209), with neurons in this region being direction selective (204,210–213). In addition to direction selective neurons being found in MT, LM perception may also rely on signals coming from the MT area, which help determine coherent or incoherent motion perception as they present LM details integrated with scene information (204,214). There are also two kinds of LM signals: glider and Fourier signals (201). When an object either comes closer to or further away from an individual, the glider signals are used (201). However, if there is translation of an object, then it is the Fourier signals

at work (201).These LM signals are discovered by a form of sensor in the middle temporal area known as the “spatiotemporal-frequency-selective sensors” (215).

Some researchers have also suggested that the medial superior temporal area is associated with LM perception. Research has found that motion representation occurs in the medial superior temporal area (a downstream target of the middle temporal area) (94,204,207,208,214,216), and neurons here are sensitive to clockwise and counter-clockwise rotations (217–220). Although the research presented here appears to support that the middle temporal area and medial superior temporal area are associated with motion analysis, and are connected to LM processing, it is also possible these areas may be sensitive to LM processing more so to be able to process GM perception rather than for LM processing itself.

Random dot kinematograms (RDK) are commonly used for the measurement of LM. The goal of a LM task is to discriminate whether the dots presented in two sequential RDK are moving in either a clockwise or counter-clockwise direction compared to one another (207). Within an LM task, there are multiple trials that occur as each trial only appears for a short period of time (94,207). Two stimuli are presented consecutively in a single trial, and the participant is then asked to judge the direction of the stimuli’s rotation between presentations (i.e., clockwise or counter-clockwise) (94,207). The participant’s answer is typically entered through their use of a keyboard or controller.

Many previous studies have investigated the effect of age on LM, demonstrating a decrease in LM performance, or increased thresholds, with increased age (189,194,221–226). All these studies used gratings as their form of measuring LM perception, rather than the RDKs. As well, these papers were using threshold measures of contrast, duration, speed discrimination, noise, and signal-to-noise ratios, rather than direction discrimination thresholds.

Not much research has been performed studying gender effect in LM perception. However, research has found that in mental rotation tasks, males tend to use more of a global approach with the task, whereas females tend to use a more local approach such as through identifying certain parts of the object to determine its rotation (227–230). Roalf et al. (2006) have also suggested women tend to respond faster to local targets compared to global targets, suggesting women have a local bias (230,231). Even when reviewing the differences in gender in relation to navigation, males tend to use more of a global approach with cardinal directions (230,232–234), whereas females often use landmarks (230,234–236) and local cues (230,232,233). Thus, it

seems females are more often found to use local cues compared to males, potentially inferring they may perform better on LM tasks.

LM perception ensures one can recognize, understand, and follow the motion of individual objects (178,200). LM has been found to play a very important role in object recognition and scene analysis, and the multiple visual processes that go along with such analysis. Some examples of LM in scene processing include tracking moving objects and detecting motion-related cues. Furthermore, LM assists individuals in their ability to navigate and comprehend the visual world around them through the interpretation of objects' movements and dynamics within their environment.

Dynamic VA is the ability to maintain clarity and discriminate fine details of moving objects (1–4). Thus, both dynamic VA and LM are related to the processing of moving visual information and the recognition of objects in motion. When tracking the motion of individual objects (LM perception), the ability to clearly see these objects is critical (dynamic VA). Likewise, seeing the detail in moving objects (dynamic VA), relies on the ability to track the motion of the individual object (LM). Although these tasks are separate and distinct visual functions, it is possible they work together to facilitate an individual's understanding of objects in motion and thus share some similarities in their mechanisms that support the visual perception of complex dynamic scenes.

1.7 Cognitive Processing of Visual Information

1.7.1 Cognitive Inhibition and the Stroop Task

Inhibition is an important concept as many successful behaviours depend on it (237). It describes the brain's ability to suppress distracting and irrelevant information and cues to determine what is important (237). Inhibition is involved in many cognitive processes, such as decision-making, attention, and memory and refers to one's ability to remove unnecessary visual information, and only keep what is relevant to the scene (237).

The Stroop effect occurs when a specific stimulus feature being processed hinders the processing of a second stimulus feature or a different attribute of the same stimulus (238). The Stroop Colour and Word Test (SCWT) is a neuropsychological test used in experimental and clinical conditions to measure inhibition (239). More specifically, the SCWT assesses the ability of one to ignore cognitive interference during the Stroop Effect (239). Processing speed, working

memory, attention, and cognitive flexibility are among the other cognitive functions that are also measured by the SCWT (238,240,241).

In the most basic form of the SCWT, a word is presented, and the goal is to determine the colour of the word rather than reading it (239). Thus participants must perform a less automated task (i.e., determining the colour), while the interference that comes from the more automated task of reading the word is inhibited (238,242). The Stroop Effect can be seen in the difficulty an individual has in inhibiting the word reading (i.e., the more automated task) (238). This relatively simple task, and the interference phenomenon it contains, is continuously helping researchers to understand and gain valuable insights on one's cognitive processing (243).

In 1886, Cattel introduced the automaticity concept to cognitive science, where he suggested extensive practice is the reason reading words is automatic (243,244). Under this concept of automaticity, reading cannot simply be "turned off" (243). Therefore, even if an individual is given explicit instructions to not read a word, they sometimes cannot refrain from doing so (243). Interference occurs with incongruent words (e.g., the word red presented in the colour green), which explains why a slower, and typically error-prone, response occurs on the SCWT when an incongruent condition is presented where the word is different than the ink colour of the word (243).

The concept of automaticity and how one processes something can be closely related; if a task to be performed is more automatic to an individual, they are likely to process the task faster (243,245). This "relative speed of processing account" contributed to further explanations of the Stroop interference effect and goes on to state that slower processes are affected by faster processes, but not vice versa (243,245). In relation to the SCWT, words can be read faster than colours can be identified, and the interference occurs when the task is to identify the colour rather than word (243) because there is more uncertainty present when determining colours of words than there is when reading a word (243). The issue humans have when attempting to determine colours over words indicates that a certain level of computational processing is involved with processing colours, and the SCWT demonstrates this processing can be disrupted (243). The cognitive processes of colour recognition further contribute to the interferences that occur when naming colours (239).

Kline introduced the law of associative inhibition, quoted as "If *a* is already connected with *b*, then it is difficult to connect it with *k*, *b* gets in the way" (196, Pg. 270). This law also helps to

explain interference and how associations between colours and their names occur and strengthen overtime as they are continuously used (239,246). Bergstrom further added to the explanation of this law by stating "the interference effect of an association bears a constant relation to the practice effect, and is, in fact, equivalent to it" (197, Pg. 441); if an association is constantly being interrupted, then the association is broken and instead a new association is being practiced. Another model related to the SCWT, proposed by Cohen, Dunbar, and McClelland, known as the parallel distributed processing or connectionist model, has stated practice causes an increase in strength for processing pathways and the degree of interference is determined by the relative strength of the pathways (243,248). Relating this model to the SCWT helps explain that colour-word pathways and colour name responses are usually more strongly connected than the colour-word pathway to colour pathways (243,248). Stroop himself concluded that a difference in training could account for the speed difference one has when identifying the colour of the word compared to reading the word (239,243). It has only been more recent studies however that have confirmed how important experience and training is (243).

In 1915, it was previously stated that practice is not the reason for the speed difference when identifying colours and reading words, but rather association (249). The associations for the two tasks are very different from one another (249). Each word has become associated with one response habit, but there seems to be a variety of response tendencies for colours (239). However, it can be seen from the ample research that has been performed with the SCWT, many researchers now believe it is the combination of association and practice that explains an individual's performance on the SCWT (239,243,246–248).

The effect of age on the Stroop task has also been studied with the majority of studies involving the Stroop task having shown there to be a greater reduction in Stroop performance the older an individual is (250–256). Although Gajewski et al. (2020) stated that older individuals who performed better on Stroop than their similar age counterparts were performing similar to middle-aged individuals (250). When referring to reaction times, younger individuals had the fastest times, with the reaction times slowing as ages increased (250). It was especially the congruent condition reaction times that slowed the most with aging individuals (256). Researchers have found that the greater Stroop interference that occurs in older adults, compared to younger adults, is partially the result of general slowing, but also is related to the changes that occur in cognitive inhibition and inhibitory control (256–260). However, Wolf et al. (2014)

stated that the cognitive inhibition measured by Stroop is not the result of general slowing, but rather a decline in cognitive processing occurring with age (256). As it was thought that the processing speed of an individual may also have an impact on the results of Stroop, this speed was studied, and it was found that processing speed described the variances occurring for incongruent conditions (257). However, when processing speed was controlled, the effect of age on Stroop was still present (257). Thus, the decline that occurred with older individuals was partially due to a decline in processing speed, but also due to other factors that were more specific to the Stroop task (257). (257).

Previous studies have also investigated the effect of gender on the Stroop task. Macleod (1991), along with multiple other researchers did not find a gender effect related to the Stroop task (261–265). However other researchers have found a gender effect, stating that shorter reaction times are present when females perform the Stroop task compared to males (266–269), although no significant differences were found in the error rates between males and females (269). Datta et al. (2020) further specified in their study that females even had shorter response times for the Stroop effect (270). Due to numerous studies including neutral conditions ("XXXX" written in red, green, blue or yellow, determine colour only; white words spelling colours, determine word), incongruent conditions (word colour does not match spelling of word, determine colour), and congruent conditions (word colour and spelling are the same, determine colour), Datta et al. (2020) were able to determine that colour processing occurred faster in females (270). However, Mekarski et al. (1996) stated it was the men that had a faster response to colours and women actually had a faster response to words (269). Datta et al. (2020) mentioned their findings may have been the results of anatomical differences of the brain, specifically the callosum and planum temporale being larger in females (270), while Mekarski et al. (1996) stated the difference in males in females that they found was due to greater spatial abilities in men and better verbal and fine motor abilities in women (269).

Based on the studies discussed above, it appears that association, practice, training, and experience are all important factors in determining how one is able to perform the SCWT. In a moving scene, one should be able to see and discern the fine details of objects in motion with the use of dynamic VA. The relationship between dynamic VA and inhibition may depend on cognitive processes associated with maintaining visual clarity with moving objects, particularly when objects are moving in unpredictable patterns. When an individual is trying to see an object

moving in an unpredictable way, such as on a dynamic VA task, they likely need to filter and inhibit irrelevant visual information such as unrelated scenery, objects (moving or static), patterns, colours or text. This inhibition allows the individual to concentrate on the target details themselves rather than exerting their cognitive energy in trying to track or predict the target's motion. Thus, inhibition may contribute to dynamic VA by assisting an individual with ignoring the motion of the target in order to focus on relevant details of the target that assist with target identification. It is likely that the better an individual's inhibition mechanisms are, the more effectively they can maintain dynamic VA in scenes with motion.

1.7.2 Multiple Object Tracking

Every day, a person is frequently required to isolate important objects from their visual world. The difficulty of this task often increases when objects are in motion, when the field of view is moving in relation to the surrounding world, or when there are multiple objects in motion that need to be monitored at the same time (271). This motion then requires individuals to be able to track important objects over time and through different fields of view (271). Tracking moving objects is crucial to one's ability to understand the dynamic world around them (271).

Perceptual-cognitive skills are important for many real-world situations such as playing sports (8). Vision scientists and sports psychologists have proposed several methods for "objective indicators of perceptual-cognitive skills" (8). Additionally, researchers in sports are attempting to develop tools to measure visual functions that are representative of sport and correlate with on-field performance (8). Multiple object tracking (MOT) and dynamic VA are two of these tools and have the potential to be used as indicators of perceptual-cognitive skills necessary for sports performance (8). Furthermore, a variety of topics involving visual cognition have been studied in research involving MOT (271). Some of these topics include (201) differences in attention amongst various age groups (272), divided or multifocal attentional limits (273,274), attention deficits in varying patient populations (275,276), and the dynamics of attention (277).

MOT is an experimental technique used to assess one's ability to visually track multiple moving targets. It is designed to measure an individual's ability to maintain focus on several identical, constantly moving targets in a dynamic environment (8,278). There are a multitude of various theories researchers have formulated over the years in an attempt to explain how we

process MOT (279). One paper specifically studied the issues associated with the mental processing of MOT and thus with these various theories (279). These issues included tracking capacity (in general and its size amongst different individuals), higher order cognition and its possible relation to tracking, and whether tracking is automatic or not (279). In their research, Oksama and Hyönä found tasks involved with attention switching and visuospatial short-term and working memory predicted MOT very well (279). They also determined that individuals had decreased tracking performance in relation to tracking time, showing that there is no automaticity to tracking, thus maintaining target tracking requires attention (279). Furthermore, they showed that tracking involved both parallel and serial processing but tracking abilities may be the result of limited tracking capacity in parallel processing (279).

Tracking capacity on MOT tasks tends to vary among individuals (271,279). Those with expertise tend to show an increase in the number of objects they are able to track (e.g., video game players can usually track more objects than non-video game players) (271,280). The number of objects one can track is not a fixed number, rather the limits of one's ability to track multiple moving targets is established primarily by a shared resource (271). The attention one gives to objects they are tracking can be flexibly distributed (271). When a person is tracking only one object, then all their resources have been allocated to tracking this object (271). However, if a person is tracking two objects, then their resources must be split amongst the two objects they are trying to track (271). This means that as the number of objects one must track increases, the amount of resources allocated to tracking each target will decrease (271). As well, the maximum speed at which one is able to track objects decreases as the number of objects to track increases; hence the reason individuals are often able to track more objects at a slower speed (271). These results are once again due to resource limitations, and most specifically, available attentional resources (271).

The first MOT experiment was created in 1988, and it was formed to test the visual indexing theory, which is also known as the fingers of instantiation or FINST theory (278,279,281). This theory assumed that tracking abilities are automatic and parallel processing with limited tracking capacity occurs when an individual is performing an MOT task (278,279,281). The limited capacity is due to there being only four or five fingers of instantiation, or pointers, available to connect to the visual objects being tracked (278,279,281). In the first experimental task, there were 10 randomly moving objects within a given trial. Of these 10 objects, a prespecified group

(anywhere from 1 to 5 objects) would be the targets an individual was to focus on. The remaining objects would be distractors. Throughout the task, one object at a time would flash, and the participant was to determine if the flashed object was a part of the targets they were tracking or a part of the distractors. Once the flash occurred, they used a response key to input their answer, and were instructed to do so as quickly and accurately as they could (278).

From the time the first MOT experiment was created, other researchers have since adapted the task to further fit how they believe MOT is processed within an individual. A frequent format of MOT testing involves eight single-coloured (e.g., black) balls on a screen with a white background (8). Three of these single-coloured balls appear in a different colour (e.g., green) for the first few seconds of the test, then turn black again before all the objects start moving in various directions (8). After a predetermined period of time (e.g., 10 seconds), the dots come to a stop and the participant must identify which balls were highlighted in a different colour at the beginning of the trial (8). This test is still run in a similar format to 1988, where one ball at a time will be highlighted at the end and the participant will be asked if that was one of the original highlighted balls they had seen.

Research performed studying the neural mechanisms that underlie MOT determined the anterior and posterior intraparietal sulcus, frontal eye fields, superior parietal lobule, middle temporal area, and medial superior temporal area were all involved with the tracking involved with MOT (282). These areas were also all activated bilaterally upon tracking. Evidence from this study showed it was likely for the middle temporal area and medial superior temporal area to represent the moving targets' locations (282). As well, the responsibility of active object tracking is associated with the anterior intraparietal sulcus (282). There were strong connections found with the anterior intraparietal sulcus and almost all of the four other neural areas mentioned, but most of the other areas only seemed to be associated with the anterior intraparietal sulcus (282). From this information, a neural pathway for MOT was drawn with the middle temporal and medial superior temporal areas determining the objects' locations, then the posterior intraparietal sulcus determined which objects were targets (282). The anterior intraparietal sulcus contains the information regarding the target, and additionally, its location, and also assists with eye movement suppression by interacting with the superior parietal lobule and frontal eye fields (282). This suppression is assumed to assist with eye movement coordination in naturalistic conditions (282).

Previous research has been performed investigating the effect of age on MOT, with their results suggesting an individual's ability to perform MOT decreases with age, with younger adults performing better than older adults (283–286). Younger adults were able to track objects and report the objects positions better (283), especially when the objects are moving at a faster speed or are shown for a longer period of time (284–286). Furthermore, older adults are more greatly impacted by increased numbers of objects they are to track (283–285). Although researchers have stated the decline in MOT performance, as an individual ages, is not the result of a change in memory (278,284), other researchers have mentioned the declined performance may be the result of the working memory changing (286) and a reduced ability to maintain tracking positions in the working memory (283). As well, Trick et al. (2005) stated the decrease in MOT performance cannot be caused by a decrease in attentional resolution (283), but Sekuler et al. (2008) mentioned the change in attention to be a potential issue (284). Other reasons that have been ruled out according to researchers include motion insensitivity and issues with concentration (283). Additionally, MOT involves controlled-endogenous processing (cognitive processing intentionally directed by internal goals or knowledge), however, the brain areas involved in this form of processing deteriorate with age (283). Finally, a reduction of stereoacuity that occurs as one ages, may cause a decrease in MOT, as the two have previously been correlated (286).

There have also been a variety of different studies that have investigated the effect of gender on MOT. Previous research has shown males to have better performance related to an MOT task, compared to females (287–289). The result was the same whether tracking one object or tracking up to four objects (287). Another study had also stated the variability they found in the results of the MOT task was due to gender, however further details were not provided as to the mechanism driving the gender difference (290). Due to the gender effect remaining present regardless of the number of targets, within the limit of the study previously performed (maximum number of targets was 4), this may suggest the effect is not necessarily related to the ability to distribute attention amongst multiple targets, but rather how efficiently genders are able to resolve and manage attention over short time intervals (287). The difference occurring between genders in their ability to resolve and manage attention could involve differences in the speed with which individuals of different genders process and respond to visual stimuli or changes in their environment (287). As well, there are morphological brain differences and hormonal differences

associated with the different genders that could account for the gender effect in MOT (287). Furthermore, participation in sports or video games could contribute to differing MOT scores (287,291,292) suggesting societal and cultural constructs likely also play a role in MOT performance. One study performed by Jin et al. (2023) even showed male and female basketball players to have similar results on an MOT task, suggesting certain skilled training involved with basketball assists females, but not males, with their performance on an MOT task (289).

There is various research that has been performed comparing MOT to other visual functions. Previous research involving stereopsis in dynamic conditions (such as in 3D MOT tasks), has revealed stereopsis to have a facilitation role (277,286). Studies have shown there to be improvements in MOT speed thresholds when stereoscopic cues and stereoscopic training are involved (291,293). Most recently, Plourde et al. (2017) looked at the effects of stereopsis on MOT in children (7-12 years), adults (18-40 years), and older adults (≥65 years) (286). They determined stereopsis to be helpful in children and adults, but not older adults, when the participants were attempting an MOT task (286). Although the performance of adults was better than that of children and older adults on an MOT task, both the adults and children benefited when stereoscopy was added to the MOT task (286).

Dynamic VA and MOT are tasks that rely on similar factors such as movement velocity and size of targets (8,271) From these relations and from previous research findings of MOT and stereopsis being associated with MOT performance (286), along with other studies associating static VA with dynamic VA (67,81), Vera et al. conducted a study involving healthy young adults to assess the relationship between static VA, dynamic VA and MOT (8). Their results determined that better performance on both the horizontal and random dynamic VA tasks was associated with improved tracking of multiple objects (8). The results showed dynamic VA and MOT to be positively correlated (8), where if one was easily able to identify horizontally and randomly moving targets (had better dynamic VA), then they were also able to track MOT targets moving with a greater target speed (8). These results suggest that the neurophysiological mechanisms of dynamic VA may have similarities with the neurophysiological pathway driving MOT.

1.8 Conclusion

One of the major problems present when speaking of dynamic VA is the visual perceptual processes involved in completing a dynamic VA task are not fully understood, limiting researchers' abilities to examine the utility of this task in greater detail.

Without a full understanding of the visual perceptual processing involved in completing a dynamic VA task, it becomes difficult to accurately assess and diagnose visual issues related to dynamic VA. Furthermore, training, or other treatments designed to enhance dynamic VA may be less effective if there is a struggle to create targeted treatments addressing the specific visual perceptual processes causing issues. Furthermore, within research, an incomplete understanding of dynamic VA mechanisms can lead to difficulty in conducting robust experiments, limiting the meaningfulness of conclusions that can be drawn about factors influencing dynamic VA.

Training and enhancement of dynamic VA has significant potential to improve performance of individuals in sport, driving, aviation, and other areas of daily life where obtaining detailed information from moving targets is of critical importance for task success. Dynamic VA, once better understood, also has tremendous potential to be incorporated into visual standard assessments for drivers and pilots alike, due to its apparent correlation with functional performance.

Understanding the underlying visual perceptual processes involved in the dynamic VA task, will help us to design training paradigms and future research projects to determine 1) if dynamic VA can be trained, and 2) if improvements in dynamic VA performance will translate to improved performance on daily living skills. There is also the potential to develop treatments for individuals with dynamic VA issues.

1.9 Thesis Objectives

Previous Dynamic VA studies have been conducted using a variety of different methods, many of which did not include a standardized and validated tool for dynamic VA. It was only in 2017 when moV& was created, tested, and validated that such a tool had come into place for researchers to use (5). Furthermore, dynamic VA as a visual function is not very well understood despite various research being performed.

Dynamic VA appears to be a better predictor of driving (1,11,12), piloting (13–15), and sport performance (20–25,34,71,75,85–87) compared with many other visual function measures,

including static VA. As we learn more about dynamic VA, we can better understand how to apply it in clinical practice, where it has the potential to improve patient outcomes in several areas, including driving, sports performance, and traumatic brain injury rehabilitation (294–298). Measuring dynamic VA takes minimal equipment (computer and display screen), so it can be incorporated into clinical practice relatively easily. Understanding the underlying visual processes involved in the dynamic VA task, will help us to design training paradigms and future research projects to determine 1) if dynamic VA can be trained and 2) if improvements in dynamic VA performance will translate to improved performance on daily living skills. The ability to improve daily living skills through vision training, has the potential to support increased quality of life and independence for large numbers of individuals across Canada.

Furthermore, understanding the underlying neurophysiological processes driving dynamic VA will also lay the foundation for future research, as it enhances our understanding of the brain, and is potentially creating new opportunities to study neuroplasticity. The more we know about dynamic VA, the more we can do to make it better and improve one's visual functioning.

The main objectives of this thesis are:

1. To explore what visual perceptual processes are driving dynamic VA.
2. To explore what cognitive processes are driving dynamic VA.

1.10 Hypotheses

1. Dynamic VA will involve similar neurophysiological pathways to both global motion perception (dorsal stream) and global form perception (ventral stream), rather than the local motion pathways (primarily V1).
2. Dynamic VA will require some level of cognitive processing and attention, similar to the MOT task.
3. Dynamic VA will involve similar inhibition practices to the Stroop task.

Chapter 2
Methods

This study was designed as an observational analysis of visual function data collected during visual task assessments.

This study was reviewed and received ethics approval from a University of Waterloo Optometry Research Ethics Committee (ORE # 44456). All participants completed an informed consent prior to their vision assessment (Appendix A). The informed consent explained the visual tests they would complete. The informed consent also explained the data collected during the vision assessments would be used for the completion of an MSc thesis and could be used for research purposes in which their identifying information would not be included.

2.1 Sample Size Calculation

Using G*Power 3.1.9.6 (Heinrich Heine University Düsseldorf, Düsseldorf, Germany), an a-priori power analysis was conducted to determine the smallest sample size required for this study. The power analysis proposed that a minimum of 128 participants were required, assuming an effect size of 0.25, an alpha of 0.05 and a power of 0.80 (Appendix B). Although 128 participants were suggested, we decided to recruit 130 eligible and successful individuals to ensure adequate sample size upon completion of our study. The effect size, alpha, and power of this study were based on previous literature (8), used to determine the relationship between MOT and dynamic VA. As this study was designed to explore the relationship between dynamic VA, MOT, and other tasks, it was decided to use similar values for the power calculation as Vera et al. (8) in an attempt to replicate what they had previously found.

2.2 Participants

The majority of participants were recruited from the University of Waterloo Department of Psychology Research Experiences Group (i.e., SONA). Additional participants were recruited from the University of Waterloo undergraduate and graduate community, the University of Waterloo Optometry Program, and the Kitchener-Waterloo Community.

2.3 Inclusion Criteria

As age has been shown to have an effect on many of the vision tasks being measured, participants for this study were healthy adults aged 18-35 years with normal or corrected-to-normal vision and no known presbyopia or pre-presbyopia. Corrected-to-normal vision was considered to be monocular and binocular visual acuities, less than or equal to 0.2 logMAR with less than 0.1 logMAR difference between eyes and binocular stereoacuity ≤ 40 seconds of arc. Participants were eligible if they met the inclusion criteria and gave consent prior to their participation. Every effort was made to recruit individuals of different genders, including individuals who identify as men, women, and non-binary, but participants were not intentionally recruited based on their gender for this study.

2.4 Exclusion Criteria

Exclusion criteria for this study were:

1. Monocular or binocular visual acuities greater than 0.2 logMAR,
2. 0.1 logMAR difference in visual acuities between eyes,
3. Self-report of pre-presbyopia or presbyopia,
4. Poor stereoacuity (greater than 40 seconds of arc),
5. Actively undergoing medical treatment for any ocular disease that could change visual acuity, and
6. Actively undergoing orthokeratology or myopia control treatment.

2.5 Eligibility

The eligibility of a participant was partially confirmed by their completion of a personal history questionnaire given to them prior to the study visit beginning (Appendix C). Additionally, participant's monocular and binocular static VAs were measured using the Early Treatment Diabetic Retinopathy Study (ETDRS) charts (Precision Vision, Woodstock, IL, USA), and their stereoacuity was assessed using the Randot Stereotest (Stereo Optical Company Inc., Chicago, IL, USA).

The International Physical Activity Questionnaire (IPAQ – Appendix D) was also given to participants prior to the start of the study, although not for eligibility. The findings from this questionnaire have not yet been analyzed as the results are beyond the scope of this thesis.

2.6 Protocol

The participants were asked to attend one study visit that was approximately 1.25 hours in length. They were reimbursed for their time with SONA participation credits or involved in a draw for a $100 visa gift card (one for every 35 participants). All measurements listed below were collected during this single study visit.

2.6.1 Static Visual Acuity

ETDRS Charts were used to assess binocular and monocular Static VAs at a 4-metre distance. Three different ETDRS charts were used (monocular left, monocular right, and binocular). The ETDRS chart is a logMAR chart with 5 letters on each line. Every line on the ETDRS chart is equal to 0.1 logMAR. This meant each letter had a 0.02 logMAR value assigned to it and a per-letter scoring system was used to calculate static VA. Static VA testing ended when a participant scored less than three of five letters correct on a single line.

2.6.2 Dynamic Visual Acuity

Binocular dynamic VA was assessed using the validated dynamic VA test known as moV& (V&MP Vision Suite, Waterloo, Canada). The task was displayed on an LG C1 55'' 4K Smart OLED television monitor (OLED55C1AUB) with a horizontal visual angle of 17.38 degrees and a vertical visual angle of 9.94 degrees at a test distance of 4 metres. The display ran at a refresh rate of 59 Hertz, with a resolution of 1920x1080. This test contained a black target, that was a tumbling E, on a white background. The tumbling E was always presented in one of four orientations with the legs facing left, right, up, or down. The display was always set at 100% contrast level. Participants were seated 4 metres from the monitor, and dynamic VA always began 0.5 logMAR higher than a participant's binocular static VA threshold.

Two motion types were examined: (1) unpredictable random motion and (2) predictable horizontal motion. The target for random motion moved in an unpredictable pathway (Figure 2.1), similar to that of Brownian particle motion. This target was unpredictable at all points during the task duration and frequently exited and re-entered the screen (i.e., it was not only shown once like with the horizontal motion). For horizontal motion, the target moved from the left to the right of the monitor, only showing once (Figure 2.2).

During each trial, the target was shown for a maximum of 20 seconds or until the participant indicated their response for the orientation of the tumbling E by pressing corresponding buttons on a control pad. The arrow keys (left, right, up, and down) on the control pad corresponded to the orientation of the target (tumbling E). The target disappeared for both random and horizontal motion when the participant inputted their response. The next trial for both motion types began immediately after a participant indicated the response on the previous trial.

The dynamic VA measurement threshold was determined similarly to that of static VA. LogMAR dynamic VA was measured within moV&. For every 0.1 logMAR line, five single letters appear. Per-letter scoring was used where a 0.02 logMAR value was assigned to each letter. moV& stops when less than three of five letters on a single line are answered correctly by the participant. The target was continually shown in incrementally smaller targets (i.e., the logMAR decreased, as in static VA) until the participant completed the task.

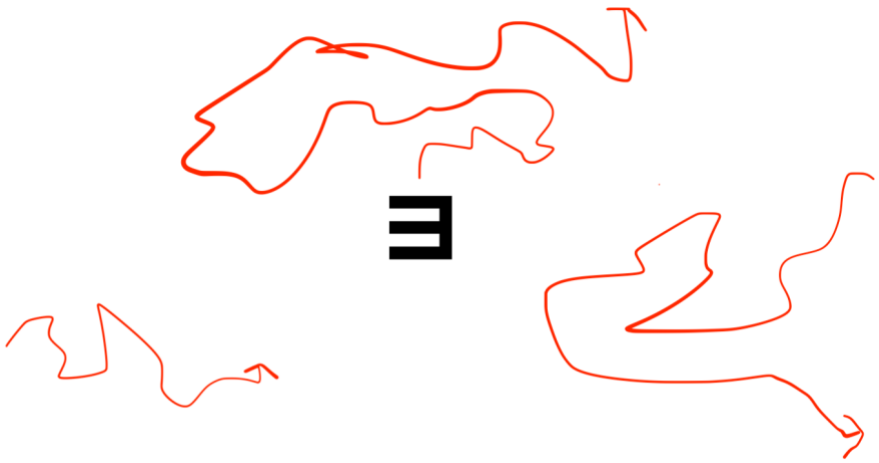

Figure 2.1: An illustration of the moV& task random walk motion with a left-facing tumbling E.

Figure 2.2: An illustration of the horizontal motion with a tumbling E pointed towards the right.

2.6.3 Cognition and Visual Perception Tasks

The remainder of the tasks mentioned below were tested using stimuli created in MATLAB version 9.13.0.2105380 (R2022b) (The MathWorks Inc., Natick, MA, USA) with the participant seated 1 m from the same LG television monitor used for dynamic VA. However, the refresh rate of these tasks was 120 Hertz with a resolution of 1920x1080, as they were running on a different operating system than the dynamic VA task. All tasks, not including the Stroop task, were presented at 100% contrast on a white background with luminance measured by a lux metre and values ranging from 317-354 lux across the monitor. Prior to each experiment, all subjects were able to practice numerous trials until they were familiar with the stimuli and visual function tasks. The number of practice trials was not controlled. Feedback was given in practice trials.

2.6.3.1 Global Motion Perception

GM perception was tested using random dot kinematogram (RDK) stimuli (Figure 2.3). Throughout the experiment, subjects were asked to maintain fixation on a grey dot (diameter = 0.4 degrees) presented at the center of the screen. The RDK consisted of 100 black dots presented within a circular annulus (outer radius = 5 degrees, inner radius = 1 degree). Dots had a diameter of 0.235 degrees and a density of 1.33 dots/degrees^2. There was a displacement of dots approximately every 8.3 milliseconds at a refresh rate of 120 Hertz. This allowed the dots to achieve a speed of 6 degrees/second. There was a very limited dot lifetime, where every dot had about a 5% chance of being randomly relocated with every frame. The stimulus was present for 0.3 seconds in a trial.

Noise dots moved in random directions and the direction of the signal dots was randomized. Subjects were asked to make a two-alternative forced-choice (2-AFC) judgment of the GM signal dots direction (right to left or left to right) by inputting their answer into a control pad. No feedback was provided. The next trial began 0.25 seconds after a subject's response.

This task employed a 2-down-1-up staircase for the measurement of the motion coherence threshold. The staircase began with a 100% coherence, and a proportional step size, increasing or decreasing by 50% before the first reversal (Equation 2.1), and 25% thereafter (Equation 2.2).

$$\boldsymbol{coh_n + 1 = coh_n * (1 \pm 0.5)}$$

Equation 2.1: The proportional step size increase or decrease that occurs before the first reversal; n denotes the nth trial.

$$\boldsymbol{coh_n + 1 = coh_n * (1 \pm 0.25)}$$

Equation 2.2: The proportional step size increase or decrease occurring after the first reversal; n denotes the nth trial.

There was termination of the staircase after 6 reversals and the threshold for motion direction discrimination was calculated with the last 4 reversals. Two staircases were run sequentially, and the average threshold of the two was used.

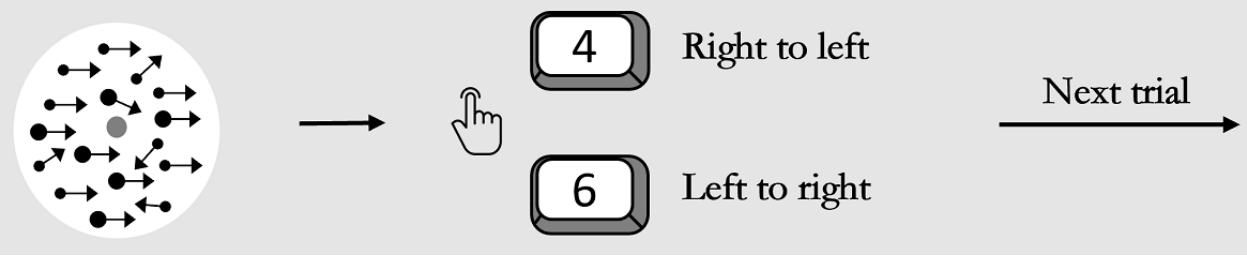

Figure 2.3: The GM perception instructions shown to participants, demonstrating an example of the left to right task, and which keys to use during the task.

2.6.3.2 Global Form Perception

GF perception was tested using a form detection task based on Glass patterns (Figure 2.4). The stimuli were presented for 2 seconds and consisted of 100 dipoles. The distance between the center of the two adjacent dipoles was 1 degree, and there were 10 dipoles in each row and column. This created a dipole array that was 9 degrees by 9 degrees.

Two populations of dot pairs known as the “signal pairs” and “noise pairs” were present. The “signal pairs” were arranged to form concentric or radial-shaped Glass patterns (Figure 2.5). The “noise pairs” consisted of a random orientation within the display. Coherence was modulated by varying the number of noise dot pairs. This GF task required participants to make a 2-AFC judgment of whether the Glass pattern was concentric or radial using designated buttons on a control pad. The next trial began 0.25 seconds after a subject’s response.

A 2-down-1-up staircase was employed for the form coherence threshold measurement. The staircase began with a 100% coherence. There was a proportional step size within the staircase, increasing or decreasing by 50% before the first reversal (Equation 2.1), and 25% thereafter (Equation 2.2). Termination of the staircase occurred after 6 reversals and the last 4 reversals were used to calculate the coherence form threshold. Two staircases were conducted sequentially, and the average threshold from both staircases was used.

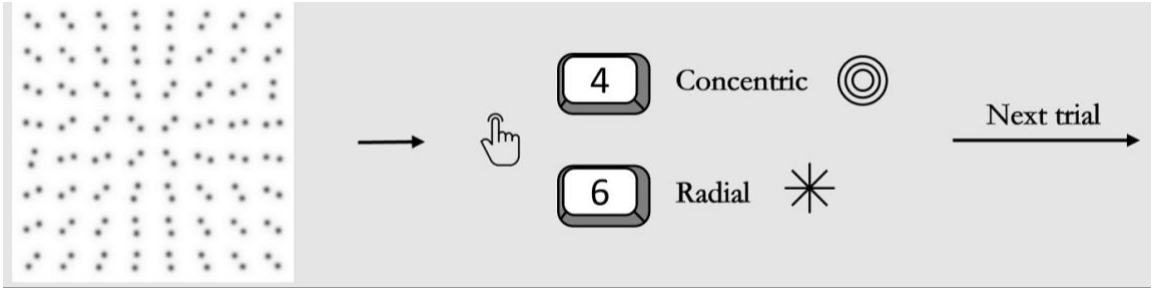

Figure 2.4: Instructions presented to the participant prior to beginning the GF perception task, with an example of the radial form task. Keys associated with the answers are also shown here.

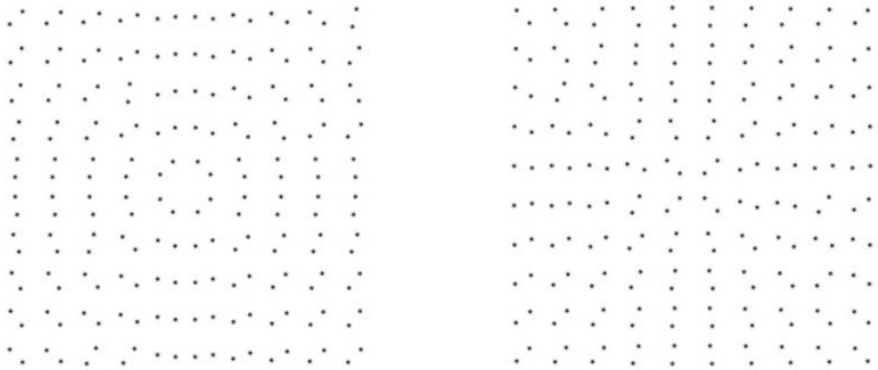

Figure 2.5: A demonstration of the two types of GF perception tasks a participant could see: Concentric (left), and Radial (right).

2.6.3.3 Local Motion Perception

LM perception was tested using RDK stimuli (Figure 2.6). Subjects were asked to maintain fixation on a grey dot (diameter = 0.4 degrees) presented at the center of the screen throughout the entirety of the experiment. The RDKs consisted of 100 black dots, all moving in the same direction. The RDKs were presented within a circular annulus (outer radius = 5 degrees, inner radius = 1 degree). The dots speed within any given trial was always consistent at 6 degrees/second.

In a single trial, two RDKs were presented successively for 0.3 seconds each, and were separated by a 0.6 second blank interval (where nothing would appear on the screen except for the grey fixation dot). Subjects were to make a 2-AFC decision on the direction of the second RDK compared to the first. The direction choice would either be a clockwise or counter-clockwise rotation of the second RDK relative to the first, to which they would input their answer through selected buttons on a control pad.

Motion directions of θ and $\theta \pm \Delta\theta$ were randomly assigned to the two RDKs, where θ was the horizontal motion direction (left to right or right to left) and $\Delta\theta$ was adjusted by a 2-down-1-up staircase for the measurement of the local motion direction discrimination threshold. The temporal order of the two RDKs were randomized.

The staircase began with a 45-degree rotation and a proportional step size, where $\Delta\theta$ increased or decreased by 50% before the first reversal (Equations 2.3a and 2.3b). After the first reversal, $\Delta\theta$ changed by 25% (Equations 2.4a and 2.4b). If the $\Delta\theta$ calculated by the staircase exceeded 80 degrees or the change was below 0.5 degrees, the $\Delta\theta$ was automatically set as 80 or 0.5 degrees. There was termination of the staircase after 6 reversals and the motion direction discrimination threshold was calculated as the mean of the threshold in the last four reversals. Two staircases were run sequentially and the average threshold of the two was used.

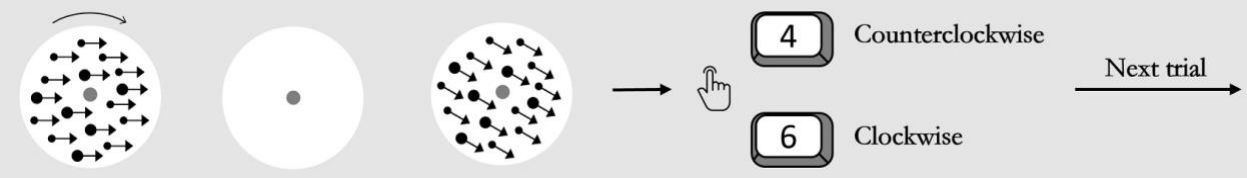

Figure 2.6: The instructions for LM perception shown to participants, with an example of the clockwise direction answer and with the keys to use for the associated answers.

a. $\Delta\theta_n + 1 = \Delta\theta_n * (1 - 0.5)$

b. $\Delta\theta_n + 1 = \Delta\theta_n * (1 + 0.5)$

Equation 2.3: The proportional step size decrease (a) and increase (b) that could occur before the first reversal. A decrease will occur with a correct trial (a), and an increase with an incorrect trial (b). n denotes the nth trial.

a. $\Delta\theta_n + 1 = \Delta\theta_n * (1 - 0.25)$

b. $\Delta\theta_n + 1 = \Delta\theta_n * (1 + 0.25)$

Equation 2.4: Following the first reversal, the proportional step size decrease (a) or increase (b). If two consecutive correct trials were accomplished, there will be a decrease (a), and if one incorrect trial occurs, then an increase (b). n denotes the nth trial.

2.6.3.4 Stroop

The Stroop task was performed using word stimuli (Figure 2.7). A grey fixation point was presented on a white background (luminance values ranging from 317-354 lux across the monitor), showing where the participant should fixate until a word appears on the screen. One of four words would appear: “blue”, “green”, “yellow”, or “red”. Participants were asked to determine the colour of the word that was presented, rather than what the word read or spelled. The colour options were the same as the word options; red, green, blue, and yellow. The participants would input their answers on a control pad with four labelled keys, associated with the colour they wished to input.

Participants were to complete a total of 36 trials. Within the task, there are a total of 16 word-colour combinations that could exist, with 4 being congruent and 12 being incongruent. Congruent word-colour combinations meant the colour of the word was the same as what the word spelled (ex. red colour for the word “red”). Incongruent word-colour combinations were when the colour of the word was different from what the word spelled (ex. blue colour for the word “green”). A 1:2 ratio of congruent to incongruent word-colour combinations was used for

this task, thus the 36 trials consisted of 12 congruent trials (3x4) and 24 incongruent trials (2x12).

The Stroop score was calculated as the difference between the average incongruent world-colour combination reaction time and average congruent word-colour combination reaction time. The Stroop score did not differentiate between correct and incorrect (error) trials, consistent with previous research conducted by Dishon-Berkovits et al. (2000), Bugg et al. (2008), and Henschel et al. (2021) (299–301).

Figure 2.7: An illustration of the Stroop task, demonstrating the two options a participant may have. There is an incongruent word-colour combination on the left, and a congruent word-colour combination on the right.

2.6.3.5 Multiple Object Tracking

MOT was tested using ball stimuli (Figure 2.8). Eight identical black balls (diameter = 2.06 degrees) were presented in a square area with a visual angle of 32 degrees. Three of these eight balls were randomly highlighted in green for 2 seconds before turning black again (Figure 2.9a). The participant was instructed to track the three balls that were highlighted while all eight balls moved randomly for 10 seconds (Figure 2.9b). After 10 seconds, all eight balls came to a stop, and a number from 1 through 8 was presented on each ball in white (Figure 2.9c). The participant was then asked to press the numbered buttons on the control pad that they believed were associated with the three balls originally presented to them in green (Figure 2.9d). No specific instructions or recommendations were given about how best to perform this task or track the balls.

Within a given trial, all balls moved randomly following a primarily linear path at a constant speed. The balls had random departures from their path, moving in unpredictable ways, and bouncing off other balls or the “walls” of the square aperture.

This task employed a 2-down-1-up staircase for the measurement of the speed threshold. This means the speed of the balls was increased if a participant correctly identified all three balls two trials in a row. However, the speed of the balls was decreased if a participant incorrectly identified at least one ball. The staircase began with a speed of 26.3 degrees/second, and a proportional step size, decreasing by 50% before the first reversal (Equation 2.5), and increasing or decreasing by 25% every reversal after (Equation 2.6). Termination of the staircase occurred after 6 reversals, and the threshold was calculated by the mean of the speeds of the last 4 reversals. Two staircases were conducted, and the average threshold of the two was used.

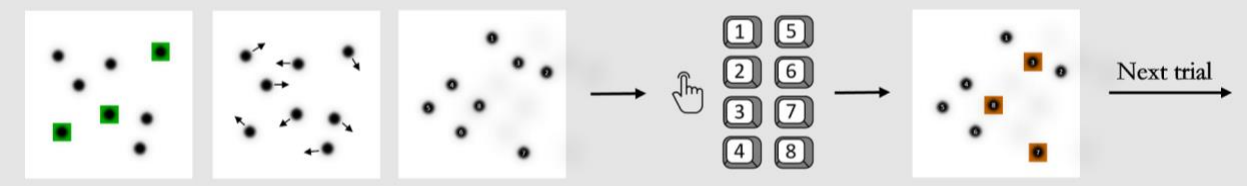

Figure 2.8: MOT instructions shown to participants prior to beginning the task. Each frame is showing the different phases of the task. The buttons associated with the task are shown.

$$spd_n + 1 = spd_n * (1 - 0.5)$$

Equation 2.5: The proportional step size decrease of the ball speed that occurs before the first reversal; n denotes the nth trial.

$$spd_n + 1 = spd_n * (1 \pm 0.25)$$

Equation 2.6: The proportional step size increase or decrease of the speed of the balls occurring after the first reversal; n denotes the nth trial.

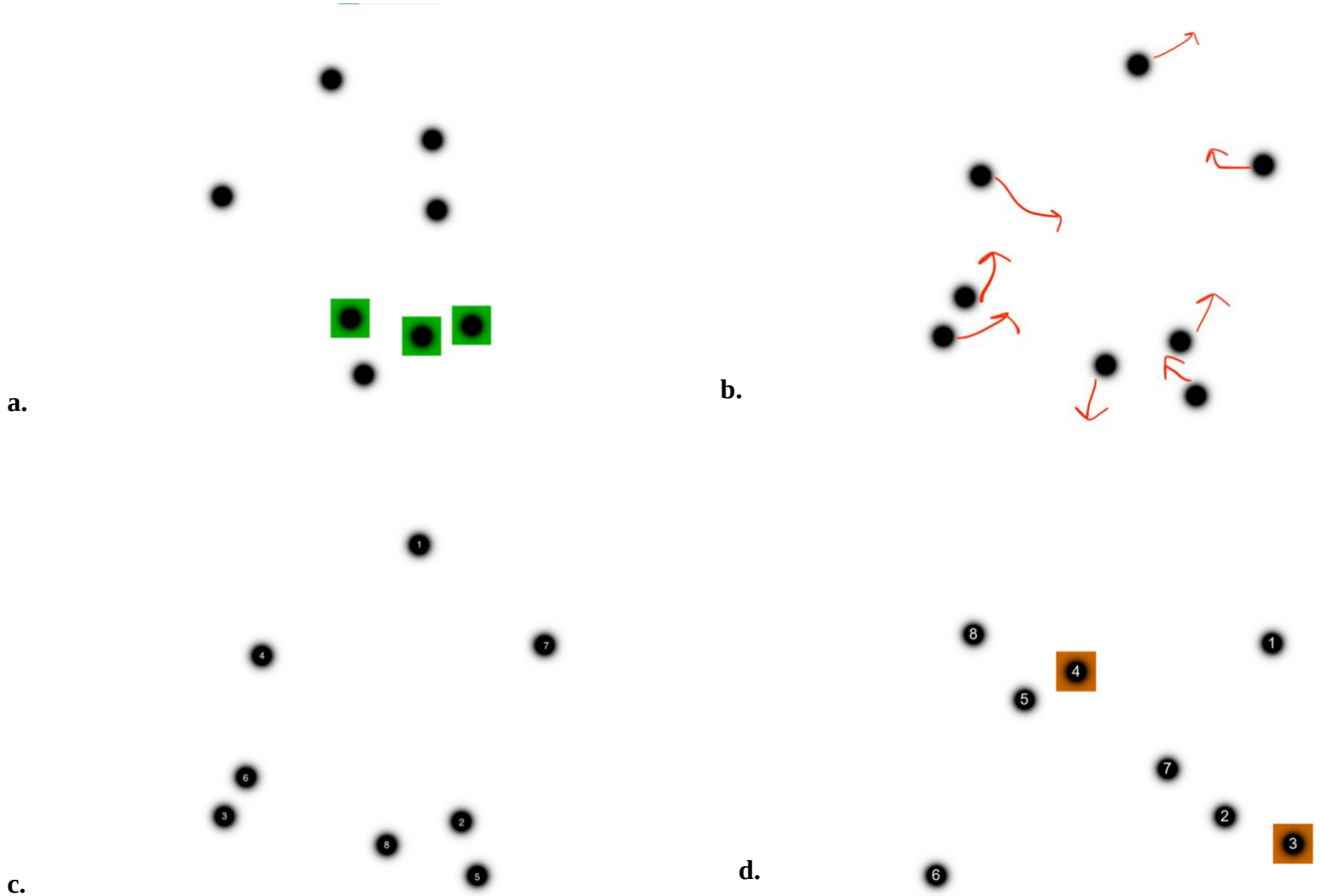

Figure 2.9: The MOT task throughout one trial. (a) The beginning of a trial, with the three balls the participant is to track highlighted in green. (b) The middle, with balls moving in various directions. (c) The end, with the balls each displaying a number. (d) The final screen, with the highlighted balls demonstrating the two of three numbers a participant has selected.

2.7 Statistical Analysis

All statistical analyses for this thesis were conducted using R Studio for Mac Version 4.2.0 (University of Auckland, Auckland, New Zealand).

Statistical analysis began with normality testing using histograms and the Shapiro-Wilks test. To improve the normality of the data, multiple transformations were attempted, including logarithmic, reciprocal, and square root transformations. Finally, linear regression models were run to examine the behaviour of the residuals prior to proceeding with parametric analyses. Q-Q plots for the residuals of the linear regression model were graphed with horizontal or random dynamic VA as the dependent variable, and the remaining visual function tasks as independent variables. Age, gender, and order were included as covariates in all these regression models, except for static VA which only included age and gender as covariates because static VA was always tested first.

Experimental effects, including the effects of participant age, participant gender, and testing order were examined using one-way independent measures ANOVAs (age and visual function task order), and two-sample t-tests (gender and dynamic VA task order). Experimental effects were examined for each task independently. Tukey post-hoc test was used to further evaluate any significant order effects found with the one-way independent measures ANOVAs.

To examine the relationships between dynamic VA performance and the visual function tasks, correlation plots, matrices, and tables including Pearson correlation coefficients were calculated. Finally, backwards stepwise regression analyses were conducted to determine which visual function tasks were most predictive of dynamic VA performance. The correlation and regression analyses were performed separately for horizontal and random dynamic VA. Co-variates were not included in the backward stepwise regression models as there were no significant findings for the effects of age or gender on task performance, and the only significant order-effect found was for GF.

P-values < 0.05 were considered statistically significant for all analyses conducted.

Chapter 3

Results

3.1 Population Demographics

There were 187 individuals (mean age = 20 ± 2.8) recruited for this study (Table 3.1), including 140 females (mean age = 20 ± 2.9), 44 males (mean age = 20 ± 2.8), and 3 individuals who identified as non-binary (mean age = 19 ± 1). The recruitment of such a gender imbalanced sample was not intentional, however, the bulk of our participants were recruited from an undergraduate psychology program, and thus the population may reflect the distribution of students within the program. Of the 187 individuals recruited, ten were not included in the analysis due to technical issues in the visual function task software, ten did not have enough dynamic VA data to be included, two did not complete the study, three were involved with ortho-keratology or had self-proclaimed binocular vision issues, one was below the age of 18. The remaining 31 individuals did not meet the study eligibility criteria because they had monocular or binocular static VAs greater than 0.2 logMAR, and/or a greater than 0.1 logMAR difference between eyes (n=25), or their stereopsis was greater than 40 seconds of arc (n=6). Thus, a total of 130 participants were deemed eligible and were included in the final analysis (Table 3.2, Figure 3.1). Of the total 130 participants (mean age = 20 ± 2.9), there was 99 females (mean age = 20 ± 3.0), 30 males (mean age = 20 ± 2.8), and 1 non-binary individual (mean age = 19).

Table 3.1: Minimum, maximum, mean, and standard deviation of the ages of all recruited participants.

	Female	Male	Non-Binary	All Genders
Min	18	18	17	17
Max	35	30	19	35
Mean	20.2	20.3	18	20.1
SD	2.87	2.76	1	2.83

Table 3.2: Minimum, maximum, mean, and standard deviation of the ages of all eligible participants.

	Female	Male	Non-Binary	All Genders
Min	18	18	19	18
Max	35	30	19	35
Mean	20.2	20.1	19	20.2
SD	3.01	2.82	N/A	2.83

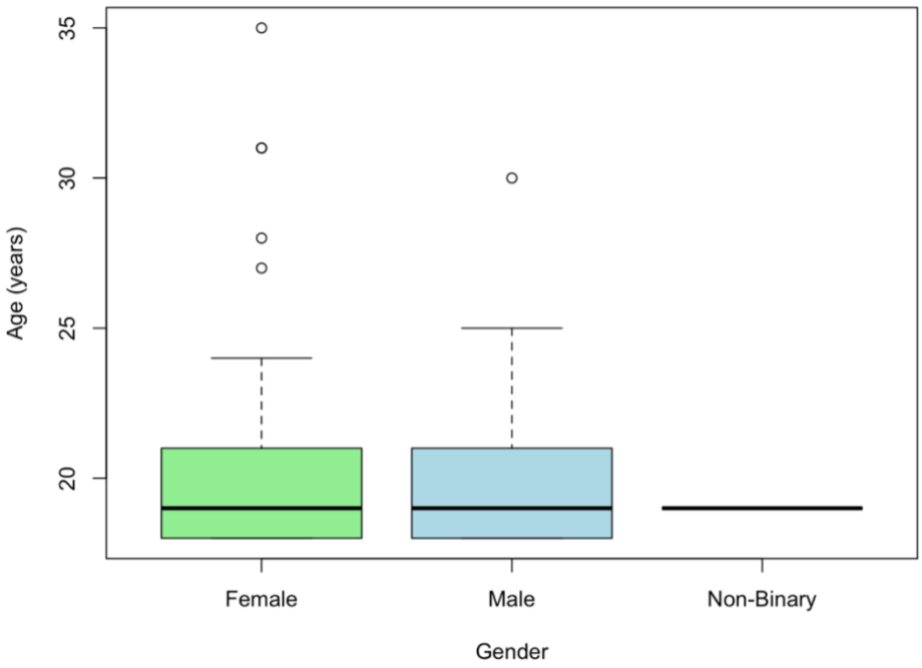

Figure 3.1: Age and gender variability amongst eligible participants.

3.2 Visual Function Tasks Performed

A summary of the results of the tasks performed by participants can be seen in Table 3.3.

Table 3.3: Summary statistics of all visual function tasks performed.

	Min	Max	Mean	Standard Deviation
SVA OU (LogMAR)	-0.30	0.06	-0.12	0.08
DVA H (LogMAR)	-0.12	0.40	0.14	0.10
DVA R (LogMAR)	-0.20	0.34	0.11	0.10
GF (%)	4.1	51.7	17.8	8.1
GM (%)	1.0	71.9	19.6	16.0
LM (°)	0.8	57.0	13.3	14.8
Stroop (sec)	-0.25	0.40	0.08	0.12
MOT (deg/sec)	5.8	33.8	20.8	5.1

3.3 Normality

Figure 3.2 demonstrates the histograms used to examine the normality of data. Shapiro-Wilks test results (Table 3.4, page 57) showed much of the data appeared to be non-normal ($p<0.05$). The transformations attempted (logarithmic, reciprocal, and square root) were not effective. Finally, the linear regression models performed showed that the residuals that were not normally distributed as per the Shapiro-Wilks method, did appear to be well behaved based on examination of the Q-Q plots (Figures 3.3 and 3.4). Based on visual examination of these graphs, it was determined that the bulk of the data was well behaved, thus it was possible to proceed with parametric testing on the data.

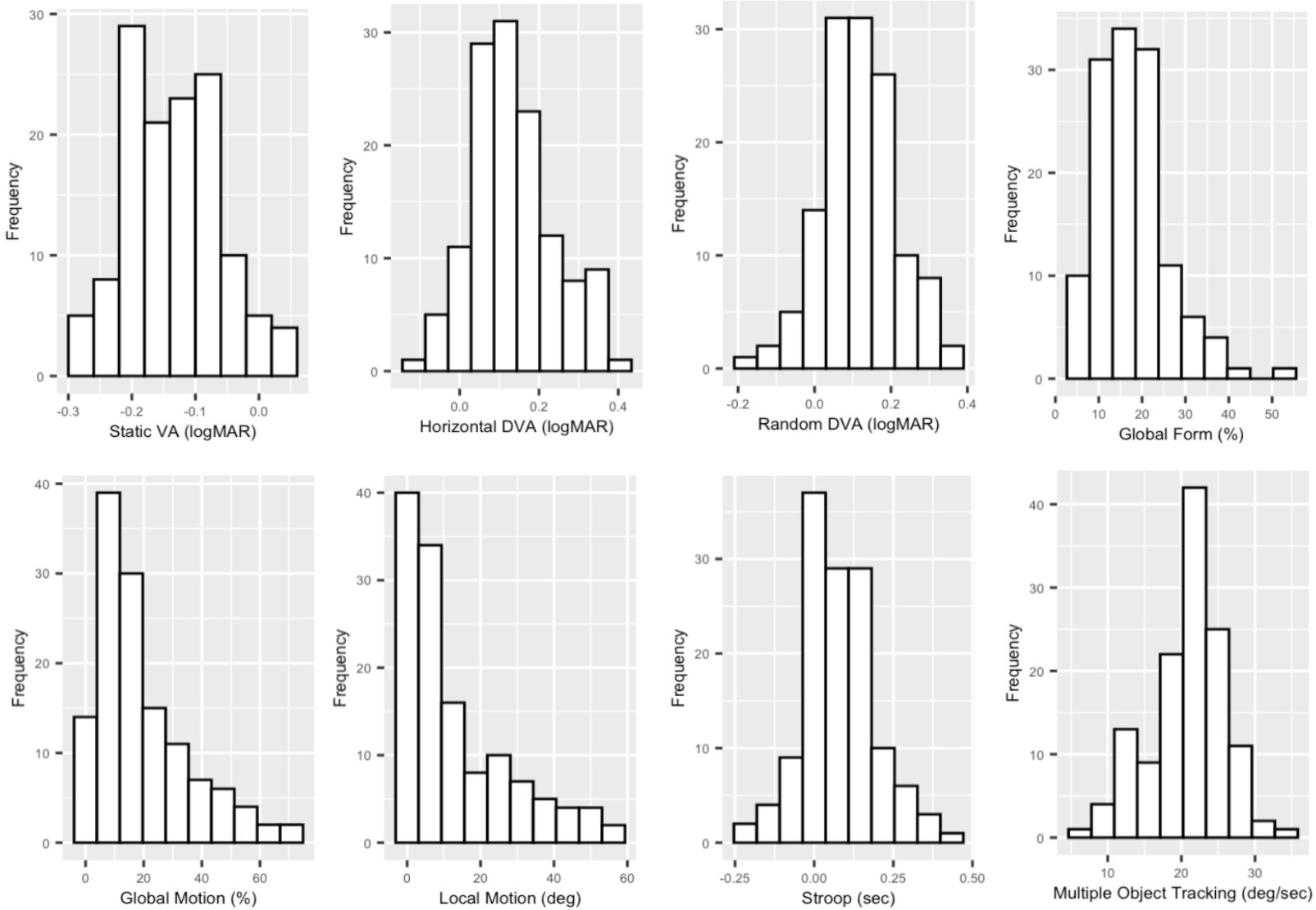

Figure 3.2: Histograms of all visual function tasks performed

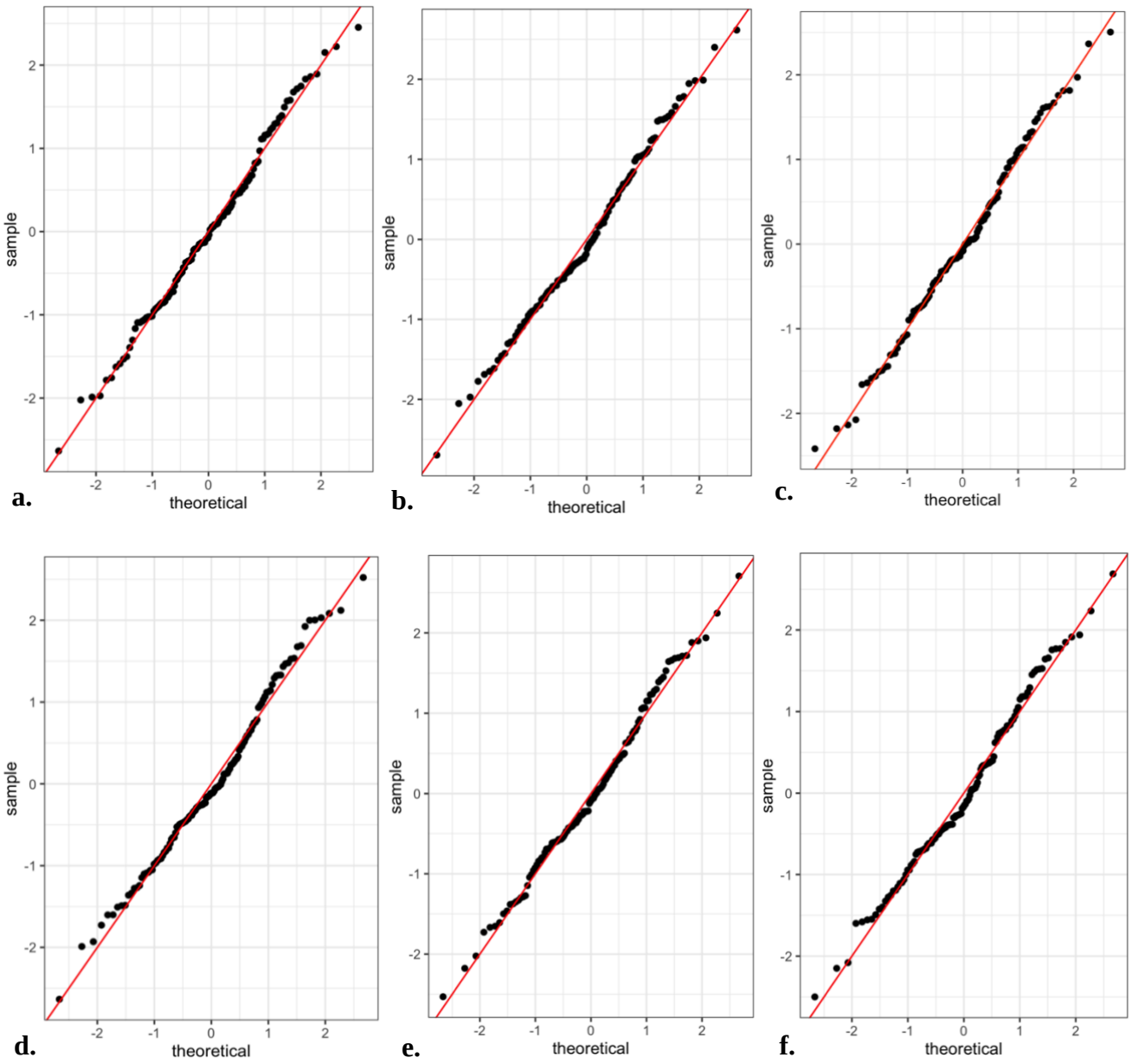

Figure 3.3: Linear regression model Q-Q plots associated with normality testing for horizontal dynamic VA vs. visual function tasks including a) static VA, b) GF, c) GM, d) LM, e) Stroop, f) MOT.

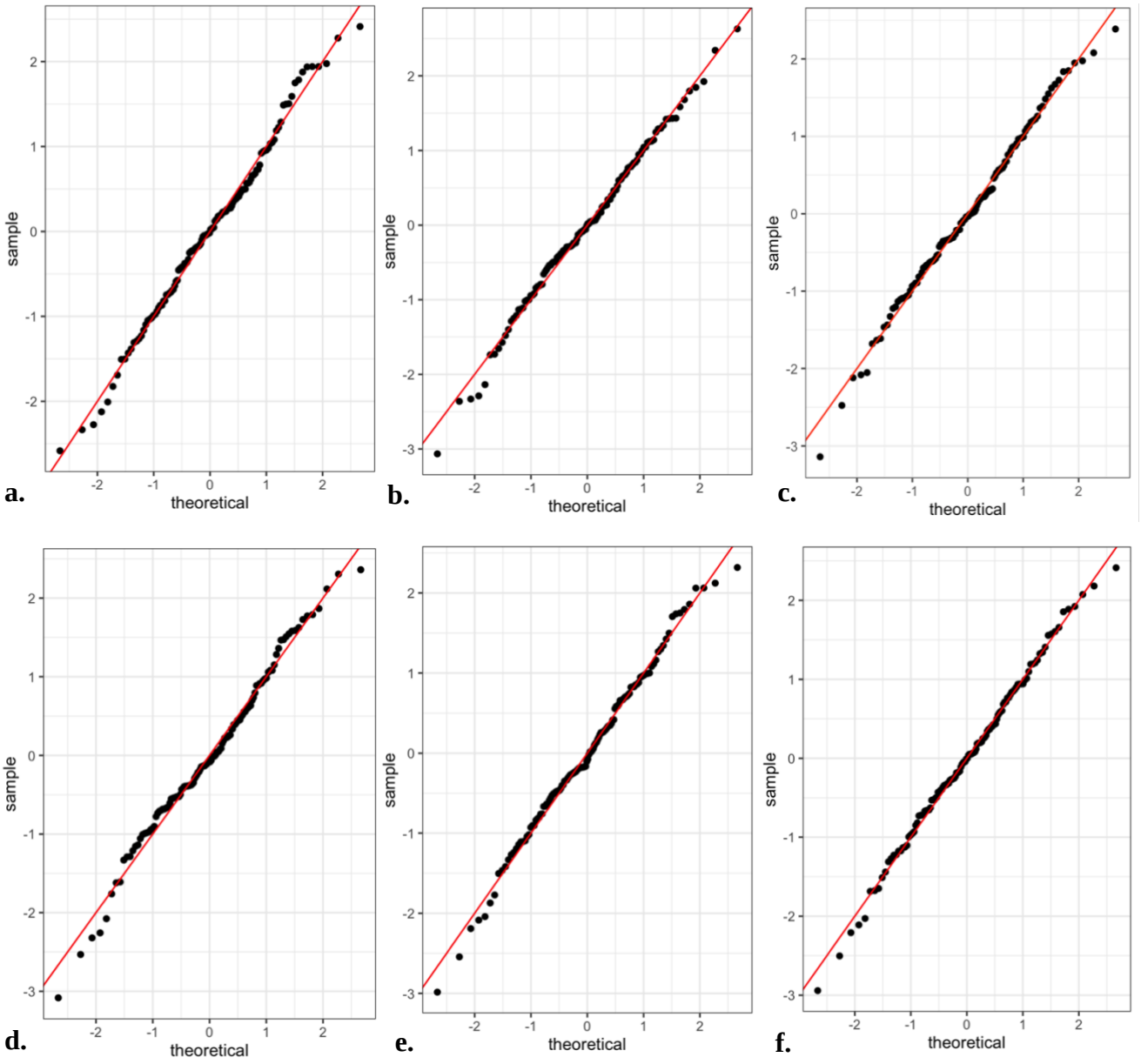

Figure 3.4: Linear regression model Q-Q plots associated with normality testing for random dynamic VA vs. visual function tasks including a) static VA, b) GF, c) GM, d) LM, e) Stroop, f) M

Table 3.4: The Shapiro-Wilks test p-value of visual function tasks performed.

Visual Function Task	Shapiro-Wilk p-value
SVA OU (LogMAR)	0.09
DVA H (LogMAR)	0.08
DVA R (LogMAR)	0.38
GF (%)	1.9e-05
GM (%)	5.3e-09
LM (°)	4.24e-12
Stroop (sec)	0.04
MOT (deg/sec)	2.2e-16

3.4 Experimental Effects

The effects of age and gender on each task were examined, along with the effect of the order in which participants performed the tasks to determine which of these parameters, if any needed to be included in the stepwise regression analysis models.

3.4.1 Age Effect

The effect of age on each task was analyzed using one-way parametric ANOVAs. Participants were categorized into three different age groups: 18-23, 24-29, and 30-35. Multiple one-way ANOVAs were performed to compare the effect of the three different age groups on results of the visual function tasks. These ANOVAs did not reveal a statistically significant difference for the effect of age on each task (Table 3.5). The age effect data can be visualized in Figures 3.5 (a, c, f), 3.6 (a, d, g), and 3.7 (a, d).

Table 3.5: The F-value and p-value of the age effect ANOVAs.

Visual Function Task	F-Value	P-Value
SVA OU (LogMAR)	0.224	0.80
DVA H (LogMAR)	0.479	0.621
DVA R (LogMAR)	0.304	0.738
GF (%)	0.346	0.708
GM (%)	0.782	0.46
LM (°)	0.66	0.519
Stroop (sec)	1.47	0.234
MOT (deg/sec)	0.499	0.608

3.4.2 Gender Effect

For the analysis of the gender effect, a two-sample t-test was conducted comparing each visual function task result to participant's self-reported gender (man and woman). As there was only one individual who identified as non-binary, the gender non-binary could not be included in this analysis. There was no significant difference found in the visual function task results between men and women (Table 3.6). Thus, the results suggest there does not appear to be a gender effect on these visual function tasks. Graphs of gender effect are shown in figures 3.5 (b, e, h), 3.6 (c, f, i), and 3.7 (c, f).

Table 3.6: The t-test value and p-value associated with t-tests for gender effect.

Visual Function Task	t-value	p-value
SVA OU (LogMAR)	0.201	0.841
DVA H (LogMAR)	-0.229	0.819
DVA R (LogMAR)	-0.407	0.684
GF (%)	-1.87	0.064
GM (%)	-0.29	0.772
LM (°)	-0.21	0.834
Stroop (sec)	0.295	0.768
MOT (deg/sec)	-0.853	0.395

3.4.3 Order Effects

The order effect analysis is an attempt to determine if the order in which participants performed tasks affected their results (e.g., if someone who performed MOT first scored better than someone who performed it last). At all study visits, dynamic VA was performed first, with the order of horizontal and random targets randomized. The remaining visual and cognitive function tasks (GM, GF, LM, Stroop, and MOT) were then performed in a randomized order.

3.4.3.1 Dynamic Visual Acuity

The randomization of the order of horizontal and random dynamic VA presentations was separate from the other visual function task randomization that occurred for each participant. As a result, there were only two groupings for the dynamic VA order effect.

A two-sample t-test was performed to examine the order effect of horizontal dynamic VA and it was found that there was not a significant difference in horizontal dynamic VA between being performed first (mean = 0.14, SD = 0.10) and second (mean = 0.13, SD = 0.10); $t(128) = 0.81$, $p = 0.42$. Another two-sample t-test was performed comparing the order effect of random dynamic VA in participants who performed the task first and those who performed it second. There was once again no significant difference between the two groups of first (mean = 0.1, SD = 0.1) and second (mean = 0.13, SD = 0.1); $t(128) = -1.92$, $p = 5.67e\text{-}2$. Figure 3.5 (d, g) demonstrates graphs of the order effect of horizontal and random dynamic VA.

3.4.3.2 Visual and Cognitive Function Tasks

One-way ANOVAs were completed to compare the effect of the order in which an individual performed each task to the results of such given task. These ANOVAs were run for GM, GF, LM, Stroop, and MOT.

GF was the only task to demonstrate a statistically significant order effect ($F(2, 127) = [4.92]$, $p = 1.02e\text{-}3$). Post-hoc Tukey HSD revealed there was a significant difference between those who performed GF first (mean = 23.0 ± 10.3%), and those who performed GF third (mean = 15.3 ± 8.7%, $p = 4.09e\text{-}3$), fourth (mean = 15.8 ± 5.6%, $p = 5.37e\text{-}3$), and fifth (mean = 16.0 ± 6.4, $p = 1.41e\text{-}2$). These results suggest that those who performed GF first, appeared to perform, on average, worse than those who performed GF later. Graphs of the order effect data for GF, GM, LM, Stroop, and MOT can be found in figures 3.6 (b, e, h), and 3.7 (b, e)

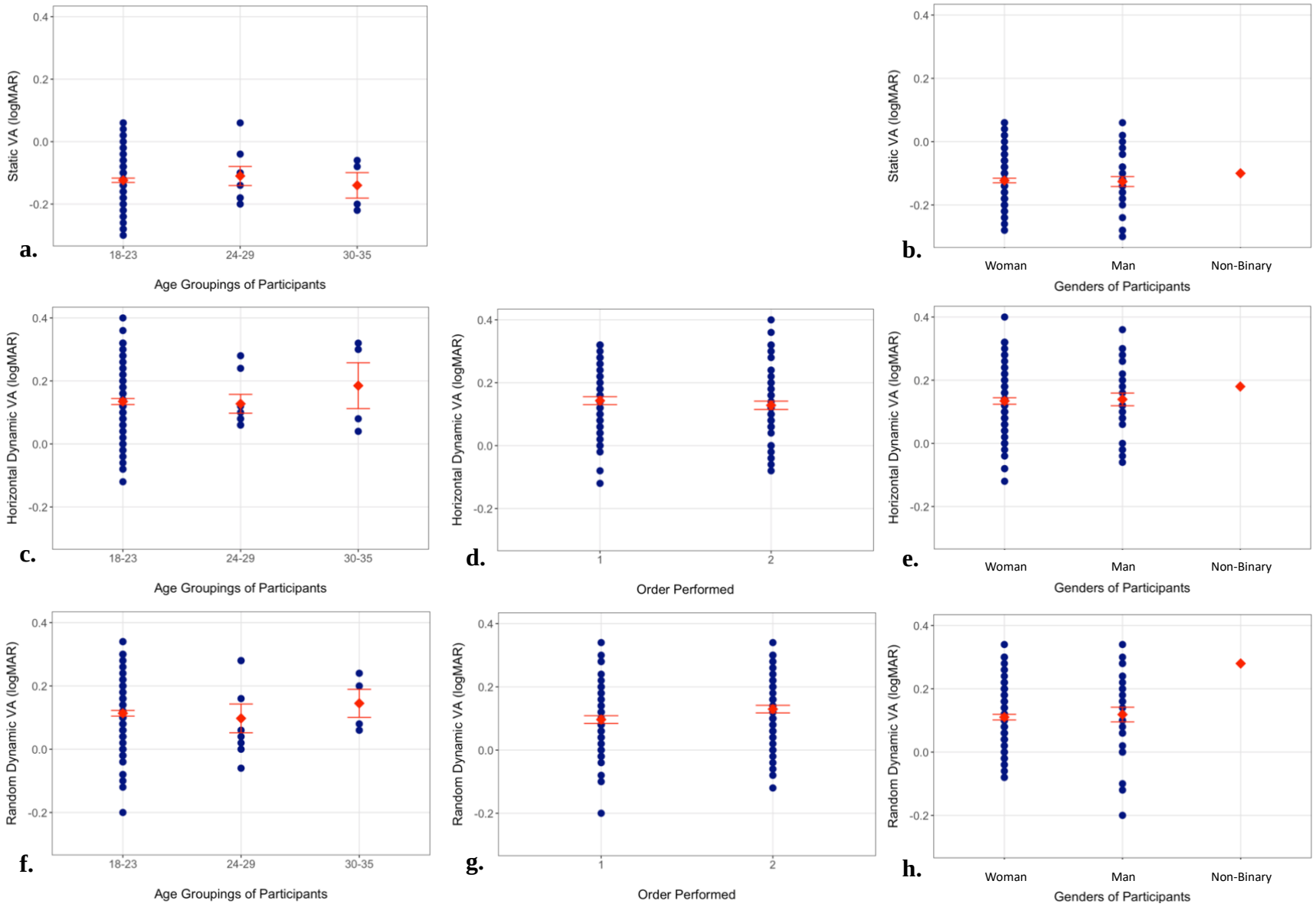

Figure 3.5: Graphs demonstrating age effect (a, c, f), order effect (d, g), and gender effect (b, e, h) for static VA (a, b), horizontal dynamic VA (c, d, e), and random dynamic VA (f, g, h).

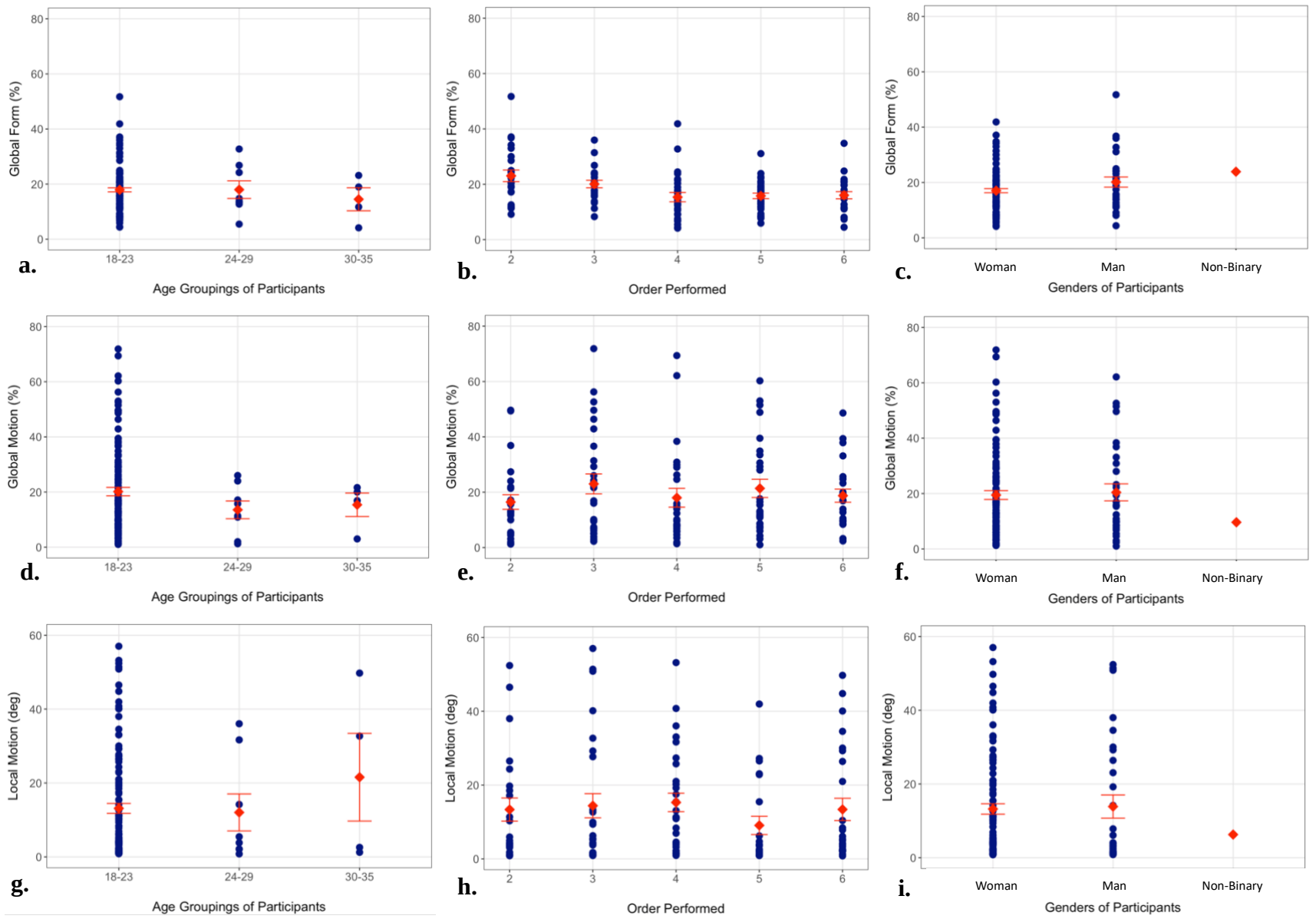

Figure 3.6: Graphs demonstrating age effect (a, d, g), order effect (b, e, h), and gender effect (c, f, i) for GF (a, b, c), GM (d, e, f), and LM (g, h, i).

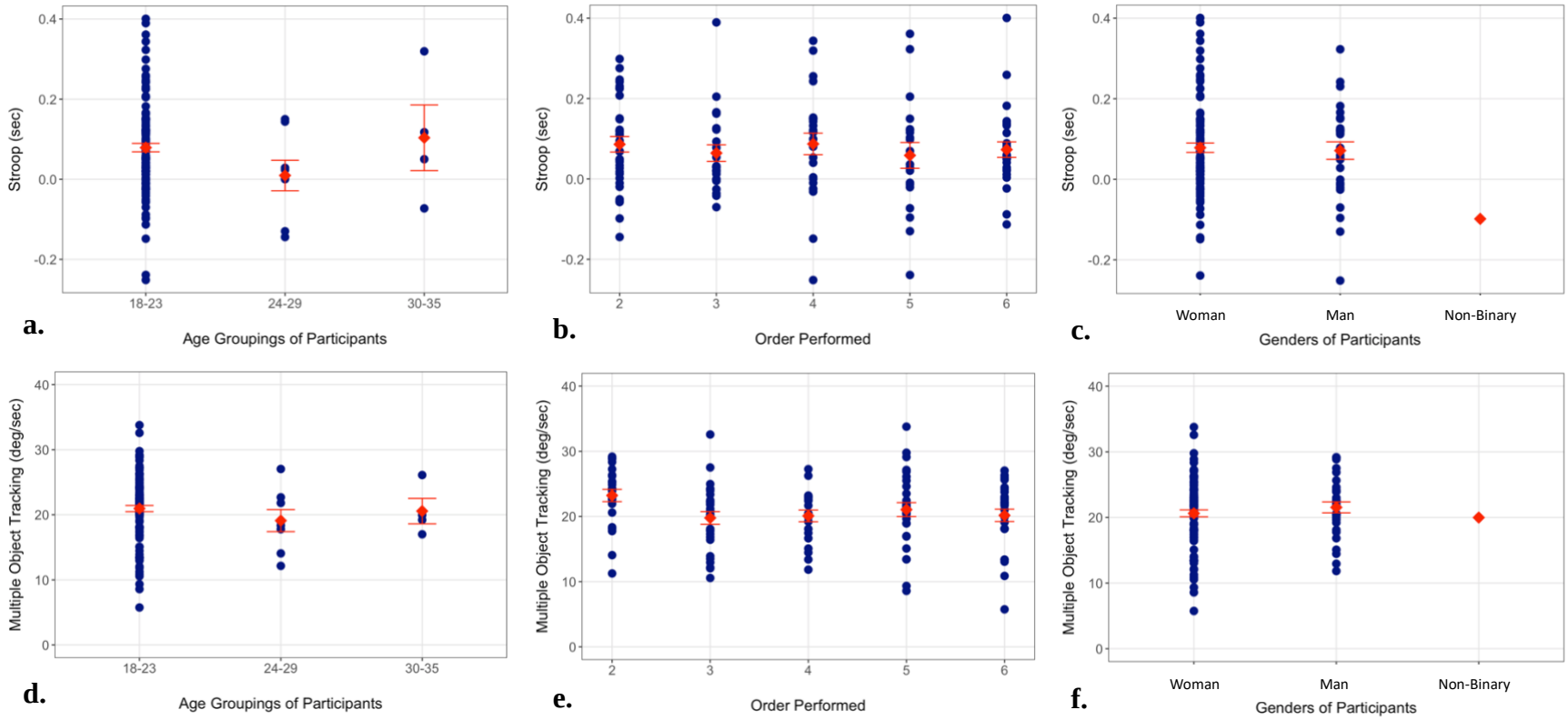

Figure 3.7: Graphs demonstrating age effect (a, d), order effect (b, e), and gender effect (c, f) for Stroop (a, b, c), and MOT (d, e, f).

3.5 Relationship Analyses

3.5.1 Correlation Analyses

The correlations between horizontal and random dynamic VA vs all other visual function tasks were studied. Significant correlations were found between horizontal dynamic VA and GM (r = 0.23, p =0.0092), LM (r = 0.32, p = 2.47e-4), static VA (r = 0.48, p = 6.35e-9) and random dynamic VA (r = 0.49, p = 4.84e-9). For random dynamic VA, there was a significant correlation with static VA (r = 0.46, p = 4.39e-8) and horizontal dynamic VA (r = 0.49, p = 4.84e-9), and non-significant correlations with GF (r = 0.15, p = 0.0989), and LM (r =0.16, p = 0.0643). No other statistically significant correlations were found with horizontal or random dynamic VA. A detailed correlation matrix can be found below (Figure 3.8) along with detailed correlation plots for each variable (Figure 3.9 and 3.10, page 66). Of the six visual function tasks graphed in the correlation plots, static VA appears to have the strongest correlation with both horizontal and random dynamic VA.

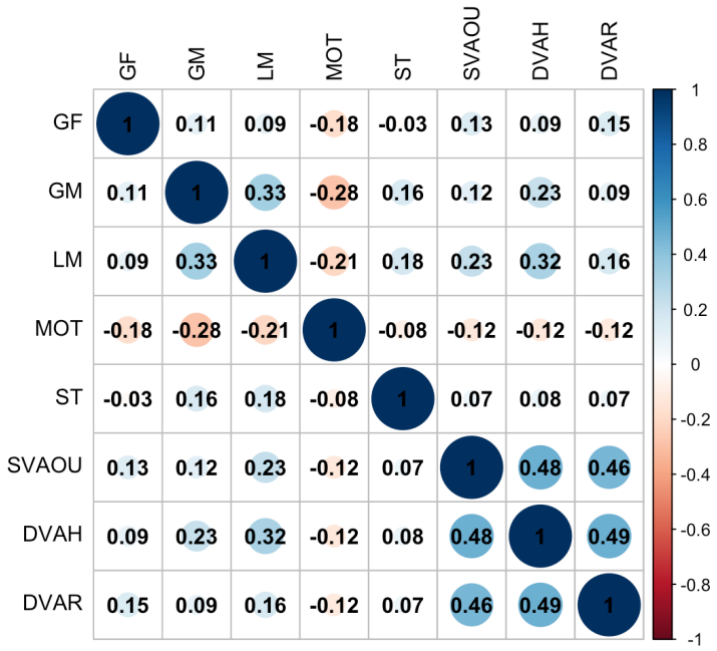

Figure 3.8: Correlation matrix plot for horizontal and random dynamic VA.

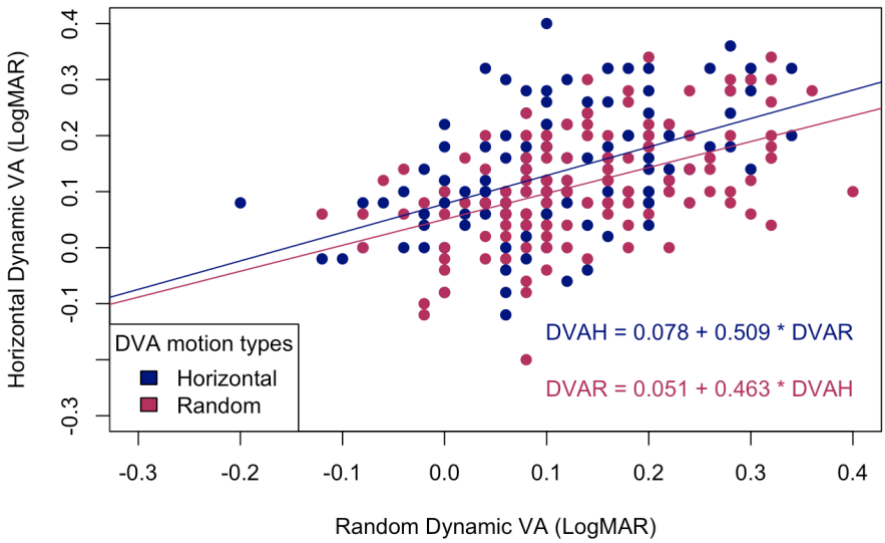

Figure 3.9: Pearson correlation plot for horizontal and random dynamic VA.

3.5.2 Backward Stepwise Regression

In the final stages of analyzing the data to explore the neurophysiological mechanisms that may contribute to the performance of dynamic VA, backward stepwise regression analyses were performed. Separate backward stepwise regression models were run for horizontal and random dynamic VA, but each model always included both horizontal and random dynamic VA. The models also included all six visual perceptual and cognitive tasks, including static VA, LM, GM, GF, MOT, and Stroop, as independent variables. Age, task order, and gender were not included as covariates since these variables did not appear to significantly impact either horizontal or random dynamic VA performance.

The final backward stepwise regression model for horizontal dynamic VA included static VA (p = 6.09e-4), LM (p = 3.96e-2), GM (p = 0.139), and random dynamic VA (p = 1.20e-4). It appears that random dynamic VA, LM, and static VA are statistically significant predictors for horizontal dynamic VA in this model, however, GM does not appear to be statistically significant in predicting horizontal dynamic VA. Although not all significant, the positive coefficients for random dynamic VA, static VA, LM and GM suggest a positive relationship with horizontal dynamic VA (i.e., the worse random dynamic VA, static VA, LM, and/or GM are, the worse horizontal dynamic VA is). An equation for this model can be seen in Equation 3.1.

$$DVAH = 0.177 + 7.73e^{-4} \times GM + 1.13e^{-3} \times LM + 0.395 \times SVA + 0.333 \times DVAR$$

Equation 3.1: Regression equation for the horizontal dynamic VA backward stepwise regression model.

Another stepwise model was performed for random dynamic VA, and the final model included static VA (p = 7.85e-4), and horizontal dynamic VA (p = 8.14e-5). However, when static VA and horizontal dynamic VA were removed from the model, LM (p = 0.087) and GF (p = 0.135) remained. The positive coefficient for static VA and horizontal dynamic VA indicates a positive relationship, implying that higher values of static VA and horizontal dynamic VA are associated with higher values of random dynamic VA (i.e., the worse static VA or horizontal dynamic VA is, the worse random dynamic VA is). The coefficients for GF and LM are also positive, once again suggesting a positive relationship with random dynamic VA, so as GF and LM performance increases, so does random dynamic VA (i.e., the worse LM and GF are, the worse random dynamic VA is). However, neither GF nor LM was statistically significant based on their p-values. The equations for both random dynamic VA models are shown below (Equations 3.2 and 3.3).

$$DVAR = 0.116 + 0.384 \times SVA + 0.329 \times DVAH$$

Equation 3.2: Regression equation for the random dynamic VA backward stepwise regression model with static VA and horizontal dynamic VA.

$$DVAR = 7.15e^{-2} + 1.61e^{-3} \times GF + 1.01e^{-3} \times LM$$

Equation 3.3: Regression equation for the random dynamic VA backward stepwise regression model without static VA and horizontal dynamic VA.

Thus, it appears LM and GM may be more definitive predictors of horizontal dynamic VA, than LM and GF are of random dynamic VA.

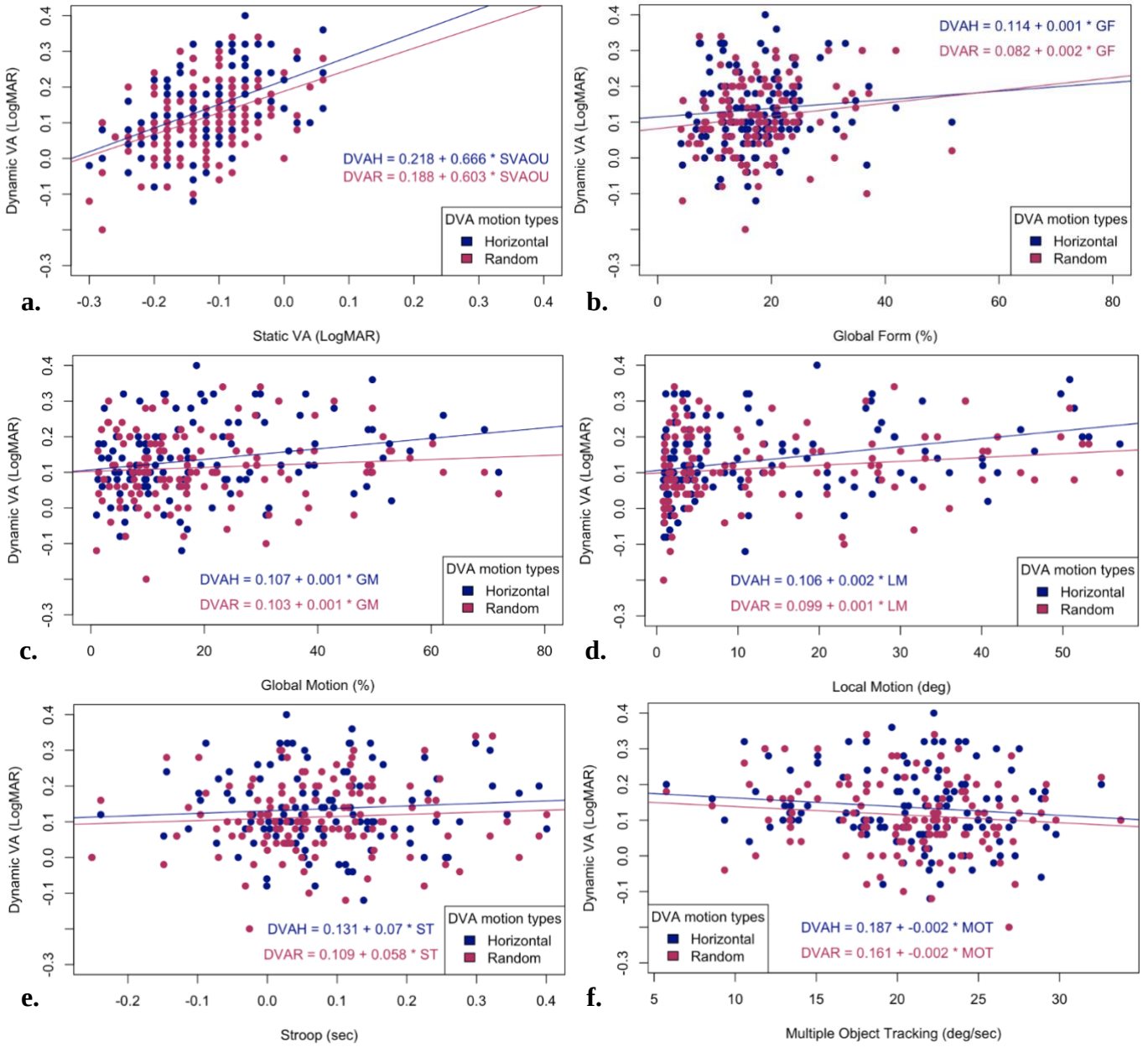

Figure 3.10: Pearson correlation plots for Static VA (a), GF (b), GM (c), LM (d), Stroop (e), and MOT (f) versus horizontal and random dynamic VA.

Chapter 4
Discussion

Dynamic VA has a crucial role in numerous real-world situations and daily activities that involve functioning in a dynamic environment, such as piloting, driving, many sports, action videogames, and crossing a busy intersection (5–8). Although various previous research has been performed on dynamic VA, this visual function and its underlying mechanisms have not been well understood. Furthermore, very few studies have used other visual function tasks in hopes of gaining a better understanding of dynamic VA. In the current study, regression models found random dynamic VA, static VA, LM, and GM to be the most predictive of horizontal dynamic VA performance. Static VA and horizontal dynamic VA also appeared to be the most predictive of random dynamic VA. However, LM, and GF also appeared to be predictive of random dynamic VA, although LM and GF appeared to less predictive than static VA and horizontal dynamic VA according to the regression models.

4.1 Visual Task Function Correlations with Dynamic VA

4.1.1 Static VA

Many previous studies have evaluated the relationship between dynamic VA and static VA with mixed results. One of the reasons for the variability in the results, may be that dynamic VA has been measured in these studies in a variety of ways, including horizontal targets on rotating mirrors, targets on rotating discs, computerized targets with horizontal or random motion (i.e., moV&), and stationary targets that are viewed while a participant turns their head from side to side (vestibular dynamic VA). The study with the most similar methods and techniques used to measure static VA and dynamic VA compared to our study was that performed by Vera et al. in 2022 (8). Vera et al. (2022) used computerized Bailey-Lovie designed logarithmic letter charts to measure static VA and the moV& dynamic VA task to measure dynamic VA (8). Their inclusion criteria for static VA was ≤ 0.0 logMAR and they recruited participants with a static VA between 0.0 and -0.2 logmar. The dynamic VA of their participants ranged from about 0.0 to 0.6 logmar, but correlation between static VA and dynamic VA was found (8). Stalin et al. (2020) also used moV& in a study of elite Paralympic alpine and nordic skiers with vision impairment (302).

Stalin et al. explored the relationships between contrast sensitivity and various other visual functions, including static and dynamic VA in athletes with static VAs ranging from -0.04 to 2.68 logMAR (302). Static and dynamic VA performance were found to be correlated with contrast sensitivity performance in this population, although only static VA was predictive of performance (302). The relationship between dynamic VA and contrast sensitivity found in this study was likely driven by the relationship between static and dynamic VA (302). However, Stalin et al. did not actually examine the relationship between visual acuity measures, thus the nature of this relationship is still unknown (302).

Numerous other studies have found some correlation between the two visual functions (2,3,77,80–82) and suggested the correlation was due to biological factors, such as image defocus, that led to the relationship between these two visual functions (2). If an image cannot be focused properly, then it will affect the results of both static and dynamic VA (2).

Conversely, other studies have found minimal to no relationship between the two tasks (4,8,33,83,84). Some researchers have suggested the supposed difference in ganglion cell types involved with static and dynamic target processing could cause the lack of relationship they have found (8,68). The ganglion cells these researchers are referring to involve the parvocellular system, associated with detailed form vision and fine spatial resolution, and the magnocellular system, dealing with motion and stereoacuity (8,303). The parvocellular system, which is thought to be driving static VA, has been linked to the ventral stream, while the magnocellular system, thought to be driving dynamic VA, has been linked to the dorsal stream (304). Some researchers thus believe the lack of association between static VA and dynamic VA is due to the tasks using different visual pathways (8). However, other researchers have argued the pathways associated with static and dynamic VA (parvocellular and magnocellular pathways, respectively) are interconnected (304) and the dual pathway hypothesis does not support the apparent lack of association between static and dynamic VA. In studies that found minimal, although still significant correlations between static and dynamic VA, researchers had said the relationship was the result of the static and dynamic targets being very similar, and there being a heterogeneous population of subjects (77).

In this study, the strongest correlations with both horizontal and random dynamic VA were found with static VA and between horizontal and random dynamic VA, with these correlations being the second strongest compared to static VA. Furthermore, static VA also appears to be a

good predictor of both types of dynamic VA. The same can be said about predictivity of horizontal and random dynamic VA of one another. Originally, it was thought that the parvocellular system would drive static VA, while the magnocellular system would drive dynamic VA , but our results suggest that there might be more complex interactions between the visual pathways associated with static and dynamic visual acuity, as static VA and both types of dynamic VA were all strongly correlated with each other. The strong correlations between static and dynamic VA in this study could be the result of shared mechanisms or communications between these pathways. Furthermore, the results of this study support the possibility that both the parvocellular and magnocellular system, and thus the ventral and dorsal stream, may be used in the processing of dynamic VA. It is also equally possible that the relationship between static and dynamic VA found in this study could be driven by biological factors, such as the relative lack of optical blur (305) or image defocus (2) our participants experienced.

4.1.2 Global Form

There is no previous research that has investigated the relationship between GF and dynamic VA, to our knowledge. Data analysis for our study found there to be some correlation between random dynamic VA and GF, along with GF potentially being predictive of random dynamic VA. As the result of no previous studies investigating these two visual function tasks, it is difficult to compare our results. However, GF has previously been associated with static VA (132), and within our study, not only was static VA significantly correlated with both horizontal and random dynamic VA, but static VA also appeared to be predictive of both forms of dynamic VA. Due to the correlation dynamic VA has with static VA, and other studies finding static VA to be correlated with GF (132), it is possible dynamic VA has reason to be correlated with GF. Furthermore, GF is associated with the ventral stream (133), which is involved with object recognition (304).

We believe object recognition is a part of dynamic VA, as one must recognize and identify the “E” target to be able to complete the task. Some of the form patterns used while deciphering different GF patterns could potentially be used during dynamic VA tasks that involve resolving the shape and fine details of objects moving in one’s visual field (1–4). Maintaining visual clarity when objects or scenes are in motion (i.e., dynamic VA) may require GF perception to be able to determine the form of objects or scenes that occur. This maintenance of visual clarity is

particularly important with random dynamic VA, as the target is continuously moving in a random and unpredictable motion pathway, making it more difficult to track and determine the direction of the target compared to horizontal dynamic VA. Thus, it is possible that GF and dynamic VA are connected, and that GF perception may be an important fundamental component contributing to the visual processes driving dynamic visual acuity.

4.1.3 Global Motion

Within our study, there was a significant correlation between GM and horizontal dynamic VA, but not random dynamic VA. As well, the backwards stepwise regression determined GM to potentially be a predictor of horizontal dynamic VA.

Former studies have not investigated whether there is a relationship between GM and dynamic VA for any motion trajectory. However, similar to GF, GM (or forms of GM) have previously been associated with static VA (132,306). As said previously in the GF section, there was a correlation between static and dynamic VA within our study, and static VA was potentially predictive of dynamic VA. It is possible that due to these relationships, GM is associated with horizontal dynamic VA.

In addition, GM is linked with the dorsal stream, which is responsible for identifying object motion (99,103,139,140). Object or target motion is also involved in dynamic VA, as the "E" moves from the left to the right of the screen or in an unpredictable pathway around the screen. This connection leads us to conclude that horizontal dynamic VA may be associated with the dorsal stream and with GM. Both GM and dynamic VA involve the integration of motion information to be able to determine the fine details of objects moving in one's visual field and they are both involved in one's understanding of dynamic scenes in a visual environment.

A particular reason GM may be associated with only horizontal dynamic VA and not random dynamic VA could be due to the motion patterns or pathways in which each of these tasks' objects or targets move. Within horizontal dynamic VA, the target is moving horizontally from the left to the right, and within GM, the signal dots are moving horizontally either towards the left or the right. Thus, when individuals perform these tasks, they may use similar methods to track such objects moving in a horizontal line. It is possible GM is also associated with random dynamic VA, although weakly, and thus the relationship was not strong enough to show up within the power of our study sample.

4.1.4 Local Motion

Research directly related to LM is quite limited, and no research has currently been performed studying the relationship between LM and dynamic VA. The data analysis performed for the study involved with this thesis showed LM to have correlations with both horizontal and random dynamic VA and to be predictive of both types of dynamic VA as well.

Both dynamic VA and LM are related to the processing of moving visual information and the recognition of objects in motion. When tracking the motion of individual objects (LM perception), the ability to clearly see these objects is critical (dynamic VA). Likewise, seeing the detail in moving objects (dynamic VA), relies on the ability to track the motion of the individual object (LM). Although these tasks are separate and distinct visual functions, it is possible they work together to facilitate an individual's understanding of objects in motion and thus share some similarities in their mechanisms that support the visual perception of complex dynamic scenes.

4.1.5 Stroop

To our knowledge, there have been no previous studies investigating both the Stroop task and dynamic VA. The Stroop task was included in our study because of the role inhibition had within it. We believed there was potentially an inhibition component associated with dynamic VA, and thus dynamic VA may have been associated with the Stroop task. When an individual is attempting to see a moving object in the real world irrelevant visual information such as unrelated objects, scenery, colours, patterns, or text will need to be ignored or filtered. Furthermore, when trying to see an object moving with an unpredictable pattern, it is possible that participants may need to inhibit the instinctive reflex to track the moving object and rather focus on a fixed point in the scene and wait for the object to move into their field of view to obtain the clearest views of the target. In the Stroop task one must inhibit the irrelevant information of the spelling/reading of the word, to be able to determine what the colour of the word is. However, the results of our study did not find there to be any notable correlation between the Stroop task and horizontal or random dynamic VA and performance on the Stroop task was not predictive of performance on either dynamic VA task.

It should be noted that in a preliminary analysis performed for this study, a relationship between dynamic VA and Stroop was shown, although with less participants recruited (307)

(Appendix E). While our current findings suggest no relationship between dynamic VA and Stroop, and as a result, inhibition to potentially not be a component of dynamic VA, our preliminary analysis and knowledge of inhibition has led us to believe inhibition still may have a role in dynamic VA. It is possible that something within the experimental design, such as the timing of task presentations or the nature of stimuli used, could have masked the effect of inhibition. Additionally, such things as measurement sensitivity, where the measures used to assess inhibition in the Stroop task may not have been sensitive enough to capture the potential specific inhibitory processes related to dynamic VA. More refined measures or additional cognitive tasks targeting inhibition should be considered in future research.

4.1.6 Multiple Object Tracking

The comparison of dynamic VA and MOT had previously been performed by Vera et al. (2022), and they found a positive correlation between the two tasks, stating that when one was able to identify horizontally and randomly moving targets with ease (had better dynamic VA), then they were also able to track faster moving MOT targets (8). These researchers had also continued to suggest that participants with better dynamic VA may also be able to better track multiple objects (8). Both dynamic VA and MOT rely on such factors as target movement velocity and target size, in addition to various other factors (8,271). Prior to the study performed by Vera et al. (2022), there does not appear to be any studies that have investigated the relationship between dynamic VA and MOT (8).

Interestingly, in the study performed for this thesis, MOT was not found to have any correlation with horizontal nor random dynamic VA. However, this was not the case in the preliminary analysis performed for this study, where MOT and dynamic VA were found to have a significant correlation, although with less participants (n=35) recruited than our final recruitment number (307)(Appendix E). The results of our study did not appear to be consistent with the results of previous research performed by Vera et al. (2022), although our preliminary findings were similar to that of Vera et al.'s (2022). For our study, the format of the MOT task used and the participant age group (18-35, mean ± SD = 20 ± 2.9 versus 18-26, mean ± SD = 21.1 ± 2.2) recruited were similar to that of Vera et al.'s (2022), however the final number of participants (130 versus 94) and the kinds of participants varied greatly. Our participants had a wide range of activity levels, and included a number of relatively in-active people while Vera et

al's study only included physically active sport science students (8). These differences in the number of recruited participants and the different populations of participants that occurred between studies could potentially explain why this study had different findings to the Vera et al. (2022) study. Having more participants could potentially lead to differing results due to an increased diversity amongst the sample, capturing a broader range of individuals and uncovering nuances within subgroups, something that may not be seen in the smaller participant samples. Additionally, having fewer athletic participants in our sample could have also contributed to the difference due to the large number of studies demonstrating that both dynamic VA and MOT performance are better in athletes compared to non-athletes (1,8,20,23,24,34,71,72,75,85,86).

4.2 Experimental Effects

In the subsequent sections of this discussion chapter, we delve into secondary, exploratory analyses that were not prioritized as part of our primary research objectives. While these particular effects were not the primary focus of the study design, their inclusion as secondary exploratory analyses stem from a recognition that they could hold potential significance and could provide additional valuable insights to our overall understanding of the mechanisms driving dynamic VA.

4.2.1 Age Effect

Our study revealed that the age of participants did not influence the outcomes of any the visual function tasks performed. It is noteworthy, however, that our inclusion criteria intentionally involved an age range of 18-35 years, thereby excluding individuals both younger and older to eliminate age as a confounding variable in this study. Furthermore, a significant proportion of participants predominantly clustered within the narrower span of age 18-24, thus an age effect was not anticipated within our sample. Therefore our results confirm that age was not a confounding variable in our analysis.

4.2.2 Order Effect

There have been no previous studies that have researched all the visual function tasks involved in our study, nor has the order effect on any of these tasks been studied (to our knowledge). We thought the later each task was performed in the randomized sequence each participant was given, the worse participant's scores would be, due to such factors as fatigue,

boredom, loss of attention/small attention spans, or loss of motivation. However, this did not appear to be the case. A learning effect, whereby performance improved for tasks completed later in the study, was also not observed in our study. Of all the tasks the order effect analysis was conducted for, including horizontal and random dynamic VA, LM, GM, GF, MOT, and Stroop, only GF showed a statistically significant order effect. Our results showed those who performed GF first, appeared to perform, on average, worse than those who performed the task later in the study. It is currently unclear as to why GF was the only task to show any signs of an order effect, and thus further research is required.

4.2.3 Gender Effect

All the visual function tasks performed in this study, including static VA, horizontal and random dynamic VA, LM, GM, GF, MOT, and Stroop were all analyzed to see if a participant's self-reported gender had an impact on the results of the tasks. Analysis of such data proved there to be no gender effect for any of the tasks, which could potentially be the result of the imbalance present amongst the genders, with there being many more women participating in this study than any other reported gender. Although some individuals who identified as non-binary were recruited (n=3), two of the individuals did not meet the inclusion criteria, only leaving one eligible non-binary individual. As a result of only having one non-binary individual, there was not enough non-binary individuals to be included in the statistical analysis, and thus they were excluded from the gender effect analysis. For future studies, if gender effect is to be studied again, there should be a greater attempt to balance the genders recruited if possible and ensure individuals who identify as non-binary are also recruited.

4.3 Limitations

While this study has contributed preliminary insights into the mechanisms underpinning dynamic VA as a visual function, several limitations should be acknowledged. Our study was not really designed to investigate age or gender effects, these analyses were secondary and exploratory, and as a result, age and gender matched individuals were not always present, nor were effects with visual function tasks seen that potentially should have been. Although our age range for recruiting participants was from 18 to 35 years, most participants fell between the ages of 18 and 23. This very small age range of participants means that not all ages were accounted for within our inclusion ages, some ages did not have any participants, and the age effect was

being studied on a very small range of ages, potentially explaining why no effect was seen. There was also a very uneven balance of genders within our participants, with females being largely the majority, and having almost no one who identified as non-binary, causing a severe gender imbalance in our study. As well, since there was only one eligible participant who identified as non-binary, some data loss occurred in our analysis for gender effect as there must be more than one participant in each gender group to continue with proper analysis for gender effect.

Furthermore, the majority of our participants were recruited from the University of Waterloo Department of Psychology Research Experiences Group (i.e., SONA) rather than an athletics department or kinesiology program, which could have impacted the variety of activity levels of the participants recruited. Most students enrolled in SONA are either enrolled in a psychology program or a psychology course and are encouraged to participate in research for course credit, which may have contributed to the specific demographic to our study that had wide variability in their athletic abilities.

Other limitations associated with this study could involve aspects of the experimental design, such as task selection. Although our tasks were picked based off previous research findings and our current understanding of dynamic VA, additional tasks may have helped study further aspects such as inhibition in more depth.

4.4 Summary

The results of this study have shown static VA, GM, LM, and random dynamic VA appear to be predictive of horizontal dynamic VA performance, while static VA, horizontal dynamic VA, GF, and LM appear to be predictive of random dynamic VA performance, although the prediction relationship was not as strong for LM and GF. Additional analysis performed involving age, order, and gender effects, found that age, gender, and task order did not seem to influence task performance overall.

The strong relationship between static VA and dynamic VA suggests that both biological factors, such as image defocus and, connections between the ventral and dorsal stream visual pathways likely influence dynamic VA performance. In addition, the V1 pathway (LM) also seems to play an important role in dynamic VA. Interestingly, it also appears that the underlying mechanisms of different dynamic VA tasks may be task specific as horizontal dynamic visual

acuity seems to rely more on the dorsal stream (GM) pathway, while random dynamic VA appears to rely more on the ventral stream (GF) pathway.

The association between horizontal dynamic VA and the dorsal stream (GM) pathway may be explained by the specific visual processing demands of tasks that involve tracking objects moving along a specific trajectory or direction. While it is true that object recognition is involved in various visual tasks, the nature of the motion and spatial processing required in horizontal dynamic VA tasks appears to align more closely with the characteristics of the dorsal stream. The dorsal stream is specialized in spatial processing and motion perception, and it is particularly accustomed for the analysis of visual information related to the location, speed, and direction of moving objects. Tracking objects along a horizontal plane (such as in horizontal dynamic VA) requires precise spatial and motion processing, which are strengths of the dorsal stream. Tracking objects along a horizontal path also requires continuous monitoring of spatial relationships and the ability to integrate information about the trajectory. The dorsal stream is well-suited for processing spatial relationships and path integration, contributing to accurate tracking along a specific (horizontal) and predictable direction. While there is still motion involved in random dynamic VA, the nature of the task appears to place a greater emphasis on object recognition, fine detail processing, and the perception of GF, all functions associated with the ventral stream.

In random dynamic VA tasks, objects may move in unpredictable patterns, and thus the ability to recognize and attend to individual objects becomes essential. The ventral stream excels at processing detailed information about object shapes, colours, and textures. The ventral stream also plays a role in maintaining object constancy, where one is able to perceive objects as stable and consistent despite changes in their orientation or position. In random dynamic VA, where objects may undergo unpredictable transformations, the ventral stream's ability to maintain object constancy is likely important for accurate tracking during the task and subsequent target recognition as a result.

Further analysis is required to continue the exploration of the neurophysiological mechanisms of dynamic VA, as this form of research has only told us about the potential relationships between tasks. A more comprehensive examination of the age and gender effects is required due to limited ages and genders being present within our study. Additionally, looking into how activity levels or sports experiences of participants impact their results on the visual

function tasks could be beneficial. Studying the change in dynamic VA compared to static VA may also be beneficial as there may be variability in how individual's perform on the dynamic VA tasks even within individual's with the same static VA, causing some results within this study to have been masked.

4.5 Conclusions

Previous research has suggested some connections between dynamic VA and a variety of different visual function tasks. These findings have provided a gateway for new research to delve into understanding the underlying mechanisms associated with dynamic VA. Our research is only able to give predictions of the types of mechanisms involved in dynamic VA based off the types of visual function tasks that were correlated with dynamic VA. However, correlations were found with static VA, dynamic VA, and LM for both horizontal and random dynamic VA, with GM and horizontal dynamic VA, and GF and random dynamic VA. These findings suggest the V1 pathway is involved with both horizontal and dynamic VA, but the ventral stream pathway is associated with only random dynamic VA, and the dorsal stream pathway with horizontal dynamic VA. Further research highlighting the use of these pathways in dynamic VA will help create a better understanding of the visual function itself, in addition to helping us understand how it could be applied in clinical practice and designing training paradigms or future research.

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Appendix A

Consent Form

The following form was provided to each participant prior to the start of the study.

Title of the study: Examining the Underlying Mechanisms of Dynamic Visual Acuity

Principal Investigator: Dr. Kristine Dalton, School of Optometry and Vision Science
Email: kndalton@uwaterloo.ca
Phone: (519) 888-4567 ext. 47915

Co-Investigator: Dr. Dania Abuleil, School of Optometry and Vision Science
Email: dania.abuleil@uwaterloo.ca

Student Investigator: Heather Hudecki, School of Optometry and Vision Science
Email: heather.hudecki@uwaterloo.ca

Student Investigator: Yiran Ge
Email: y6ge@uwaterloo.ca

To help you make an informed decision regarding your participation, this letter will explain what the study is about, the possible risks and benefits, and your rights as a research participant. If you do not understand something in the letter, please ask one of the investigators prior to consenting to the study. You will be provided with a copy of the information and consent form if you choose to participate in the study.

Invitation to participation/What is the study about?

This study is being completed as part of an MSc thesis.

Dynamic visual acuity is a functional vision test that determines the smallest moving letters a person can see clearly. Better performance on dynamic visual acuity tasks appears to be associated with better performance on daily living skills such as driving and playing sports.

Despite our understanding of how dynamic visual acuity relates to performance on some daily activities, we do not understand how the brain processes the visual information used in this task. Therefore, the aim of this study is to determine what mechanisms the brain uses to complete a dynamic visual acuity task by comparing performance on the dynamic visual acuity task to performance on various vision perception tasks whose underlying perceptual mechanisms are well understood.

The tasks we will be comparing with dynamic visual acuity are static visual acuity, stereopsis (depth perception), local motion, global motion perception, global form perception, and multiple object tracking.

We hypothesize that dynamic visual task will involve the neurophysiological pathways similar to both global motion perception (dorsal stream) and global form perception (ventral stream), rather than the local motion pathways (primarily V1). We hypothesize that dynamic visual

acuity will also require some level of cognitive processing and attention, similar to the multiple object tracking task.

I. Your responsibilities as a participant

What does participation involve?

Participation in this study will consist of 1 study visit with a total time commitment for this study being approximately 1.25 hours.

At the study visit, you will be asked questions about your ocular healthy history and various vision tests will be performed with your habitual vision correction (e.g., glasses, contact lenses, or no glasses / contact lenses), including static and dynamic visual acuities, Randot Stereotest (depth perception), autorefraction, stroop task, local motion, global motion perception, global form perception, and multiple object tracking.

These assessments will not require anything to touch your eye and eye drops are not required for testing.

Some tests will involve looking at an eye chart or at moving targets (letters and dots), and pressing direction keys on a keyboard. Some tests will also involve the investigator temporarily covering one of your eyes at a time with a hand-held paddle/occluder, while others will involve you wearing special glasses.

All study visits will take place at the University of Waterloo School of Optometry and Vision Science.

Who may participate in the study?

It is expected there will be 130 participants involved with the study.

In order to participate in the study, you must be 18-35 years of age with normal visual acuities (with or without wearing glasses or contact lenses). You must not be undergoing any medical treatment for any ocular disease that could change visual acuity and must not be actively undergoing orthokeratology or myopia control treatment.

Individuals with binocular vision issues, (e.g., intermittent exotropia), are pre-disposed to an eye turn, or who have reduced depth perception are not eligible to participate in this study.

Participants with a disability are welcome to participate if they meet the visual criteria outlined above and have enough manual dexterity to operate a computer keypad.

Participants will not be excluded on the basis of sex, gender, sexual orientation, linguistic proficiency, culture, religion, and/or language.

Your eligibility to participate will be determined at the study visit by the student investigator.

II. Your rights as a participant

Is participation in the study voluntary?

Your participation in this study is voluntary, you may decide to withdraw or leave the study at any time by communicating this to the study investigator. If you withdraw from the study, any study data collected during your visit will be removed from the study data.

You can request your data be removed from the study up until **Jan 31, 2023** as it is not possible to withdraw your data once papers and publications have been submitted to publishers.

Will I receive anything for participating in the study?

In appreciation of your time, you will receive 0.5 SONA credits/hour involved in the study. Upon arrival to the study visit, initial screening will take about 30 minutes. If you do not meet the eligibility criteria, you will be thanked for your assistance and awarded 0.5 SONA credits, but will not be asked to complete the rest of the study.

If you withdraw from the study early you will receive a prorated number of SONA credits based on how much of the study you completed (e.g., if you attend 1 hour of the study, you will receive 1 SONA credit). A maximum of 1.5 SONA credits can be obtained for participation in this study. You will receive your SONA credits when your study participation ends.

If needed, the study investigator will provide you with a parking pass to cover your parking costs for the study visit.

What are the possible benefits of the study?

There are no direct benefits to you for participating in this study.

Understanding the underlying visual perceptual processes involved in the dynamic visual acuity task will help us to design training paradigms and future research projects to determine 1) if dynamic visual acuity can be trained, and 2) if improvements in dynamic visual acuity performance can translate to improved performance on daily living skills.

The data collected during this study may be presented and/or published. Please note, personal identifying information will not be shared, presented, or published; only aggregate, anonymized data will be shared.

What are the risks associated with the study?

There is potential for exposure to COVID-19 as a result of participation in the study.

Participants and researchers will all wear medical- grade masks during the study visit, and social distancing will be maintained wherever possible. Finally, the researchers will follow the strict safety protocols currently in place at the School of Optometry & Vision Science, where the study will be taking place.

These assessments will not require anything to touch your eye and eye drops are not required for testing. There are no additional risks associated with the vision tests performed.

Will my identity be known?

Only members of the research team (H. Hudecki, Y. Ge, D. Abuleil, and K. Dalton) will know which data is from your participation. Personal identifying information will not be shared, presented, or published.

Will my information be kept confidential?

Your identity will be kept confidential. When you are enrolled in the study, you will be assigned a numerical ID code that will be associated with your study data. Only the research team will have access to the master list linking your ID code to your name, and this master list will be stored separately from the study data.

Electronic data will be securely stored on a password-protected server and only members of the research team will have access to the study data. Hard copies of study materials (e.g., consent forms) will be stored in a locked filing cabinet in a locked office that is only accessible to members of the research team.

Research data will be retained for minimum of 7 years at which time it will be destroyed.

III. Conflict of interest/disclosure

The principal investigator, Kristine Dalton, is currently exploring commercialization option for the dynamic VA test being used in this study.

Will I be paid if this test is commercialized?

The results of this study may help inform how the test is commercialized.

Participants in this study will not receive any payment if the dynamic visual acuity test is commercialized.

IV. Questions, comments, or concerns

Who is sponsoring/funding this study?

This study is funded/sponsored by the University of Waterloo School of Optometry and Vision Science.

Has the study received ethics clearance?

This study has been reviewed and received ethics clearance through a University of Waterloo Research Ethics Board (REB *44456*). If you have questions for the Board contact the Office of Research Ethics, at 1-519-888-4567 ext. 36005 or reb@uwaterloo.ca.

Who should I contact if I have questions regarding my participation in the study?

If you have any questions regarding this study or would like additional information to assist you in reaching a decision about participation, please contact **Heather Hudecki** by email at *heather.hudecki@uwaterloo.ca*.

You can also contact other members of the research team, as outlined below.

Principle Investigator
Kristine Dalton
Email: kndalton@uwaterloo.ca

Co-Investigator:
Dr. Dania Abuleil
Email: dania.abuleil@uwaterloo.ca

Student Investigator
Heather Hudecki
Email: Heather.hudecki@uwaterloo.ca

Student Investigator
Yiran Ge
Email: y6ge@uwaterloo.ca

Consent Form

By providing your consent, you are not waiving your legal rights or releasing the investigator(s) or involved institution(s) from their legal and professional responsibilities.

Title of the study: Examining the Underlying Mechanisms of Dynamic Visual Acuity

I have read the information presented in the information letter about a study conducted by Dr. Kristine Dalton, Dr. Dania Abuleil, Heather Hudecki and Yiran Ge; University of Waterloo School of Optometry and Vision Science. I have had the opportunity to ask questions related to the study and have received satisfactory answers to my questions and any additional details.
I was informed that participation in the study is voluntary and that I can withdraw this consent by informing the researcher.

This study has been reviewed and received ethics clearance through a University of Waterloo Research Ethics Board (REB ***44456***). If you have questions for the Board contact the Office of Research Ethics, at 1-519-888-4567 ext. 36005 or reb@uwaterloo.ca.
For all other questions contact *heather.hudecki@uwaterloo.ca*.

I agree of my own free will to participate in this study.

Participants' name: _____ Date: _____

Participants' signature: _____ Date: _____

Researcher's / Witness' signature : _____ Date: _____

Appendix B

Sample-Size Calculations

Using G*Power 3.1.9.6 (Heinrich Heine University Düsseldorf, Düsseldorf, Germany), an a-priori power analysis was conducted to determine the smallest sample size required for this study. The effect size, alpha, and power of this study were based on previous literature (8), used to determine the relationship between MOT and dynamic VA. The power analysis proposed that a minimum of 128 participants were required, assuming an effect size of 0.25, an alpha of 0.05 and a power of 0.80.

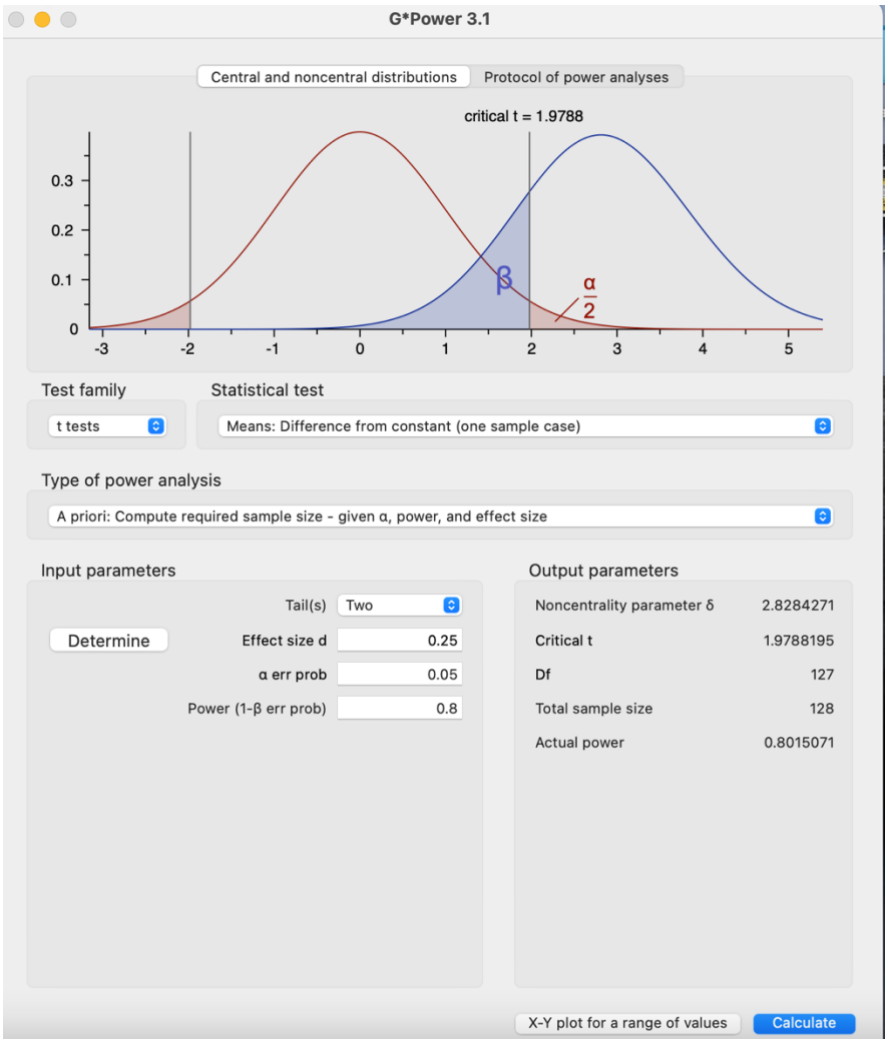

Figure A.0.1: G*power sample size calculation screenshot.

Appendix C

Participant Personal History Questionnaire

The following form was provided to each participant prior to the study beginning.

Mechanisms of Dynamic Visual Acuity – Participant History Questionnaire

Participant ID: _____ **Date: _____**

Please complete all the following questions as accurately as possible.

1. PERSONAL INFORMATION:

Year of birth: _____ Age: _____

Gender: _____

2. RECREATIONAL ACTIVITES:

What recreational activities do you participate in (e.g., sports, video games, music, crafts, board games, role-playing games)?	On average, how many days per week do you participate in your activity (activities)?	On average, how much time do you usually spend participating in your activity on those days (hours, minutes)?	How long have you been participating in your recreational activity (months, years)?	Which of the categories (*as defined below the chart) best describes your engagement with your recreational activity?

*Categorical description of your engagement with your recreational activity (continues on next page):

(1) Experienced – You participated in the activity at this level for a minimum of 5 years, and at least 8 hours per week.
(2) Intermediate – Participation at this level for 5 years or less and 4-8 hours per week.

(3) Beginner – Participation at this level for 3 years or less and less than 4 hours per week.
(4) No recreational activity – Participation with less than 1 year experience and less than 4 hours per week.

4. OCULAR HISTORY (please circle as appropriate):

A) When was your last eye exam?

<1year *1-2 years* *2-3 years* *>3 years* *Never*

B) Do you wear glasses? *Yes* *No*

C) Do you wear contact lenses? *Yes* *No*

D) Are you wearing contact lenses for the study visit? *Yes* *No*

E) Has your optometrist stated you are pre-presbyopic or presbyopic? *Yes* *No*

F) Have you been diagnosed with an eye disease such as glaucoma, macular degeneration, cataracts, etc? *Yes* *No*

G) Are you actively undergoing orthokeratology or myopia control treatment? *Yes* *No*

H) Have you ever had vision therapy or patching? *Yes* *No*

I) Have you been diagnosed with a binocular vision issue (amblyopia/turned eye (strabismus))? *Yes* *No*

J) Are you currently being treated for any eye diseases (if yes, please explain)?

_____

_____

Investigator: _____ Date: _____

Appendix D

International Physical Activity Questionnaire (IPAQ)

The following form was provided to participants prior to the start of the study. The information from this questionnaire has not been analyzed yet.

INTERNATIONAL PHYSICAL ACTIVITY QUESTIONNAIRE

We are interested in finding out about the kinds of physical activities that people do as part of their everyday lives. The questions will ask you about the time you spent being physically active in the **last 7 days**. Please answer each question even if you do not consider yourself to be an active person. Please think about the activities you do at work, as part of your house and yard work, to get from place to place, and in your spare time for recreation, exercise or sport.

Think about all the **vigorous** activities that you did in the **last 7 days**. **Vigorous** physical activities refer to activities that take hard physical effort and make you breathe much harder than normal. Think *only* about those physical activities that you did for at least 10 minutes at a time.

1. During the **last 7 days**, on how many days did you do **vigorous** physical activities like heavy lifting, digging, aerobics, or fast bicycling?

   _____ days per week

   No vigorous physical activities ***Skip to question 3***

2. How much time did you usually spend doing **vigorous** physical activities on one of those days?

   _____ hours per day _____ minutes per day

   Don't know/Not sure

Think about all the **moderate** activities that you did in the **last 7 days**. **Moderate** activities refer to activities that take moderate physical effort and make you breathe somewhat harder than normal. Think only about those physical activities that you did for at least 10 minutes at a time.

3. During the **last 7 days**, on how many days did you do **moderate** physical activities like carrying light loads, bicycling at a regular pace, or doubles tennis? Do not include walking.

   _____ days per week

   No moderate physical activities ***Skip to question 5***

4. How much time did you usually spend doing **moderate** physical activities on one of those days?

   _____ hours per day _____ minutes per day

Don’t know/Not sure

Think about the time you spent **walking** in the **last 7 days**. This includes at work and at home, walking to travel from place to place, and any other walking that you have done solely for recreation, sport, exercise, or leisure.

5. During the **last 7 days**, on how many days did you **walk** for at least 10 minutes at a time?

   _____ **days per week**

   No walking ***Skip to question 7***

6. How much time did you usually spend **walking** on one of those days?

   _____ **hours per day**

   _____ **minutes per day** Don’t know/Not sure

The last question is about the time you spent **sitting** on weekdays during the **last 7 days**. Include time spent at work, at home, while doing course work and during leisure time. This may include time spent sitting at a desk, visiting friends, reading, or sitting or lying down to watch television.

7. During the **last 7 days**, how much time did you spend **sitting** on a **weekday**?

   _____ **hours per day**

   _____ **minutes per day** Don’t know/Not sure

This is the end of the questionnaire, thank you for participating.

Appendix E

COSRC Poster

Examining the Underlying mechanisms of Dynamic Visual Acuity

Heather Hudecki[1], Yiran Ge[1], Karen Fan[1], Dania Abuleil[1], Ben Thompson[1], James Danckert[2], Ewa Niechwiej-Szwedo[3], and Kristine Dalton[1]

School of Optometry & Vision Science[1], Department of Psychology[2], Kinesiology and Health Sciences[3]
University of Waterloo, Canada

Introduction

Dynamic visual acuity (dynamic VA) is a complex perceptual ability of the visual system and involves determining fine details of objects as they move across one's field of view [4]. It also involves oculomotor functioning, peripheral awareness, target detection, and information processing [3]. Dynamic VA has a crucial role in a variety of real-world situations and daily tasks that involve functioning in a dynamic environment, such as driving, piloting, crossing a busy intersection, and many ball sports [1,2]. Training dynamic VA to enhance performance is of great interest, however there is currently no standardized and validated dynamic VA test that is commercially available, and the underlying mechanisms driving dynamic VA are currently unknown, which limits our ability to examine the utility of this task in more detail.

Aim: To begin to understand what perceptual and cognitive processes are involved in completing a dynamic visual acuity task.

Hypothesis: The dynamic VA task will involve the neurophysiological pathways similar to both global motion perception (dorsal stream) and global form perception (ventral stream), rather than the local motion pathways (primarily V1). The dynamic VA task will also require some level of cognitive processing and attention, similar to the MOT task.

Research Questions:
- ❑ What visual perceptual processes are driving dynamic visual acuity?
- ❑ What cognitive processes are driving dynamic visual acuity?

Methods

Participants

- ❑ Healthy adults aged 18-35 years with normal or corrected-to-normal vision
  - ❑ Participants are excluded if they have binocular vision issues and/or reduced stereoacuity
  - ❑ Participants must not have an active ocular disease currently requiring treatment, and must not be undergoing orthokeratology or myopia control treatment

Visual Function Tasks

Visual function tasks – Screening and DVA

- ❑ Static visual acuity (SVA)
  - ETDRS
- ❑ Steroacuity
  - Randot Stereotest
- ❑ Dynamic visual acuity (DVA)
  - movⅧ V&mp Vision Suite
  - Random (DVAR) and horizontal (DVAH) motion

Visual function tasks - Cognitive

- ❑ Multiple object tracking (MOT)
- ❑ Stroop Task (ST)

Visual function tasks - Perceptual

- ❑ Global motion perception (GM)
  - Vertical translation and radial motion
  - Random dot kinematograms
- ❑ Global form perception (GF)
  - Concentric or radial formation
- ❑ Local motion (LM)
  - Clockwise or counterclockwise motion
  - Random dot kinematograms

Study Design

- ❑ Following screening tasks, participants completed the DVA task and all other tasks were randomized.
- ❑ Global form, MOT, Stroop, and DVA (both horizontal and random motion) were normally distributed.
- ❑ Global motion and Local motion were not normally distributed.
- ❑ Correlations for Global form, MOT, and Stroop were examined using Pearson's correlation coefficient.
- ❑ Correlations for Global motion and Local motion were examined using Spearman's rho.

Results

Population Demographics and Visual Tasks Summary Data

- ❑ 35 participants have enrolled in this study as of November 23, 2022.
- ❑ Data analysis was performed on 22 participants.
  - ❑ Gender: 15 Female, 7 Male
  - ❑ Age: 21.45 ± 3.97 years (range 18-35)

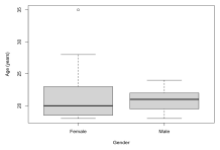

Figure 1: Participant demographics

Table 1: Visual Tasks Summary

	Min	Mean	SD (±)	Max
SVA (logmar)	-0.28	-0.163	0.0642	-0.04
DVA - H (logmar)	-0.04	0.106	0.0924	0.30
DVA - R (logmar)	-0.20	0.891	0.111	0.34
GF (%)	4.13	15.8	6.541	32.7
GM (%)	7.13	22.4	17.4	69.4
LM (°)	0.845	11.5	14.6	44.8
MOT (deg/sec)	11.7	20.8	3.58	26.9
Stroop (sec)	-0.252	0.0320	0.11	0.209

DVA vs Visual Tasks: Results

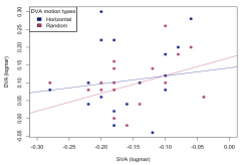

Figure 2: SVA Vs. DVA, r = 0.1567 (DVAH) r = 0.2884 (DVAR)

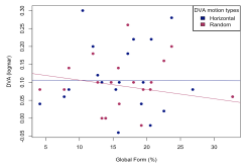

Figure 3: Global form vs. DVA, r = -0.004348 (DVAH) r = -0.1528 (DVAR)

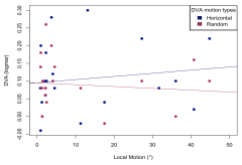

Figure 4: Local Motion Vs. DVA, ρ= 0.2502 (DVAH) ρ= 0.05398 (DVAR)

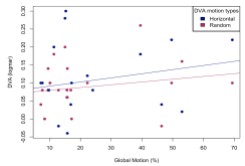

Figure 5: Global Motion Vs. DVA, ρ= 0.07917 (DVAH) ρ= 0.1350 (DVAR)

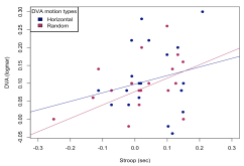

Figure 6: Stroop Vs. DVA, r = 0.2866 (DVAH) r = 0.3709 (DVAR)

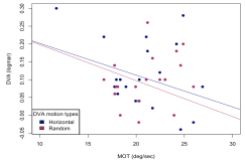

Figure 7: MOT Vs. DVA, r = -0.3450 (DVAH) r = -0.3242 (DVAR)

Conclusions

- ❑ DVA was shown to have relationships with MOT, and Stroop.
  - DVA was also correlated with SVA, as expected.
- ❑ Counter to our initial hypothesis, there was no strong relationship between DVA and global motion or global form.
- ❑ The relationship between DVA and Stroop was not expected.
  - These results suggest that DVA may be more of a cognitive process more than perceptual processes.

Disclosures

This study was funded by internal, faculty support funds from the School of Optometry and Vision Science at the University of Waterloo. Dr. Kristine Dalton, is the co-inventor of the dynamic VA task (movⅧ, V&mp Vision Suite) used in this study and is currently exploring commercialization options for this task.

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Figure A.0.2: Poster with preliminary results presented at the Canadian Optometry School Research Conference.