The Validation of a Novel Dynamic Visual Acuity Test, and Examination of the Effects of Different Factors on Dynamic Visual Acuity

by

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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this 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.

Abstract

Purpose: When a target is in motion, two thresholds can be measured: dynamic visual acuity (DVA, the smallest target size at which an observer can resolve target detail) and speed threshold (the fastest target speed at which an observer can resolve target detail). Many different factors can influence DVA and speed threshold, including target trajectory, velocity, size, contrast, and colour. The limitation with research to date is that there is no standardized, validated tool with which to assess either DVA or speed thresholds. The Vision & Motor Performance Lab at the University of Waterloo School of Optometry has recently developed a distance visual acuity chart (moV&, V&MP Vision Suite) that can measure static visual acuity, DVA, and speed thresholds. moV& allows for the specifications of target trajectory, speed, size, contrast, and colour of both the target and background when measuring DVA. The primary objective of this dissertation is to examine the validity and repeatability of the high contrast (100% contrast), low contrast (61% and 20% contrast), and colour (red target on a white background and white target on a blue background) functions of moV&. If reliable, the data will then be used to examine the effect of target trajectory, speed, and size on DVA and speed threshold.

Methods: Three cross-sectional studies were conducted in order to address the research objectives. Each experiment required participants to attend 2 study visits separated by a minimum of 14 days. All participants completed the static visual acuity tests before completing the dynamic tests in a randomized order. Experiment 1 (n = 25) determined the validity and repeatability of moV& using targets at 100%

contrast. At each visit, static and dynamic visual acuity was measured using Snellen, ETDRS, and moV& charts. Experiment 2 determined the repeatability of the low contrast and coloured functions of moV&. Participants were assigned to either the contrast (n=21) or colour (n=21) study block. For the contrast block, low contrast (61% and 20% contrast) static and dynamic visual acuities were measured using Snellen and moV& charts. For the colour block, coloured optotype and background (red target on a white background, white target on a blue background) static and dynamic visual acuities were measured using the ETDRS and moV& charts. Experiment 3 (n = 67) examined the effect of target trajectory, speed, and size on DVA and speed threshold using the targets studied in Experiments 1-2. Data from Experiments 1 and 2 was used to determine the effect of target trajectory, speed, and size on DVA and speed threshold. A repeated measure ANOVA was used to compare static moV& visual acuity to ETDRS and Snellen charts. Test-retest reliability was determined via Lin's correlation coefficient of concordance (CCC). Three-way ANOVA was used to determine the effect of trajectory, speed, and size on DVA and speed thresholds.

Results: moV& yielded similar high contrast static visual acuity when compared to the EDTRS and Snellen charts. All high contrast static and dynamic visual acuities demonstrate good test-retest repeatability (CCCs ranged 0.451 to 0.953). moV& static visual acuities were significantly better than Snellen at both 61% and 20% contrast ($p<0.05$) with good repeatability ($CCC_{61\%}$ = 0.80 and $CCC_{20\%}$ = 0.60). CCCs for DVAs ranged from 0.05 to 0.74, but were better at 61% contrast. For the coloured targets, moV& coloured static visual acuities were significantly better than ETDRS black and white static visual acuities ($p<0.05$) and coloured DVA demonstrated good test-retest repeatability (CCCs ranged from 0.50 to 0.88, and were similar for both colours). Trajectory had a significant effect on dynamic visual acuity for all contrast and colour combinations, and a significant effect on speed threshold for all optotypes except the white target on a blue background ($p = 0.153$). Target speed had a significant effect on dynamic visual acuity for all contrast and colour combinations tested except the red target on a white background ($p = 0.112$), while target size had a significant effect on speed threshold for all optotypes.

Discussion: moV& high contrast static visual acuity is comparable to both the Snellen and ETDRS charts. moV& static visual acuity demonstrated good repeatability for all optotypes tested. moV& DVA demonstrated good test-retest repeatability for targets at 100% contrast, red targets on a white background, and white targets on a blue background. At 61% and 20% contrast, test-retest repeatability was worse, especially at 20% contrast. Target trajectory, speed, and size have an effect on dynamic visual acuity and speed threshold, with the exception of a few optotype colour combinations. Further research is needed to explore the role of a wider range of target contrasts and colours on DVA and speed threshold.

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Chapter 1 – Introduction and Thesis Objectives

1.1 General Introduction

In order to easily navigate the visual world, humans must be able to recognize objects when relative motion exists between the target and the observer. For example, a driver needs to be able to recognize a road sign while travelling at a fast speed in order to take the correct exit on a highway. Similarly, grocery shoppers quickly scan the shelves while walking in order to correctly identify the items they need without having to stop and read the details of every label. Movement while playing sports also requires athletes to quickly and accurately recognize a moving target in order to perform safely and successfully. In fact, according to a 2007 study, 87% of American Olympic athletes believe that vision is an important factor for success in sports.[1] A specific example of a sport requiring specific visual skills is ice hockey - research on the visual skills used by ice hockey players has shown that peripheral vision, reaction time, and dynamic visual acuity all play an important role in successfully passing and shooting a puck.[2] A significant number of points scored in ice hockey are related to the ability to discriminate between competing visual stimuli and inhibit unnecessary responses.[3]

Much of the literature on dynamic visual acuity (DVA) defines it as the ability to recognize a target in the presence of relative motion between the observer and target.[4–11] This definition, although vague, has allowed for the term "DVA" to be used to describe either the smallest size of, or fastest speed at which, a moving target can be seen. When considering DVA as a visual acuity measurement, as the term DVA is used in this dissertation, it can be more appropriately defined as the smallest target size at which an observer can recognize an object in the presence of relative motion between the observer and target. DVA requires the detection of a moving target in the observer's field of view, uses saccades and smooth pursuit eye movements to visually acquire the target, and requires resolution of critical detail for recognition within a brief exposure time.[12] Numerous processes must function together in order for an observer to correctly identify a moving target; therefore many variables exist which influence DVA. For example, a longer exposure time results in better DVA.[6] An improvement in DVA has also been shown in targets which move in a horizontal trajectory compared to an oblique trajectory.[9] Furthermore, DVA improves as optotype velocity decreases.[13] However, comparison of current research on DVA is difficult as there is currently no widely accepted standardized method with which to assess DVA.

Additional optotype and background characteristics that influence DVA are contrast and colour. Decreasing the contrast between an optotype and the background results in worse static visual acuity.[12] It has also been found that DVA becomes worse with decreasing contrast.[14,15] The impact of target colour on visual acuity is less well understood. For example, it has been found that a combination of a black optotype on a white background yields the same static visual acuity as a yellow optotype on a red background, and a 40% higher acuity than a blue optotype on a red background.[16] The colour of a luminous target on a white background (grey, blue, yellow, and red) has been studied and has been found to effect DVA under scotopic and mesopic light levels in dark-adapted viewers, but not under photopic conditions – however, this effect may be due to differences in target brightness as opposed to any effect of target wavelength.[17] Literature on the effect of contrast and colour on DVA is limited, likely because a “gold standard” test with which to measure low contrast or coloured visual acuity (dynamic or static) does not currently exist.

When a target is in motion, either the speed or the size of the target can be varied to determine two different thresholds – DVA and speed threshold. DVA is the smallest size at which an observer can resolve target detail at a constant target speed. Alternatively, speed threshold is the fastest speed at which an observer can resolve target detail when the target size is kept constant. Since both target speed and size effect the visualization of a moving target, it is important to determine which threshold is most beneficial to measure before beginning testing.[5,13]

The Vision & Motor Performance (V&MP) Lab at the University of Waterloo School of Optometry & Vision Science has recently developed a new computerized test (moV&, V&MP Vision Suite) with which to measure static visual acuity, DVA, and speed thresholds. moV& allows for 5 different target motion types (random walk, horizontal, vertical, oblique, and jitter) as well as options for the random presentation of target size and presenting one or five letters at a time. The different targets available include a Landolt C, Tumbling E, or a 10 Sloan[18] letter option. moV& has the potential to become a useful tool in sports vision and binocular vision assessments for measuring DVA and speed threshold at differing contrast and colour combinations, if its different features can be validated.

1.2 Summary of Objectives and Hypotheses

The primary objective of this thesis was to determine the validity and repeatability of the static and dynamic visual acuity functions of the moV& software using high contrast targets, low contrast targets, and coloured optotype and background combinations. The secondary objective of this thesis was to examine the effect of target trajectory, speed, and size on DVA and speed thresholds using high and low contrast targets as well as targets with coloured optotypes and backgrounds. These objectives were achieved through the completion of three experiments, which are summarized in the following sections (1.2.1 to 1.2.3).

1.2.1 Experiment 1

The purpose of the first experiment conducted was to determine 1) the validity and repeatability of the high contrast static visual acuity functions of moV&, and 2) the test-retest repeatability of moV& DVA. Static visual acuity measured using moV& was compared to the gold standard ETDRS chart and the clinically used computerized Snellen chart as an assessment of validity. Test-retest repeatability of moV& static visual acuity was also determined. Since no gold standard test exists for DVA testing, the test-retest repeatability of the various moV& DVA tests (predictable linear motion, random walking motion, and jitter) was examined. It was hypothesized that moV& static visual acuity would not differ from the static visual acuity measured with the ETDRS or Snellen chart and would be repeatable, and that the moV& DVA measures would also be repeatable.

1.2.2 Experiment 2

The second experiment determined the repeatability of the low contrast and coloured static and dynamic visual acuity functions of moV& since no standard exists for low contrast or coloured static or dynamic visual acuity testing. The test-retest repeatability of the static and dynamic visual acuity tests was determined for two low contrast (61% and 20% contrast) and two coloured optotype-background combinations (red target on a white background and white target on a blue background). It was hypothesized that moV& static and dynamic visual acuity would be repeatable for all low contrast and coloured optotype-background combinations investigated. In addition to measuring test-retest repeatability, construct validity of the low contrast features of moV& were also assessed by comparing low contrast static visual acuities between moV& and a computerized low contrast Snellen visual acuity chart.

1.2.3 Experiment 3

The third and final experiment looked at the DVA and speed threshold data collected during Experiments 1 and 2, and examined the effect of target trajectory, velocity, and size on DVA and speed threshold measures with high contrast, low contrast, and coloured optotype and background combinations. It was predicted that 1) the dynamic visual acuity measures for all targets would be worse compared to the same participant’s static visual acuity, 2) participants would be able to recognize smaller optotypes moving in a horizontal trajectory compared to the oblique, vertical, and random walk motion trajectories, and 3) DVA would be worse at faster target speeds, and speed threshold would be worse (at a slower speed) for targets smaller in size.

1.3 Thesis Overview

The following thesis is composed of three experiments which have been formatted as manuscripts. These manuscripts can be read independently or as a part of the larger dissertation. The first experiment determined the validity and repeatability of the high contrast static and dynamic visual acuity functions of the moV& software. Once the high contrast function was determined to be valid and repeatable, the second experiment was done in order to determine the repeatability of the low contrast and coloured target and background functions of moV&. The third experiment examined the dynamic visual acuity and speed threshold data collected during experiments 1 and 2, and explored the possible effects of target trajectory, velocity, and size on measures of dynamic visual acuity and speed threshold.

The following sections will outline the objectives of the research, show a review of the literature, and present each of the experiments conducted. Chapter 1 included a General Introduction (1.1), Summary of Objectives and Hypotheses (1.2) and a Thesis Overview (1.3). Chapter 2 is a review of the literature on static visual acuity (2.1), dynamic visual acuity (2.2), the factors which can influence dynamic visual acuity (2.3), and how a novel test is validated (2.4). Chapters' 3 – 5 detail the research, and are presented as individual manuscripts. Chapter 6 includes a discussion about the overall objectives of the thesis in the context of the experimental results as well as direction for future work.

Chapter 2 – Review of Literature

2.1 Static Visual Acuity

Visual acuity measurements are commonly done in routine oculovisual assessments and traditionally involve patients reading letters, numbers, or pictures from a chart presented at a specific distance. The patients begin reading the targets which are easy for them to see and the targets gradually decrease in size. The patient continues to read the targets until they are no longer able to resolve them or until a stopping rule is fulfilled (usually if the patient incorrectly identifies a certain number of targets per line). Visual acuity is defined as the smallest size of a target which can be resolved by an eye.[19] Often, this is measured by determining the smallest target size which an observer can correctly recognize more than 50% of the time. Visual acuity testing is easy to administer, understood by the majority of patients, requires minimal equipment, and provides a quantifiable measure of vision. Often, the targets used in visual acuity tests are static and high contrast black-on-white print. Static visual acuity measures give clinicians a general idea of the state of the patient's visual system from their macular function to visual pathways in the brain, as the patient must resolve, recognize, and state the name of the target they are viewing.

2.1.1 The Snellen Chart

The Snellen visual acuity chart (created by Dr. Hermann Snellen in 1862) is the most popular static visual acuity chart used in clinical practice.[19] The chart consists of multiple rows of letters, and is completed at a testing distance of 6 metres in order for the letters on the 6/6 Snellen visual acuity line to each subtend a visual angle of 5 minutes of arc.[19] The letters are large at the top of the chart, and gradually decrease in size between each row as the patient continues to read down the chart. Both printed and computerized versions of the Snellen chart are available. Printed paper charts or projected charts have the disadvantage of being easily memorized, as clinicians are unable to present the letters in a random order. With the advancement of technology over the past few decades, computerized visual acuity charts have become popular among clinicians as they allow for a larger range of visual acuity to be tested from a single test distance, single or multiple target presentations, and the use of a variety of optotypes.[20]

Some disadvantages of the Snellen chart include an inconsistent number of letters per line, different intervals of increasing/decreasing letter size between lines, the difference in legibility of the letters used as targets, and the variable spacing between letters and rows.[19] Changing the number of letters presented per line results in a larger influence on visual acuity measurements if a patient incorrectly identifies one letter on a larger sized line (with fewer letters) compared to a smaller sized line (with more letters). The fact that the letters do not decrease in size in a systematic way from line to line leads to an overestimation of vision at lower acuity levels when changing the viewing distance of the chart to less than 6 metres.[19] The difference in spacing of the letters within and between lines varies the crowding effect on visual acuity – letters which are closer to other letters on the chart will be harder to read compared to those with more space between letters.[19] Additionally, the letters used as targets on the Snellen chart vary in legibility.[21] Finally, it is important to note that the term “Snellen chart” is not standardized, therefore different manufacturers can vary the font, letters, and spacing which they use for their visual acuity charts and still label them as a “Snellen visual acuity chart”.[19] Even with these limitations, the Snellen chart is still the most commonly used method to measure static visual acuity in clinical practice.

2.1.2 The ETDRS Chart

In order to address some of the issues present with the Snellen chart, the Bailey-Lovie chart was developed. The Bailey-Lovie chart was designed to standardize the measurement of static visual acuity by using letters of equal legibility, the same number of letters on each row, uniform between-letter and between-row spacing, and a consistent logarithmic decrease in letter size between lines.[22] In 1982, the Bailey-Lovie chart was modified for use in the Early Treatment Diabetic Retinopathy Study (ETDRS) by the Committee on Vision of the National Academy of Sciences and since then, the ETDRS chart and its protocol for administration have become the “gold standard” for measures of static visual acuity.[19] The ETDRS chart is administered at a distance of 4 metres, and each row contains 5 of 10 possible Sloan letters (non-serifed, uppercase letters with equal legibility, consisting of the letters C, D, H, K, N, O, R, S, V, Z).[19] The spacing between the letters and rows is consistent and proportional to the letter size, and the letters decrease in size in equal logarithmic steps (0.1 logMAR decrease in size per line).[19]

Printed and computerized versions of the ETDRS chart are available, although the gold standard is the printed high contrast chart administered at 4 metres.[19] The limitations that exist with all printed charts (clinicians are unable to randomize the presentation of the letters, therefore it is easy for patients to memorize charts) are present with the printed ETDRS charts, although the ETDRS chart is available with different optotype permutations, allowing clinicians to switch charts so letters are not as easily memorized.[23] Due to the optimization in font, spacing, and decrease in letter size, the ETDRS chart provides a measure of static visual acuity with less confounding factors compared to the Snellen chart. Still, the Snellen chart is still used in most optometric clinics as it is more convenient, easier, and quicker to administer.[19]

2.1.3 Effect of Contrast on Static Visual Acuity

Clinical measures of static visual acuity are commonly done using high contrast targets (a black target on a white background). However, it is often beneficial to measure a patient's low contrast static visual acuity. Low contrast acuity measures one's ability to identify gray letters on a white background – the letters gradually decrease in size, but the contrast level stays the same.[24] Low contrast versions of Snellen and ETDRS charts (both printed and computerized) exist with targets available at a variety of contrast levels, ranging from 1.25% to 100% contrast.[25,26] Low contrast static visual acuity differs from measures of contrast sensitivity where the letter size is kept constant and the contrast of the letters decreases, such as in the Pelli-Robson chart.[24]

The ETDRS low contrast visual acuity charts provide sensitive measures of disability, especially in patients with diseases which impact contrast sensitivity such as multiple sclerosis.[24] However, the repeatability of visual acuity measures (being able to obtain similar measurements for the same subject on two separate occasions) has been shown to be poorer with low contrast targets compared to high contrast targets in healthy patient populations.[26] This is due to increased task difficulty when visualizing low contrast targets compared to high contrast targets.[26] Greater intra-subject variability has also been found on low contrast acuity tests, likely stemming from the increased difficulty of the task.[26]

2.1.4 Effect of Colour on Static Visual Acuity

In addition to the effect of target contrast, the colour of both the target and background can influence visual acuity. There is a limited amount of literature available which examines the effect of coloured optotypes on static visual acuity. Visual acuity measured using coloured sinusoidal gratings showed that a blue and yellow combination of colours results in worse acuity compared to a red and green colour combination.[27] Research with letter optotypes found participants had better static visual acuity (were able to resolve detail from smaller targets) with a black letter on a white background compared to a blue letter on a red background, however there was no statistically significant difference found in static visual acuity measured with a black letter on a white background compared to a yellow letter on a red background.[16] It is important to note that no standardized, validated test is currently available with which to measure the static visual acuity of coloured optotypes. This is likely the reason why limited research is available on this topic, but with the advancement of computer-based visual acuity technology it is becoming easier to create programs which can change the colour of both the targets and background of visual acuity charts.

2.2 Dynamic Visual Acuity

Another type of visual acuity measurement is dynamic visual acuity. Dynamic visual acuity (DVA) is a measure of object recognition in the presence of relative motion between the observer and the target.[4] In order for an observer to recognize a target that is moving within a single two-dimensional plane, they must detect the target as it crosses their field of view, use saccadic and/or smooth pursuit eye movements in order to visually acquire the target, and resolve enough critical detail in order to make an appropriate judgment on target recognition, all within the brief time that the target is within their field of view.[12] This differs from the visual strategies used for static visual acuity, as DVA requires observers to make the appropriate eye movements in order for the target image to fall on their fovea, and target exposure time can vary depending on the speed and trajectory of the target.

As stated previously, the term “visual acuity” refers to the smallest size of an object which can be visually resolved.[19] It follows that dynamic visual acuity would refer to the smallest size of a moving object which can be resolved with an eye. This differs from measurements of the fastest speed at which a target of a constant size can be resolved, which will be termed “speed threshold” for the remainder of this dissertation. DVA and speed threshold are both measurements of the ability to visualize a moving target, but are different variables. DVA is a measurement of size, while speed threshold is a velocity measurement. Therefore, it is important to distinguish between these two thresholds when reviewing research on “dynamic visual acuity,” as the term has been used interchangeably throughout the literature to refer to both DVA and speed thresholds.

A weak correlation exists between static and dynamic visual acuity, although this correlation is not seen in studies with strict subject inclusion criteria (such as best corrected static visual acuity, age, and athletic background).[4,6,28] This weak, but significant positive correlation between dynamic and static visual acuity decreases as target velocity increases.[28] A significant interaction also exists between speed threshold and static visual acuity (good static visual acuity is related to good [faster] speed thresholds).[29] Despite these correlations, measures of static visual acuity are consistently better than dynamic visual acuity - subjects are able to resolve smaller target detail with a static target compared to a moving target, and the disparity between static and dynamic visual acuities increases with increasing target speed.[12]

One factor which has limited our understanding of DVA is the lack of research done exploring the sensory aspect of how we detect target detail when a target is in motion. It is known that the magnocellular layers of the lateral geniculate nucleus are responsible for motion perception and contrast, while the parvocellular layers are important for visual acuity and colour perception.[30,31] Therefore, DVA reflects an interaction between these two visual pathways as it involves measuring the visual acuity of a moving target. Research still needs to be done in order to determine the nature of this interaction, the sensory processes which are required in order for someone to successfully resolve target detail when the target is in motion, and how these processes may differ based on factors such as target speed, size, trajectory, contrast, and colour.

2.2.1 Eye Movements used to Track Moving Objects

When a stationary observer views a moving target, they use a combination of eye and head movements in order to stabilize the image on the fovea and resolve target detail.[5] Specific eye movements such as saccades and smooth pursuits are used to track moving objects. Saccades are rapid eye movements used to quickly change the point of fixation in order to visualize a moving target.[32] Smooth pursuits are slower, tracking eye movements meant to keep a moving image on the fovea.[32]

2.2.1.1 Tracking Moving Targets in Dynamic Visual Acuity

The above definition of DVA involves a target moving across the visual field in a "walking" motion (i.e. following a path or trajectory across the screen). Walking motion can be predictable (e.g. horizontal, vertical, or oblique motion) or the movement can be random. Better DVA (the ability to resolve smaller moving targets) is linked to better image tracking as opposed to image processing in the visual pathways of the brain, although both skills play an important part in the visualization of a moving target.[5]

Eye movements used to track horizontally moving objects at speeds ranging between 0-90 degrees per second showed no consistent trend between participants, but large differences in eye movement parameters (increase in number of saccades, decrease in saccade latency, and increase in pursuit velocity) existed within the same participant based on the target speed.[33] Smooth pursuits were shown to be faster, smoother, and more accurate when the speed of the target was slower.[5] However, the onset and minimum positional error of smooth pursuits, and reverse saccades (saccades made in the opposite direction of target movement in an attempt to intercept the target before it reaches the point of fixation) were unaffected by optotype speed.[5] Smooth pursuit eye movements are typically used to track objects moving at speeds up to 50 degrees per second – at faster speeds, catch-up saccades are needed in order to accurately foveate the image.[5]

2.2.1.2 The Vestibulo-Ocular Reflex

So far, we have explored the methods used by stationary observers to track a moving object. It is important to note that the strategies used to visually acquire a moving object vary depending on the method used to measure DVA. However, there are actually two common methods used in the literature to measure DVA – they involve either target movement across a screen, or a static target viewed while the observer makes repetitive rotational head movements (usually along a transverse or sagittal plane).[5] As previously stated, tracking a moving target requires the use of smooth pursuit and saccadic eye movements. Using head rotation to stimulate movement invokes the vestibulo-ocular reflex (VOR), which helps to keep a target on the fovea during head movement.[5] The vestibuo-ocular reflex responses stabilize the eye relative to the target, hence compensating for head movement and stabilizing the image on the retina.[32]

The neural mechanisms used to invoke voluntary eye movements differ from those used for the VOR. The VOR is an eye movement initiated by the vestibular system and is the body's way of keeping a stationary object on the fovea during head rotation.[5] A stable gaze is maintained by the VOR as the body generates compensatory eye movement responses in the opposite direction and of equal magnitude to the head movement.[34] Since the VOR is a reflex, it uses cortical vestibular processing as well as integration of the insular and temporo-parietal brain regions in order to integrate all available information and give the appropriate motor response.[34] This differs from the retinogeniculate neural pathways activated when performing a smooth pursuit or saccadic eye movement - therefore, it is important to specify the method of testing used when describing DVA measurements.[13]

2.2.2 Methods of Measuring Dynamic Visual Acuity

Past research involving measures of DVA use a variety of experimental equipment and methods in order to create relative motion between the observer and target. A summary of the equipment used in the literature can be found in Table 2.1. Traditionally, DVA was measured using a projector and a front surface mirror on a turntable, such as the Kowa Dynamic Vision Analyzer HI-10.[6,33,35] By using a standardized acuity chart and creating a motorized set up, researchers were able to conveniently measure DVA. However, this method had the limitation of restricting the movement of the target to a single trajectory. Additionally, unless a specific test and protocol were used, the experimental set up was not consistent between experiments as the models of projectors, turntables, and fields of view differed depending on availability.

Clinically, the Wayne Robot Rotator is often used in vision training and sports vision in order to measure DVA.[36] This instrument consists of printed letter targets of various sizes on a spinning disc, causing the targets to move in a circular motion at a fixed speed.[37] Patients are asked to read the smallest line of letters which they can visualize. However, this limits the available trajectories to predictable circular motion in either a clockwise or counter clockwise direction, and makes it difficult to vary the optotype size and order. Additionally, it varies the eye movement demand required by the patient in order to successfully track the target. Although this device is used in vision training clinics, it is not often used for research on dynamic visual acuity; therefore it is not mentioned in Table 2.1.

More recently, computer software such as the DinVA 3.0 has been used to measure DVA – this allows for the target to move across a screen while the observer remains stationary.[8,9] The V&MP lab at the University of Waterloo has created computer software named moV& which has the capability of creating relative motion between the observer and the target by allowing the experimenter to set the trajectory and speed of the target.[38] By using computer software to generate target movement it is easier to modify tests for different screen sizes and testing distances, as well as change target variables such as trajectory, speed, and size. However, limitations exist when using computerized DVA systems. The refresh rate of the system used to display the test often provides a cut-off for the stimulus speeds available.[9] Additionally, LCD screens hold their luminance until the next refresh cycle, which can lead to motion blur when an observer is following a moving object on the display.[39] In order to reduce motion blur, a refresh rate of 120 Hz or more is required.[39]

Table 2.1: Summary of dynamic visual acuity tests that use a moving optotype to create relative movement between the target and observer

Study	DVA Test Name	Optotype	Trajectory	Optotype Speed	Optotype Size	Study Sample	DVA in logMAR	Speed Threshold in °/sec
Brown (1971)[33]	Projected targets onto a rotating front surface mirror mounted on a gramophone turntable Free head movement	Landolt C	Horizontal (left to right)	20 °/sec	Dependent Variable	n = 25 males Age range 19-28 Static VA ≤ 6/6	0.114	Not measured
				30 °/sec			0.146	
				40 °/sec			0.301	
				50 °/sec			0.380	
				60 °/sec			0.380	
				80 °/sec			0.462	
				90 °/sec			0.518	
Goodson & Morrison (1980)[12]	Front surface mirror on a variable speed motor turntable Free head movement	Landolt C	Horizontal (right to left)	20 °/sec	Gap sizes ranging from 0.65 to 20.38 min of arc	n = 10 males Age range 18-22 Static VA ≤ 6/6, Student naval aviators	0.172	Not measured
				50 °/sec			0.131	
				80 °/sec			0.217	
				110 °/sec			0.606	
Long & May (1992)[6]	Kodak Ektagraphic Projector and a front-surface mirror on a turntable Free head viewing	Landolt C	Horizontal (left to right)	60 °/sec	Dependent Variable	n = 39 females, 21 males Age range 18-25 Static VA ≤ 6/12	0.778	Not measured
				90 °/sec			0.903	
				120 °/sec			0.954	
				150 °/sec			1.204	

Demer & Amjadi (1993)[7]	Front surface mirror mounted on a pivoting galvanometer Fixed head rest	Sloan letters	Vertical sinusoidal motion	7.5 °/sec	Dependent Variable	n = 13 (male:female not reported) Age range 19-40 Static VA ≤ 6/6	~0.10	Not measured
				15 °/sec			~0.20	
				30 °/sec			~0.30	
				45 °/sec			~0.65	
				60 °/sec			~0.75	
				75 °/sec			~0.82	
				100 °/sec			~0.95	
Miyao et al. (1994)[40]	Target projected onto a rotating front surface mirror controlled by a variable speed turntable Fixed head rest	Landolt C	Horizontal (left to right)	Up to 35 rpm (rotations per minute)	8 min of arc	n = 12 males, 6 females Age range 18-25 Static VA ≤ 6/7.5	Not measured	150
					14 min of arc			162
					28 min of arc			174
					42 min of arc			192
Ishigaki & Miyao (1994)[41]	Target projected onto a rotating front surface mirror controlled by a variable speed turntable Fixed head rest	Landolt C	Horizontal (left to right)	Up to 210 °/sec	40 min of arc	n = 433 males, 393 females Age range 5-92 No inclusion/ exclusion criteria stated	Not measured	140 at 5 years old
								170 at 10 years old
								180 at 15 years old
								110 at 80 years old
Nakatsuka et al. (2006)[29]	Dynamic Vision Analyzer HI-10 (Kowa) Rotating mirror on a turntable Free head viewing	Landolt C	Horizontal (left to right)	Up to 240 °/sec	10 min of arc	n = 13 males, 8 females Mean age 30.8 ± 5.1 Static VA ≤ 6/6	Not measured	161.4

Ueda et al. (2007)[42]	Dynamic Vision Analyzer HI-10 (Kowa) Rotating mirror on a turntable Fixed head rest	Landolt C	Horizontal (left to right)	Up to 300 °/sec	15/600	n = 60 males Mean age 28.1 ± 3.9 Static VA ≤ 6/6	Not measured		203.05 °/sec
Quevedo-Junyent et al. (2012)[8]	DinVA 3.0 Computer Software Free head movement	Palomar Universal Optotype	Horizontal (right to left)	1.14 °/sec	Dependent Variable	n = 16 females, 17 males Mean age 23.4 ± 3.92 Static VA ≤ 6/6	0.220 for horizontal motion	0.234 at 1.14 °/s	Not measured
			Diagonal (45°)	8.58 °/sec			0.235 for 45° diagonal motion	0.304 at 8.58 °/s	
			Diagonal (135°)	14.1 °/sec			0.237 for 135° diagonal motion	0.423 at 14.1 °/s	
Hoshina et al. (2013)[35]	Dynamic Vision Analyzer HI-10 (Kowa) Rotating mirror on a turntable	Landolt C	Horizontal (right to left)	Up to 300 °/sec	1.0 logMAR	n = 102 males Age range 19-40 Japanese professional baseball players	Not measured		267.6
			Horizontal (left to right)						286.2

Another common method used to create relative motion between an observer and target is having the observer view a stationary target while rotating their head horizontally or vertically in a back-and-forth manner.[7] This head rotation can be active or passive. Active rotation refers to having the participant rotate their head freely, while passive rotation involves having a trained experimenter rotate the participant's head.[34] A more consistent way of accounting for variability in speed of head rotations is to use a computerized set up such as the inVision System by NeuroCom® - this system consists of a head mounted device which measures the direction and speed of the observer's rotational head motion, and only presents the optotype once the desired speed is achieved at a constant rate.[43] As previously mentioned, the DVA measurements obtained using these methods stimulate the VOR, and DVA obtained through target movement with a stationary observer cannot be compared to DVA obtained using head rotation and a stationary object as they use different neural mechanisms in order to stabilize the target image on the retina.

2.3 Factors which affect Dynamic Visual Acuity

DVA and speed thresholds can be influenced by a variety of factors, including characteristics of the observer and the target. Age has a significant effect on DVA – DVA improves between 5 to 15 years of age, after which it declines at a constant rate until 80 years of age.[41] In addition, uncorrected refractive error has a significant effect of speed thresholds, as an increase in uncorrected refractive error creates image blur which can decrease the contrast of the target for the observer and result in a slower speed threshold.[29] Varying results have been found when exploring the possible effect of biological sex on DVA. Most studies have found that sex does not have a significant effect on DVA.[9,44] Studies which have found a difference between the DVA measured in males and females did not take into account population differences or other confounding factors which have the potential to affect DVA.[6] In addition to these population characteristics, optotype attributes such as velocity, target size, trajectory, exposure time, contrast, and colour can also have an effect on DVA – these will be explored in the following subsections.

2.3.1 Velocity

When introducing relative motion between a target and an observer, target velocity must be taken into account as the speed of a target affects DVA. Subjects have better DVA (are able to visualize smaller target details) when a target is moving at slower speeds (target speeds usually range from 1 – 100 degrees per second in order to encompass speeds which can be tracked using both smooth pursuits and saccades).[6,7,9] The variance of DVA measures also increases at faster target velocities, which indicates a larger spread of data.[12,33] The relationship between DVA and the angular velocity of a moving target has been shown to be approximately linear for targets moving between 20-90 degrees per second.[33] When relative motion between the observer and the target is created using a static target and rotational head movements, head rotational velocity does not impact acuity measures.[7] This highlights a difference in DVA measured using head rotation and a static target compared to DVA measured with a moving target, and shows that DVA measured using these two techniques should not be considered equivalent.

2.3.2 Target Size

As summarized above, there is a relationship between target speed and target size – smaller targets are better visualized at slower speeds. It follows that target size has an effect on speed threshold (constant target size with decreasing target speed). Speed thresholds are significantly affected by target size – as target size decreases, speed thresholds become worse.[40] This means that smaller targets need to move at slower speeds in order to be recognized by an observer. Therefore, both target speed and size have an effect on each other when relative motion is present between a target and an observer. It is important to keep one of these variables constant when measuring the other, as varying both will not yield a useful DVA or speed threshold. Additionally, it is important to specify the target speed when reporting DVA and the target size when reporting speed threshold measurements.

2.3.3 Trajectory

Trajectory has been shown to have an effect on DVA – objects moving in a horizontal (left to right) walking motion result in better DVA compared to objects moving in an oblique direction (diagonally from the top right hand corner of a screen to the bottom left, or from the top left hand corner of a screen to the bottom right).[9] Trajectory also has a significant effect of speed thresholds. Objects moving in a left-to-right horizontal motion have faster speed thresholds compared to the same sized object moving with a right-to-left horizontal trajectory.[35] However, since the majority of literature on DVA and speed thresholds uses motorized turntables to create target motion, there has been a limitation to the trajectories studied as only horizontal motion can be simulated with this method. With computer software, it is easier to create target motion in any linear direction as well as random non-linear motion patterns since it is not reliant on a motorized, spinning platform.

Another unique type of motion, termed “jitter,” involves the target quickly shifting in all directions around a fixed central point in an attempt to mimic the type of image motion produced by oculomotor instability.[45] In healthy subjects, target orientation perception of an “E” target has been shown to be robust to jitter – the separation of features on the “E” determines a subject’s tolerance to motion, not the standard deviation of jitter.[46] Additionally, jitter has been shown to have an insignificant effect on separation discrimination tasks (being able to determine if a pair of parallel lines are separated by more or less distance compared to another pair of parallel lines presented 100ms prior).[45,47] Since jitter acuity involves target motion with little to no eye movement, it can be used as a control for DVA.

2.3.4 Exposure Time

The amount of time which a moving target is viewed by a stationary observer varies with target speed unless specifically controlled for – if the target is moving in a linear trajectory, faster moving targets will be in the subject’s field of view for a shorter amount of time compared to slower moving targets. The exposure time of the target has a significant effect on DVA – the longer the exposure time, the smaller the target which can be visualized.[6,44] Exposure time can be controlled in a variety of ways: by having the target repeatedly travel across a screen with the same trajectory and speed, by limiting the presentation time of a slower moving target to match that of the fastest moving target, or by having targets move randomly around a screen for a set amount of time. However, each of these methods involves different strategies of eye tracking to be used in order to visualize the target, which must be considered when comparing measures of DVA.

2.3.5 Contrast

In addition to features of target motion which can be varied to influence DVA and speed thresholds, optotype characteristics can also have an effect on DVA. For example, target contrast significantly effects both DVA and speed thresholds. DVA is superior (observers are able to resolve smaller targets) when a high contrast target is used (100% Weber contrast) compared to a low contrast target.[8,9,44] Low contrast targets result in slower speed thresholds compared to high contrast targets of the same size.[8,44] DVA and speed threshold tasks using low contrast optotypes are more sensitive to increased target speed (for DVA) and decreased target size (for speed threshold) compared to their high contrast counterparts.[44] The effect of contrast on DVA and speed threshold raises interesting questions about the influence of ocular diseases such as multiple sclerosis, which can worsen contrast sensitivity, and their effect on real life tasks involving the recognition of moving targets, such as sports or driving.

2.3.6 Colour

Colour perception is a sensory process in which an observer can discriminate between stimuli based on differences in their distribution of spectral energy.[48]

However, research looking at the effect of target colour on visual acuity has focused more on the wavelength and brightness properties of the target instead of how the colour is perceived by an observer. It has been speculated that target wavelength has an effect on DVA due to the difference in temporal processing between the different cone types. Research by Long and Garvey showed that target wavelength may influence DVA under scotopic and mesopic light levels with dark-adapted viewers.[17] Under photopic conditions, no effect of target wavelength was found.[17] However, this experiment only had two participants; therefore further investigation is required in order to draw solid conclusions on the effect of colour on DVA. No similar research has been conducted since. Even with the expansion of computer based technology over the past few decades, a standardized, validated test available with which to measure static or dynamic visual acuity using a coloured optotype or background is not available.

2.4 Validating a Novel Test

When a new test is developed and introduced into the research or clinical population, users expect proof that the test is valid and repeatable in order to trust their results. Often, validation of a novel test is determined by comparing it to the current gold standard[49,50]; however, in cases where a gold standard does not yet exist, validity needs to be examined in terms of other aspects. There are different features of validity which provide evidence for how well a novel test works. The construct validity of a test demonstrates that a test is collecting data or providing measurements which correctly and appropriately represent the construct proposed by the creators of the test.[8,50,51] Test repeatability, or its ability to yield consistent measurements for the same subject over time, is also important in assessing the validity of a test,[50] and convergent validity describes the ability of a novel test to yield data which accurately represents understood relationships among concepts.[51] External validity is the extent by which the test can yield results which agree with those found in previous research, and can thus be generalized.[50,51] In order to validate a novel test, the instrumentation needs to be administered in a standardized manner – this ensures that a protocol is developed by which valid results can be obtained.[49] All of these aspects of test validity are important, as they each provide a different kind of evidence which helps in determining the usefulness of a test.

The Vision & Motor Performance (V&MP) Lab at the University of Waterloo School of Optometry & Vision Science has developed a novel test named "moV&." moV& is a computerized test which can measure static visual acuity and DVA. It allows for 5 motion types (random walk, horizontal, vertical, oblique, and jitter) and has options for random target size presentation and the presentation of one or five letters at a time. The different targets available include a Landolt C, Tumbling E, and a 10 Sloan letter option. Additionally, target contrast and the colour of the optotype and background can be varied by inputting the desired target A (alpha) and R, G, B values into the software. The validation and reliability of the static and dynamic visual acuity functions of moV& would allow for data on the effect of different factors (such as size, speed, trajectory, contrast, and colour) to be collected in a standardized and comparable manner.

Chapter 3 - Validity and Repeatability of a Novel Dynamic Visual Acuity System

Hirano M, Hutchings, N, Simpson T, Dalton K. Validity and repeatability of a novel dynamic visual acuity system. *Optom Vis Sci*, 2017;94(5):616-625. https://journals.lww.com/optvissci/Abstract/2017/05000/Validity_and_Repeatability_of_a_Novel_Dynamic.10.aspx.

3.1 Chapter Summary

Purpose: In many sports, athletes rely on visual information from the environment to perform. Some literature suggests athletes have superior visual abilities to non-athletes, particularly on tasks representative of the visual demands of their sport, such as dynamic acuity, eye movement accuracy and speed, and peripheral vision. Other literature suggests there is no difference between athletes and non-athletes, at least when standard clinical assessments are employed. A limitation of the literature is that almost none of the research has been conducted with standardized, validated tools. This is partly due to a lack of readily available tools to measure tasks representative of the visual demands of sport, and available tests have typically not been validated against current clinical standards. The purpose of this study is to examine the validity and repeatability of a novel visual acuity system (moV&, V&MP Vision Suite) recently developed in the Vision & Motor Performance Lab (V&MP). moV& permits the measurement of many visual function parameters including dynamic visual acuity with predictable, random, and jittering target motion.

Methods: Twenty-five participants attended two study visits, separated by a minimum of two weeks. At each visit, static and dynamic visual acuity was measured using Snellen, ETDRS, and moV& charts. Static visual acuities were compared to determine the validity of moV&, and both static and dynamic visual acuities were compared between visits to determine the test-retest repeatability. *Results:* moV& static visual acuities are clinically similar to visual acuities measured with the ETDRS chart (mov& -0.09±0.13, ETDRS -0.03±0.11, CCC 0.726). Additionally, all static, dynamic and jitter visual acuities demonstrate good test-retest repeatability (Lin's concordance correlation coefficient range 0.451 to 0.953). *Conclusions:* moV& provides good clinical measures of static visual acuity that are comparable to both Snellen and ETDRS measures. Dynamic visual acuity measures demonstrate good test-retest repeatability.

3.2 Introduction

In almost all sports, athletes rely primarily on visual information from the environment to perform. For example, in golf putting, golfers rely on visual information to be able to accurately read the green, to choose an aim line and a target, to line their ball up with the target, and to line their club up with the ball. A 2007 study of American Olympic athletes conducted by the Johnson & Johnson Vision Care Institute found that 87% of athletes believed that vision was important for success in sport.[1]

Several qualitative literature reviews examining the role of vision in sport have been conducted.[52–54] These have concluded that vision is the 'signal' allowing muscles to respond in sports activities, and suggest that the visual skills that are important for each sport are unique and sport specific.[52–54] For example, the ability of an athlete to discriminate the markings on a baseball or tennis ball may provide them with more information regarding the speed and rotation of the ball.[55] Despite this research, the debate as to whether or not athletes have better visual skills than non-athletes is still contested. Some literature suggests that highly proficient athlete groups have superior visual abilities compared to less proficient athlete groups, and both have superior performance in comparison to non-athlete groups, particularly on tasks that could be considered to be more representative of the visual demands of sport (dynamic acuity, depth perception, eye movement accuracy and speed, peripheral vision measurements and visualization).[56–61] Other literature suggests that when standard (often static) clinical assessments are employed, there is no difference between athletes and non-athletes.[62,63]

The current literature is limited, in that there is not a consistent method of defining athletes and control groups, and factors such as refractive error correction, age, contrast, and testing criteria are dealt with in a variety of different ways, making comparison between studies difficult.[55] An additional limitation of the literature is that almost none of the research has been conducted with standardized, validated tools[52]; this is partly due to a lack of available tools to measure tasks that are representative of the visual demands of sport (e.g. dynamic acuity), and also because some of the tests used have not been validated against the current clinical standards (e.g. ETDRS visual acuity, Pelli-Robson contrast sensitivity).

3.2.1 Static Visual Acuity

Static visual acuity is perhaps the most commonly conducted clinical test. It determines the visual status of patient's eyes, including the need for, or effectiveness of refractive corrections and the effects of disease or disease treatments on the visual system. The Bailey-Lovie chart[22] is widely accepted as the current gold standard for measuring distance visual acuity in population studies and clinical research, and uses 5 letters of equal size and spacing for each line.[22] The Early Treatment Diabetic Retinopathy Study (ETDRS) chart[64], designed based on the principles of the Bailey-Lovie chart, is the current clinical gold standard for measuring visual acuity, and uses a logMAR scale of distance visual acuity, which allows for a per letter acuity measurement - this improves the repeatability and precision of the test.[65,66] Printed charts such as the ETDRS chart have the disadvantage (among many others) of being easily memorized, as clinicians are unable to present the letters or sentences in random order. More recently, computerized visual acuity charts have been developed that allow for the presentation of letters in a random order to avoid memorization effects.[65] Additional challenges with computerized visual acuity charts include difficulties controlling the displays to ensure that letters have the correct size, spacing, luminance and contrast for the measurement of static visual acuity on these systems.[65,67]

3.2.2 Dynamic Visual Acuity

Dynamic visual acuity is a measure of one's ability to recognize moving optotypes during voluntary ocular pursuit.[12] Since many real world situations involve the recognition of moving targets, dynamic visual acuity has applications in sports and athletic performance, driving, piloting, etc. Dynamic visual acuity requires the observer to detect a target as it moves across their field of view, visually acquire and stabilize it using saccadic and smooth pursuit eye movements, and resolve the necessary critical detail for recognition, often during a relatively brief exposure time.[12]

Although there is currently no widely accepted standardized method with which to assess dynamic visual acuity there is a number of technically relevant dynamic visual acuity results that are pertinent in the design of a dynamic visual acuity system. For example, the exposure time of the target has an effect on the dynamic visual acuity results: the longer the exposure time, the better the subject's dynamic visual acuity.[6] It has also been demonstrated that dynamic visual acuity becomes worse as the velocity of the target increases.[13,68] Ludvigh and Miller demonstrated that visual acuity decreases as the angular velocity of the test object increased, and that the relationship between visual acuity and target velocity is equivalent to $Y=a+bx$.[53,68] One of the reasons dynamic visual acuity decreases as target velocity increases is that on average humans are unable to make pursuit eye movements accurately beyond approximately 50° per second.[69–71] At speeds greater than 50° per second, the number of saccades used increases and dynamic visual acuity may be worse due to a decrease in the accuracy of saccades.[13] It may also be due to the mechanisms of saccadic suppression (which reduces system sensitivity to stabilize perception) or saccadic omission (reduces amount of time stimulus is perceived to eliminate perception of blurred visual images).[13] Finally, it has been demonstrated that target trajectory can impact dynamic visual acuity. It has been reported that, dynamic visual acuity is better when target motion has a horizontal trajectory, compared to an oblique trajectory (although this trajectory itself can be systematic [unidirectional] or random).[9]

While it is currently thought that dynamic visual acuity is heavily influenced by oculomotor movements, it is possible that dynamic visual acuity may also be dependent upon individual’s abilities to interpret retinal smear. Induced retinal-image jitter or “jitter,” is another type of target motion that has been used previously to measure visual acuity and involves the target quickly shifting in any direction around a fixed central point on a screen. In normal and amblyopic eyes, target orientation resolution is robust to jitter, and separation of features as opposed to the standard deviation of the jitter is responsible for a subject’s tolerance to the motion.[46] In individuals with vision impairment, jitter has even been shown to improve word and facial recognition.[72] Therefore, jitter can be used as a control in the study of dynamic visual acuity, because it creates a simulated moving target that does not depend on eye movements, such as pursuits and saccades for interpretation. Arguably, individuals will make some small eye movements when doing a jitter task, but the magnitude of these eye movements is much smaller than those made in traditional dynamic visual acuity tasks.

Previous studies have examined the relationship between static and dynamic visual acuity. Some have found a high correlation between the two measures, or a small but significant relationship.[29,73,74] Other studies show no correlation between static and dynamic visual acuity.[75–77] It is hypothesized that the correlation between static and dynamic visual acuity is influenced by the use of the sustained p-cell pathway for static visual acuity while dynamic visual acuity makes use of the transient m-cell pathway.[13] The difference in foveal fixation methods may also influence dynamic visual acuity in comparison to static visual acuity, as dynamic visual acuity is influenced by eye movements such as saccades and smooth pursuits, which are used to keep the image on the fovea.[13]

A possible source of discrepancy between the studies is the difference in methods used to measure dynamic visual acuity in particular. In these studies, dynamic visual acuity has been measured using projected letters and rotating mirrors, rotating discs, or by having targets move across a screen.[55] Therefore, the development of a standardized, validated dynamic visual acuity chart that is comparable to a static visual acuity chart is needed. It would be ideal if the dynamic visual acuity chart were comparable to current clinical and gold standard visual acuity charts, incorporating principles such as uniform logMAR size reduction and presentation of 5 letters of equal size and spacing. Furthermore, if both the newly developed dynamic acuity chart and the static acuity chart it was being compared with were measured with the same system, then one could ensure complete consistency in the testing conditions.

3.2.3 Purpose

The purposes of this study are to validate a newly developed distance static and dynamic visual acuity chart (moV&, V&MP Vision Suite) that has recently been developed in the Vision & Motor Performance Lab (V&MP), against the standard ETDRS chart, and to examine the test-retest relationship of the various dynamic visual acuity tests (predictable motion, random walking motion and jitter).

3.2.4 Hypotheses

It is hypothesized that moV& distance static visual acuity will not statistically differ from the acuity measured with the ETDRS visual acuity chart. It is also hypothesized that the dynamic visual acuity obtained with moV& will be repeatable.

It is predicted that the walking motion dynamic visual acuity of the subject will become worse relative to the subject's stationary visual acuity and jitter dynamic visual acuity as the velocity of the target increases. The horizontal trajectory will provide better dynamic visual acuity compared to vertical, oblique, or random walking motion and jitter dynamic visual acuity should be statistically similar to the static visual acuity.

3.3 Methods

This study followed the tenents of the Declaration of Helsinki and received ethics approval from the University of Waterloo Office of Research Ethics. Prior to enrollment in the study, all participants signed an informed consent after explanation of the nature and possible consequences of the study. Twenty-five adult participants (age range 20-55 years, mean 26.5 ±9.9; 8 males, 17 females) were recruited for this study, which used a repeated measures design, whereby participants attended two separate one hour study visits separated by a minimum washout period of 14 days. Participants were asked to wear their habitual distance refractive correction for the study and were included if they met the criteria of being a healthy staff or student member of the University of Waterloo. Participants were asked about their binocular vision and ocular health status before they were enrolled in the study and excluded if they had amblyopia or any other binocular vision or ocular health issue that had the potential to impact visual acuity in either eye. The same trained clinical investigator (MH) took all visual acuity measurements during this study.

At each visit, participant's static visual acuity was measured using a computerized Snellen chart, a printed ETDRS chart and the newly developed moV& software. Additionally, participant's dynamic visual acuity was measured using moV&. moV& is a computerized chart capable of measuring static, dynamic (horizontal, vertical, oblique and random), and jittered visual acuities (Fig. 3.1). It is a single letter test where participants are asked to identify the letter on the screen by selecting one of the ten letter options on the keypad. Random walk motion targets continuously move, and can exit and re-enter the screen at random locations, whereas the linear motion targets only move across the screen once (at a constant speed). The static and jitter targets remain in the center of the screen at all times. Snellen and ETDRS static visual acuities were measured using standard clinical testing methods. On both charts rows of 5 letters were presented to the participants, and they were asked to identify which letters were on the chart. Participants were not given a restricted set of letters to choose from on either of these tests.

We endeavored to use the same psychophysical methods and stopping rules (similar to what might be used clinically) so that comparisons across tests would not be complicated by psychophysical method differences. Essentially, regardless of what was measured, a ‘row’ of letters comprised 5 letters of the same size, and ‘acuity’ was the point at which 3 of the 5 letters were correctly identified. The computerized tests were all scaled logarithmically in 0.1 logMAR steps (anchored at 20/20 or 0.0 logMAR). For the static tests, 5 of 10 Sloan letters (selected randomly) were presented in single letter sequences in descending runs (i.e. starting with large letters), each letter in the center of the display, until 3 of 5 were correctly read. For the dynamic letters, again 5 of 10 randomly selected Sloan letters were selected, and these were presented, a letter at a time, initially positioned in the center of the display and then moved randomly. If 3 of the 5 letters of the ‘row’ of letters (i.e., a sequence of same-sized letters) were correctly identified, the next smaller (in 0.1 logMAR steps) was chosen, 5 random letters selected and the single letter display sequence was re-initiated. The letters were systematically reduced in size until 3 out of 5 of the ‘row’ could no longer be correctly identified. For all tests, letter counting acuities were then estimated (each letter correctly identified valued at 0.02 logMAR).

Using moV&, we measured static, dynamic (horizontal, vertical, oblique and random), and jittered visual acuities. As mentioned, single letter were presented and participants indicated the letter using a ten-letter-option keypad. Random walk motion targets continuously moved in a Brownian particle motion pattern where each subsequent position on the screen was randomly determined. Brownian motion was chosen for the random walk targets to ensure their motion path was unpredictable. The unpredictable motion paths of the Brownian random walk targets, makes these targets difficult to track accurately with pursuits or saccades alone and observers must use a combination of eye movements, including fixations, pursuits and saccades, to successfully complete these tasks. Dynamic visual acuity for horizontal, vertical, oblique and random walk motion paths were measured for five target speeds (1m/s, 3m/s, 6m/s, 9m/s and 12m/s which are approximately equal to constant angular velocities of 14°/s, 37°/s, 56°/s, 66°/s and 72°/s). These speeds were chosen based on the limitations of ocular pursuit and the intention was to have some speeds that were relatively easy to pursue and some that exceeded the capabilities of the ocular pursuit system. It is important to note that the random walk target and could exit and re-enter the screen at random locations (for up to a maximum of 16s)[7] whereas the linear motion targets (horizontal, vertical and oblique) moved across the screen only once; this was done to ensure that there were no areas on the screen where the letter was present longer than others (i.e. the letter could not bounce at the edge of the screen on the random walk motion or be anticipated to arrive at a consistent point on the edge of the screen for the linear targets). Jitter visual acuity was also measured using a jitter standard deviation of 1mm/s (0.01°/s) and the jitter target remained on the center of the screen for up to a maximum of 16s. All dynamic visual acuities measured with moV& were size thresholds, whereby the letter speed remained fixed and the size of the letter got smaller as the task was done. Dynamic visual acuity can also be measured using speed thresholds, whereby the target size is fixed and the speed varies, but this was assessed in a separate study.[78]

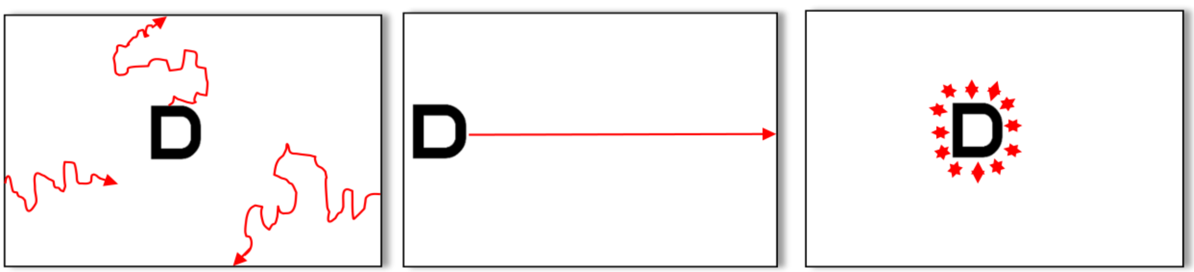

Figure 3.1: Illustrations of random walk, horizontal, and jittered motion produced by moV& software.

All visual acuities were measured monocularly, from one randomly selected eye in each participant. The same eye was used for all tests on both visits, which were separated by a washout period of 14 days.[79] Snellen visual acuity was always measured first, followed by ETDRS and moV& static visual acuity and then the various dynamic visual acuity tests. The order of the ETDRS and moV& static visual acuity test were randomized for each subject, as were the orders of the dynamic visual acuity tests. The same method, instrumentation, and clinical investigator was used for each of the two visits, in order to best test repeatability.

3.3.1 Statistical Analysis

All data analysis was conducted using R (v 3.0.2).[80]

In order to determine the convergent validity of the static moV& test to the gold standard ETDRS chart and the Snellen chart, repeated measures ANOVA was used to test whether the mean differences between the 3 visual acuity tests, for each visit, significantly differ from zero. Due to intra-subject variation of refractive error and visual acuity, the mean difference between tests for each visit was used to determine validity and repeatability. A statistical significance level of $p \leq 0.05$ was defined for the analysis. This quantitatively determined the validity of the static moV& test. In the event of statistically significant differences between the tests, the visits or their interaction, pairwise post hoc comparisons were conducted using the Holm test.[81]

Tests were considered to be significantly different clinically if there was a three letter difference (0.06logMAR) in acuity between them. This difference is consistent with our stopping criteria (3 of 5 letters correct on a line to move onto the next line) and with common clinical practice. A threshold value could not be obtained for participants in some trials at the constant speed testing condition due to a floor effect – some participants could not correctly guess any letters at the first speed and size combination presented, hence no threshold could be measured. One data point at the 6m/s random motion constant speed trial was missed on visit 2 due to a programming error by the clinical investigator. Calculations dealing with comparison between visits were done excluding data points that had no comparison data available, while calculations involving averages used all data points available.

Agreement between static visual acuity measures by different tests was assessed using Lin’s concordance correlation coefficient (CCC). Repeatability, i.e. agreement between two measures of the same test, was assessed numerically with Lin’s concordance correlation coefficient and graphically with Bland-Altman plots for the moV& dynamic visual acuity, static visual acuity, and jitter tests.

3.4 Results

All 25 participants successfully completed both study visits.

3.4.1 Static Visual Acuity

LogMAR mean (±standard deviation) static visual acuity for each of the tests was as follows: Snellen 0.02 ± 0.12; ETDRS -0.03 ± 0.11, and moV& static -0.09 ±0.13 (Fig. 3.2).

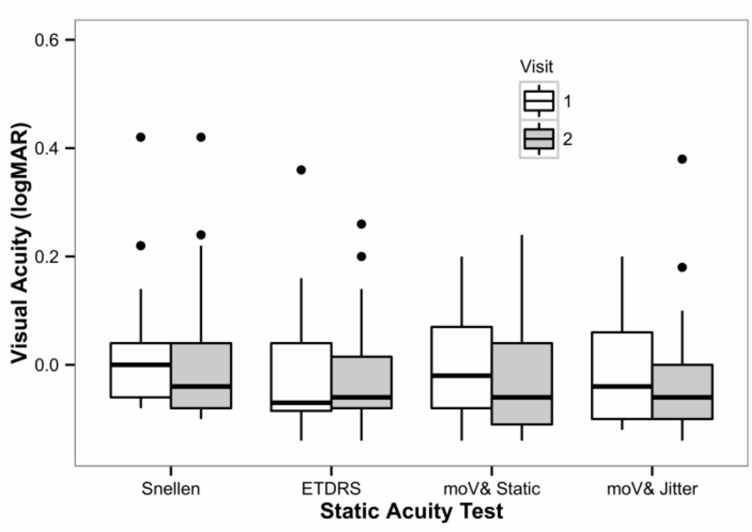

Figure 3.2: Boxplots comparing static visual acuity tests, including the newly developed moV& software. The median result is displayed and the lower and upper hinges correspond to the 1st and 3rd quartiles. Whiskers are 1.5 X IQR.

3.4.2 Validity

When comparing static visual acuity measures between the Snellen chart, ETDRS chart, and novel moV& static chart, there were significant differences ($p<0.001$) between tests, but not between visits ($p=0.14$) or the test-visit interaction ($p=0.94$) (Fig. 3.3). Visual acuity was poorest when measured using the Snellen chart (0.02 ± SE 0.017), followed by the ETDRS chart (-0.03 ± SE 0.016) and the moV& static chart (-0.09 ± SE 0.019). Post-hoc analysis revealed that the moV& static acuity was different from Snellen acuity ($p=0.0002$) but not from ETDRS ($p=0.086$). Snellen and ETDRS were not statistically different from each other ($p=0.183$). Lin's concordance correlation coefficient (CCC) demonstrated that visual acuity on all three tests were statistically correlated with each other and that the Snellen and moV& static tests showed similar agreement with the ETDRS chart (ETDRS vs. Snellen CCC_{V1} = 0.704, CCC_{V2} = 0.776 and ETDRS vs. moV& static CCC_{V1} = 0.712, CCC_{V2} = 0.737). There was lower concordance between Snellen and moV& acuities (CCC_{V1} = 0.473, CCC_{V2} = 0.673), with moV& recording slightly better acuities across the range of acuity measurements (-0.20 to 0.40) than the standard clinical tests.

Bland-Altman analysis was carried out between the ETDRS chart and the moV& static acuities (Fig. 3.4). The mean difference between ETDRS and moV& Static at the first visit was 0.053 (Upper LOA, 95% CI: 0.217, 0.183 to 0.286; Lower LOA, 95% CI: -0.111, -0.077 to -0.181). Corresponding data for the second visit was 0.058 (Upper LOA: 0.211, 0.179 to 0.276; Lower LOA: -0.096, -0.064 to -0.16).

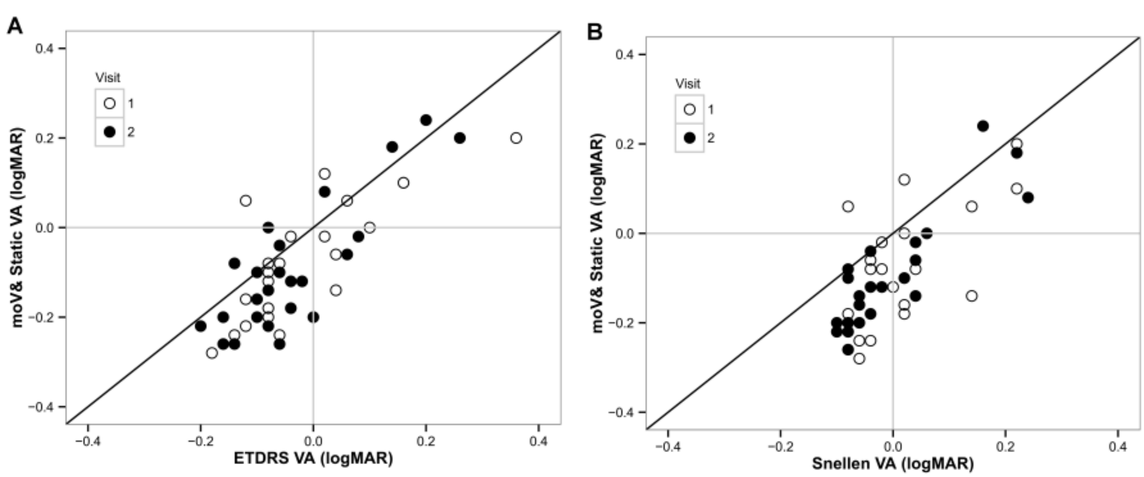

Figure 3.3: Concordance plots between moV& software static visual acuity and current static visual acuity clinical tests: (A) ETDRS and (B) Snellen.

3.4.3 Test-Retest Repeatability

Overall, there was no significant difference in static visual acuity measured on visit 1 vs. visit 2 on these tests (p=0.077). Post-hoc individual comparisons confirmed that visual acuities were no different on each test between visits (visit 1 vs. visit 2: Snellen p=1.000, ETDRS p=1.000, moV& Static p=1.000, Jitter p=1.000). Lin's concordance correlation coefficient between visit 1 and visit 2 for each of the static visual acuity tests were 0.746, 0.767 and 0.609 (Snellen, ETDRS and moV& respectively).

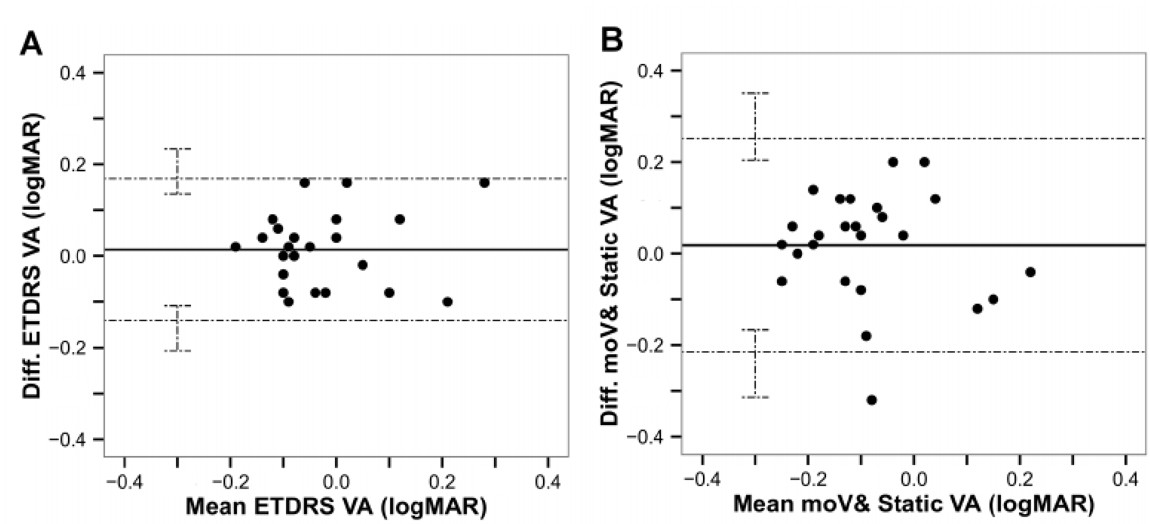

Figure 3.4: Bland-Altman plots between visit 1 and visit 2 for (A) ETDRS and (B) moV& software static visual acuities.

3.4.4 Dynamic Visual Acuity

Jittered visual acuity (-0.06 ± 0.13) was found to be more similar to static visual acuity than to dynamic visual acuity, but all of the dynamic visual acuity measures (horizontal, vertical, oblique and random) were worse than the static visual acuity measures.

On average, horizontal, vertical and oblique dynamic visual acuities were three lines (0.3 logMAR) worse than static visual acuities, except for horizontal dynamic visual acuity at 1m/s which was approximately 1.5 lines worse than the static visual acuities (Table 3.1). Random dynamic visual acuity was approximately two lines worse (0.2 logMAR) than static visual acuities at all speeds (Table 3.1).

Table 3.1: Mean (±SD) dynamic visual acuity (logMAR) for each direction and speed on the moV& software, averaged across the two visits (static visual acuities are also shown for comparison)

	SPEED				
	1m/s	**3m/s**	**6m/s**	**9m/s**	**12m/s**
Horizontal	0.15 ± 0.12	0.29 ± 0.15	0.30 ± 0.14	0.33 ± 0.14	0.33 ± 0.12
Vertical	0.28 ± 0.13	0.25 ± 0.16	0.30 ± 0.14	0.33 ± 0.14	0.33 ± 0.13
Oblique	0.34 ± 0.14	0.30 ± 0.15	0.35 ± 0.15	0.38 ± 0.15	0.39 ± 0.13
Random	0.24 ± 0.16	0.23 ± 0.16	0.21 ± 0.14	0.23 ± 0.16	0.20 ± 0.16
	ETDRS	**Snellen**	**moV& static**	**moV& jitter**	
Static VA	-0.03 ± 0.12	0.02 ± 0.12	-0.09 ± 0.13	-0.06 ± 0.13	

3.4.5 Test-Retest Repeatability

Mean logMAR jittered acuity ranged from -0.25 to 0.28 and test-retest CCC=0.666, and the repeatability is illustrated in Fig. 3.5. The mean difference between moV& jittered acuity at the first visit and second visit was 0.03 (Upper LOA, 95% CI: 0.238, 0.195 to 0.326; Lower LOA, 95% CI: -0.178, -0.135 to -0.267).

Test–retest repeatability was reasonably good for all of the dynamic visual acuity tests (with CCC's ranging from 0.45 to 0.95) and was comparable to test-retest repeatability for the static visual acuity tests (Table 3.2). The number of completed trials, where the subject was able to correctly respond at the largest letter size or smaller, is shown in Table 3.3. It can be seen that, except for random motion of the target, the number of completed trials reduces as the speed of the target increases.

Table 3.2: CCC between visits 1 and 2 for dynamic visual acuities at each speed

	1m/s	**3m/s**	**6m/s**	**9m/s**	**12m/s**
Horizontal	0.613	0.610	0.715	0.557	0.569
Vertical	0.692	0.678	0.451	0.783	0.725
Oblique	0.744	0.686	0.697	0.852	0.953
Random	0.730	0.732	0.617	0.700	0.614

Table 3.3: Number of completed trials for dynamic visual acuities at each speed and visit

	1m/s	3m/s	6m/s	9m/s	12m/s
Horizontal	Visit 1 = 25 Visit 2 = 25	Visit 1 = 23 Visit 2 = 23	Visit 1 = 21 Visit 2 = 24	Visit 1 = 20 Visit 2 = 20	Visit 1 = 17 Visit 2 = 20
Vertical	Visit 1 = 24 Visit 2 = 24	Visit 1 = 24 Visit 2 = 23	Visit 1 = 18 Visit 2 = 18	Visit 1 = 17 Visit 2 = 15	Visit 1 = 17 Visit 2 = 11
Oblique	Visit 1 = 22 Visit 2 = 22	Visit 1 = 21 Visit 2 = 21	Visit 1 = 16 Visit 2 = 18	Visit 1 = 9 Visit 2 = 10	Visit 1 = 10 Visit 2 = 7
Random	Visit 1 = 24 Visit 2 = 24	Visit 1 = 25 Visit 2 = 25	Visit 1 = 24 Visit 2 = 22	Visit 1 = 24 Visit 2 = 25	Visit 1 = 25 Visit 2 = 25

Fig. 3.6 shows the between visit repeatability for each target direction at a speed of 6m/s. The mean differences (±LOA) for horizontal, vertical, oblique and random motion were 0.024 (±0.186), 0.032 (±0.250), 0.031 (±0.265), and 0.005 (±0.239) respectively.

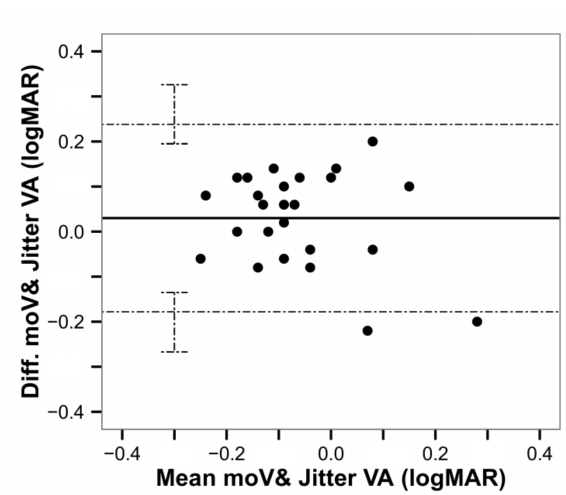

Figure 3.5: Bland-Altman plot for visual acuity (logMAR) between visit 1 and 2 for the novel moV& software jittered acuity.

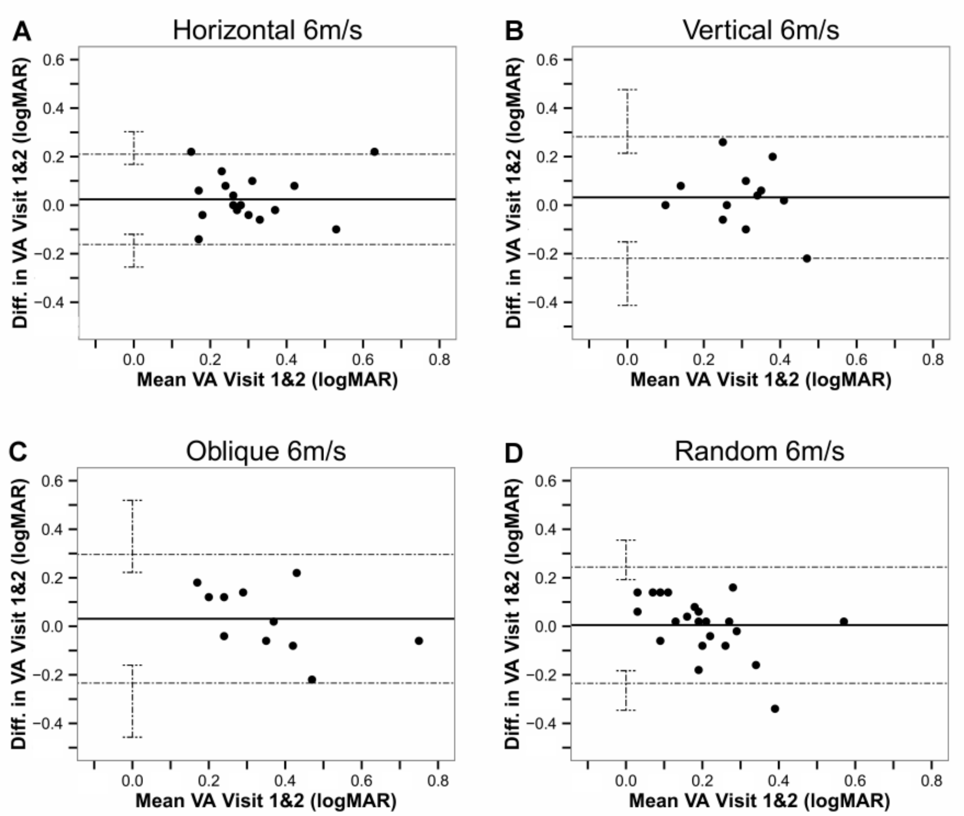

Figure 3.6: Bland-Altman plots for visual acuity (logMAR) between visit 1 and 2 for (A) horizontal, (B) oblique, (C) random walk, and (D) vertical motion at 6 m/s.

3.5 Discussion

The development of new tests places some responsibility on the developer to at least demonstrate if the new metrics perform as intended. In this paper we demonstrated the validity of a suite of computerized static and dynamic acuity measures inasmuch as we showed that the newly developed moV& measures compared to traditional (Snellen) and "gold standard" ETDRS acuity charts. In addition, we demonstrated that the repeatability of the moV& measures were high and were similar to the repeatability of a gold standard. The other aspects of validity of dynamic visual acuity and its utility remain to be demonstrated. There is no gold standard to which a new device will be compared and so validity will require somewhat indirect demonstration, and the utility of tests developed, especially for athletes, will require testing on the intended samples.[82]

The moV& static test appears to produce clinically similar results to the current gold standard static visual acuity chart, the ETDRS chart. Additionally the static test demonstrates good test-retest repeatability.

Clinically, the differences in acuities measured with the Snellen and ETDRS charts was approximately half a line (2.5 letters) and between moV& static and ETDRS charts was also approximately half a line (3 letters). Although the difference between the moV& static chart and the ETDRS charts was at our level of clinical significance (3 letters), the difference between the Snellen chart and the ETDRS chart was also very similar (2.5 letters). As both the Snellen and ETDRS charts are accepted as measures of static visual acuity clinically, we believe that the moV& static test demonstrates equivalent clinical utility. Furthermore, it should be noted that there were only 10 letter choices on the moV& keypad, and moV& static is a single letter test; both of these features have the potential to make this test slightly easier than both the Snellen and ETDRS tests; this may contribute to the higher visual acuities measured with moV&.

Dynamic visual acuities appeared to be worse than static visual acuities by approximately 0.3 logMAR, on average. The random walk dynamic visual acuity was approximately two lines worse (0.2 logMAR) than the static acuities on average (Table 3.1). It can also be seen that, particularly as the speed of the target increased, the average group dynamic visual acuity was better for the random walk target than for the horizontal, vertical and oblique trajectories. This may be because the randomly moving targets were on the screen longer than the other target trajectories, because the random targets could go off the screen and come back whereas the linear motion targets only moved across the screen once. This factor may be contributing to the difference in the acuity values between these types of moving targets, but more investigation is needed to fully understand the difference.

Although this study was not designed to examine the impact of target velocity on dynamic visual acuity, it is interesting to note that apart from the horizontal target, all dynamic visual acuities (random, vertical and oblique) measured at different velocities were relatively consistent. This may be because, humans appear to be better at reading targets with horizontal trajectory from left to right than other trajectories, as previously demonstrated.[9] The presence of a floor effect within the participants also supports this idea, as it demonstrates certain conditions are more challenging for participants than others. The change in horizontal dynamic visual acuity with increasing speed may be related to the limited target presentation time at the higher speeds, as the target only crossed the screen once which limited the amount of time available to detect and recognize the target.

Each of the dynamic visual acuity tests demonstrated good test-retest repeatability and also, dynamic test-retest repeatability was similar to the test-retest repeatability of the static tests. Overall, Lin's concordance correlation coefficients (CCCs) were high between the different dynamic visual acuity tests (Table 3.2); the lowest correlations appeared to occur between the slowest horizontal visual acuity measure (H1) and the highest speeds (12m/s) for the other systematic trajectory visual acuities (H12, O12 & V12). The CCC's for the horizontal visual acuity is likely due to horizontal visual acuity at 1m/s being much better than all of the other dynamic visual acuity-measures. It is likely because this is a task participants were most familiar with, in that the targets moved left to right and at 1m/s mimicked tasks that are done every day in Canada. Differences between the horizontal 1m/s and the other dynamic visual acuities may reflect differences between the task of the threshold at which velocity has its greatest impact; however more investigation is needed to understand this precisely.

Jittered visual acuity appears to be more similar to static visual acuity than to dynamic visual acuities with moving targets, which is consistent with previous literature.[46] Test-retest repeatability was good for the jittered test as well.

The results presented here demonstrate that moV& could be used to measure static visual acuity clinically as well as dynamic visual acuities. moV& can also be used to compare static and dynamic visual acuity within the same system. Further investigation should be done regarding the effect of age on dynamic visual acuity as ocular pursuits decline with age, and the age range of the participants (age range 20-55 years) may be large enough for this effect to be shown.[55] The correlation between static visual acuity and dynamic visual acuity has been shown to be influenced by the velocity of the target, although, more research is needed to understand the relationship between dynamic visual acuities and static visual acuities.[74]

Stimulus trajectory has also been shown to be an important factor for dynamic visual acuity, especially during linear motion (horizontal, vertical, and oblique).[83] moV& provides a system where trajectory as well as size, speed, and exposure time can be controlled and manipulated to provide different testing conditions as required. Additional research is needed to validate the low contrast features of this chart and to establish clinical norms for visual acuities measured with chromatic combinations of target and background. All of these features can be modified in V&MP Vision Suite visual acuity tools.

3.6 Dissertation Progress I

The Progress sections at the end of Chapters 3, 4, and 5 will summarize how the findings from each experiment contribute to the following Chapter. These contributions will be displayed in a figure, which will expand as each Experiment is added. Fig. 3.7 outlines the purpose of Experiment 1.

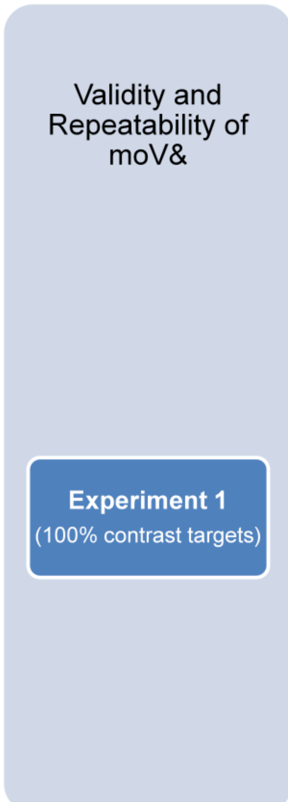

Figure 3.7: Dissertation Progress I, outlining the purpose of Experiment 1.

The findings of Experiment 1 show that moV& is valid and repeatable for static and dynamic visual acuity measurements using 100% contrast black targets on a white background. Since we now know that moV& works for a standard target, we must show that moV& is also valid and repeatable for its other functions – low contrast targets and coloured target/ background combinations (Experiment 2).

Chapter 4 – Repeatability of the Low Contrast and Coloured Functions of a Novel Dynamic Visual Acuity Chart

4.1 Chapter Summary

Purpose: The ability to recognize moving targets, also known as dynamic visual acuity, is important for safety and performance during activities such as driving or sport. Target contrast and colour have both been shown to effect dynamic visual acuity; however, a "gold standard" validated test does not exist with which to measure low contrast or coloured dynamic visual acuity. The purpose of this study is to determine the test-retest repeatability of the static and dynamic visual acuity functions of a novel visual acuity system (moV&, V&MP Vision Suite) using two low contrast (61% and 20%) and two coloured optotype-background combinations (red target on a white background and white target on a blue background). *Methods:* Forty-two participants were assigned to either the contrast (n=21) or colour (n=21) study block. Each block consisted of two visits separated by a minimum of 2 weeks. At each visit for the contrast block, low contrast (61% and 20% contrast) static and dynamic visual acuity was measured using Snellen and moV& charts. For the colour block, coloured optotype and background (red target on a white background, white target on a blue background) static and dynamic visual acuity was measured at each visit using the moV& chart, as well as black and white high contrast static visual acuity using the ETDRS chart. Visual acuity was compared between visits to determine repeatability. *Results:* moV& static visual acuities were significantly better than Snellen at both contrast levels (moV&: 20%: -0.01±0.09, 61%; -0.08±0.12;

Snellen: 20%: 0.13±0.09, 61%: -0.01±0.09, p<0.05). Repeatability of moV& static visual acuity was good (Lin's concordance correlation coefficient was 0.80 for 61% contrast and 0.60 for 20% contrast). Lin's concordance correlation coefficients for dynamic visual acuity ranged from 0.05 to 0.74, but were better at 61% contrast. For the coloured targets, moV& static visual acuity was significantly better than ETDRS (moV&: red/white: -0.09±0.18, white/blue: -0.11±0.17; ETDRS: -0.02±0.15, p<0.05. Dynamic visual acuities demonstrated good test-retest repeatability (Lin's concordance correlation coefficients ranged from 0.50 to 0.88, and were similar for both colour combinations). *Discussion*: moV& low contrast and coloured static visual acuities demonstrated good repeatability and were comparable to the Snellen and ETDRS charts. moV& coloured dynamic visual acuities showed fair to good repeatability, but repeatability with low contrast targets was poor, especially at 20%.

4.2 Introduction

The ability to recognize moving targets is an important visual skill required to navigate the world, especially in situations where motion occurs at a relatively high speed. In many cases, the recognition of moving targets is imperative in order to coordinate movements to navigate our environment. Athletes in particular rely heavily on visual information from their environment in order to successfully perform. Several qualitative literature reviews and studies have concluded that vision plays a vital role in guiding motor actions during sports, and that the visual skills used during sports are unique and sport specific.[52–54] For example, ice hockey players use peripheral and dynamic vision with short reaction times in order to successfully pass and shoot the puck.[2] It has been shown that a significant number of points scored in ice hockey are related to players' ability to discriminate between competing visual stimuli and inhibit non-target motor responses in a decision making task.[3]

A limitation of the current literature which explores the visual function of athletes is the inconsistencies present in the research methods – for example, the definition of an athletes' skill level (e.g. professionals vs. novices) varies, as does the way in which different experimental factors (specifically ones which have the potential to influence the results of visual testing) are controlled (e.g. refractive correction, contrast, and testing criteria).[55] Furthermore, most of the research has been conducted without standardized, validated tools to measure visual skills common in sport, such as dynamic visual acuity or visual speed thresholds.[52] This may be due to the lack of available tools to assess these functions.

4.2.1 Dynamic Visual Acuity

The smallest target size at which an observer is able to resolve critical detail during voluntary ocular pursuit (when the target is in motion) is known as dynamic visual acuity.[12] Dynamic visual acuity has important applications in real-life, such as during driving and athletic performance. It requires the detection of a moving target in the observer's field of view, the use of saccades and smooth pursuit eye movements to visually acquire the target (ideally 'stabilising' the target image close to the fovea on the retina), and the resolution of critical detail for recognition within a brief exposure time.[12] A moving target usually exhibits "walking" motion (i.e. follows a path or trajectory across the screen). Walking motion can be predictable (e.g. horizontal, vertical, or oblique motion) or unpredictable (random).

When a target is in motion, either the speed or the size of the target can be varied to measure two different dependent variables – dynamic visual acuity and speed threshold. Dynamic visual acuity is measured at a constant target speed, and is the smallest size which an observer can resolve target detail. Speed threshold is the fastest speed at which an observer can resolve detail at a constant target size. Since both target speed and size can affect how a moving target is visualized, it is important to determine which dependent variable is most beneficial to measure before beginning testing.[5,13]

There are two methods that are commonly used to measure dynamic visual acuity: 1) the observer's head is kept stationary while they view a target moving across a screen, or 2) a static target is viewed while the observer makes rotational head movements.[55] Target movement across a screen has been achieved using a variable speed turntable and a front surface mirror, or more recently using computer programs.[9,12,35,44] These methods require the observer to make smooth pursuit eye movements and saccades in order to resolve the moving target.[5] Alternatively, studies which have used head rotations in order to create relative motion between the target and the observer have done so by either using a head mounted device in order to monitor the frequency of rotations being made by the observer, or by having trained personnel rotate the observers head.[34,43] This methods invokes the vestibulo-ocular reflex, which helps to keep the target on or close to the fovea during rotational head movement.[5] Due to the differences in the methods used to create relative motion between a target and observer in the measurement of dynamic visual acuity, comparisons between the different studies are difficult. The use of a similar, standardized testing method would make research on dynamic visual acuity and speed thresholds more consistent and applicable across a variety of conditions.

The lack of a standardized method with which to assess dynamic visual acuity and speed thresholds may be due to the large number of variables which can be modified to affect how an observer views a moving object. These variables must be considered when designing a test. For example, a longer target exposure time has been shown to result in better dynamic visual acuity.[6] Velocity also has an effect: as the angular velocity of an optotype increases, dynamic visual acuity becomes worse.[13] Additionally, dynamic visual acuity improves if a target moves in a left-to-right horizontal trajectory compared to an oblique or right-to-left horizontal trajectory.[9,35]

4.2.2 Colour and Contrast

Other optotype and background characteristics that have the potential to influence dynamic visual acuity include contrast and colour. It has been shown that decreasing the contrast between the optotype and background results in worse static visual acuity, dynamic visual acuity, and speed thresholds.[9,12,14,15] Low optotype contrast and speed also have an effect on the eye movements used to track moving objects – lower contrast levels and faster target speeds result in larger initial deviations of the pursuit eye movements.[84]

Literature exploring the impact of target colour on visual acuity is limited. Static visual acuity research using coloured targets have demonstrated that a black optotype on a white background yields the same static acuity as a yellow optotype on a red background, and a 40% higher static acuity than a blue optotype on a red background.[16] Target colour may also influence DVA, as it has been shown that under scotopic and mesopic conditions target wavelength can affect DVA; however this affect was not present in photopic conditions, and this paper only collected data from two participants, making it difficult to draw solid conclusions from the findings.[17] At this time, there is no further available literature reporting the investigation of the impact of colour on dynamic visual acuity. One of the reasons the literature in this area is so limited is likely because a "gold standard" validated test with which to measure coloured visual acuity (static or dynamic) does not currently exist. This limitation also applies to available research on low contrast visual acuity, as there is not a standardized, validated test available to measure low contrast dynamic visual acuity.

Measuring low contrast and coloured dynamic visual acuity can have important practical and clinical applications. For example, low contrast dynamic visual acuity can be used to assess a patient's ability to read a sign while driving with ocular conditions which impact contrast sensitivity (e.g. nuclear sclerotic cataracts, multiple sclerosis, etc.). In the case of athletes, contrast on the field, court, or arena can vary based on lighting conditions. This can impact performance as it has been shown that performance on a dynamic visual acuity task can be optimized by controlling target contrast.[15] Additionally, the target and background colours on a dynamic visual acuity task can be customized to the colours encountered in an athlete's specific sport. This would allow for the measurement of dynamic visual acuity to be more representative of what the athlete would encounter while on the field. Dynamic visual acuity improves with vision training, therefore specifying the training to include specific colour combinations encountered in sport may aid in the translation to on-field performance.[85]

The Vision & Motor Performance (V&MP) Lab at the University of Waterloo School of Optometry & Vision Science has recently developed and validated the high contrast functions of a new computerized test (moV&, V&MP Vision Suite) with which to measure static and dynamic visual acuity.[38] It allows for random walk, horizontal, vertical, or oblique motion of targets, as well as options for the random presentation of target size and presenting one or five letters at a time. The different optotypes available include a Landolt C, Tumbling E, and a 10 letter Sloan optotype option. In addition to the various target presentations described above, both target contrast and the colour of both the target and the background can be varied.

4.2.3 Purpose

The purpose of this study is to determine the test-retest repeatability of the static and various dynamic visual acuity tests of moV& using two low contrast (61% and 20% contrast) and two coloured optotype-background combinations (red target on a white background and white target on a blue background). The two low contrast levels were chosen to reflect a low and middle level contrast value similar to those studied in previous literature on low contrast dynamic visual acuity.[9,10,12,14] The two colour combinations were selected to reflect those commonly encountered in sport – the red and white detailing of a cricket ball or baseball, and a white ball against a blue sky.

4.2.4 Hypotheses

It is hypothesized that moV& distance static and dynamic visual acuity tests will be repeatable for both low contrast values and colour combinations measured.

4.3 Methods

This study followed the tenets of the Declaration of Helsinki and has been reviewed and received ethics clearance though a University of Waterloo Research Ethics Committee. Prior to study enrollment all participants signed an informed consent form after explanation of the nature and possible consequences of the study. Adult participants from the University of Waterloo were recruited for both the contrast (n=21, age range 20-28 years, mean age 22.0±1.97; 7 males, 14 females) and colour (n=21, age range 20-24 years, mean age 22.2±1.18; 8 males, 13 females) blocks of this study. This study used a repeated measures design – participants attended two separate 1.5 hour study visits separated by a minimum washout period of 14 days. Participants wore their habitual distance refractive correction for both visits. Exclusion criteria for this study included a self-reported binocular vision defect, amblyopia, or an ocular disease with the potential to impact the visual acuity of either eye. The same trained clinical investigator (M.H.) took all visual acuity measurements during this study, using the same psychophysical methods and stopping rules for all participants in order to best determine repeatability. Visual acuity testing was stopped when the participant incorrectly identified at least three of five letters presented with the same combination of contrast, colour, speed, size, and motion type. All measures of acuity were scaled logarithmically into 0.1 logMAR steps (anchored at 20/20 or 0.00 logMAR).

This experiment used moV& for all measurements of low contrast and coloured static and dynamic visual acuities. In addition, a low contrast Snellen chart was used to measure static visual acuity for the contrast block, and a standard, high contrast (black and white) paper ETDRS chart was used to measure static visual acuity for the colour block. moV& is a computerized visual acuity chart capable of measuring both static and dynamic visual acuity as well as speed thresholds. moV& can display optotype motion in four directions: horizontal (left to right), vertical (top to bottom), oblique (top left to bottom right corner), and random walk motion. Linear motion targets (horizontal, vertical, and oblique) only moved across the screen once, while random walk motion targets could exit and re-enter the screen at random locations for up to a maximum of 16 seconds.[7] This ensured that there were no areas of the screen where the letter was present for a predictably longer amount of time (as would be the case if the letter bounced off the edge of the screen) and kept the target exposure time constant for random walk motion. Random walk motion consisted of the targets continuously moving in a Brownian particle motion pattern, with each subsequent direction of movement being randomly determined. This ensured that the motion path of the target was unpredictable, making the targets more difficult to accurately track with only pursuits or saccades – a combination of fixations, pursuits, and saccades are needed to successfully track the target during random walk motion.

For the low contrast block of this study, participants' static visual acuity was measured at both 61% and 20% contrast using a computerized low contrast Snellen chart (Innova Systems, Burr Ridge, Illinois) and the moV& software (V&MP Vision Suite, Waterloo, Ontario). The Weber contrast of the displays of both units was determined using a spotmeter (Konica Minolta Sensing Americas, Inc, Ramsey, New Jersey). Low contrast Snellen static visual acuities were measured using standard clinical testing methods – 5 lines of 5 letters were presented to participants on the same screen at a given contrast level, and they were asked to identify the letters on the chart. For low contrast moV& static visual acuity measures, single letters were randomly presented in a descending run sequence (in 0.1 logMAR steps) – 5 Sloan letters of each logMAR size were presented. Each letter was presented at the centre of the screen, and participants answered by selecting their response on a 10-letter-option keypad. Testing stopped when three of the five letters of a given size were not correctly identified. Per-letter acuities were determined for both tests. Since moV& presents letter size in logMAR notation, each correctly identified letter had a value of 0.02 logMAR. For visual acuities obtained using the Snellen chart, the logMAR acuity was calculated by taking the log of the reciprocal of the threshold value in 20/20 notation, and attributing a value of -0.02 logMAR for each additional letter guessed, or +0.02 logMAR for each incorrectly identified letter. For example, if a participant had a Snellen acuity of 20/25 -2, their logMAR acuity would be log(25/20) = 0.10 + 0.04 (as they incorrectly identified 2 letters on the 20/25 line) = 0.14 logMAR.

For the colour block of this study, participants' static visual acuity was measured using a standard black and white printed ETDRS chart, and two target and background colour combinations on moV&: a red target (R=160, G=34, B=34, A=210) on a white background (R=255, G=255, B=255), and a white target (R=255, G=255, B=255) on a blue background (R=54, G=109, B=181). The two coloured target and background combinations had equal contrast between the target and the background (83% Weber contrast). The colour combinations were chosen due to their prevalence in popular sports – the red and white is representative of the detailing and colour of a cricket ball, and the white and blue is similar to detecting a white ball against a blue sky on a sunny day. ETDRS static visual acuities were measured using standard clinical testing methods (multiple rows of 5 letters were presented, participants were asked to identify the letters with no restricted set of letters to choose from, a per-letter logMAR acuity was determined by assigning each letter a value of 0.02 logMAR). For the coloured moV& targets, the same protocol as the low contrast targets was used (5 of 10 possible Sloan letters randomly presented in a single-letter descending run sequence), and per-letter acuity was again determined.

Dynamic visual acuity was measured at 61% and 20% contrast as well as with the red target on a white background and the white target on a blue background using moV& software. Similar to the static visual acuities measures, 5 of 10 possible Sloan letters were randomly presented one at a time and participants indicated their letter guess using a 10-letter-option keypad. Letters were presented in a descending run sequence, starting with large targets (+1.0 logMAR above their static visual acuity measured on the corresponding low contrast Snellen chart or the ETDRS chart) and decreasing after every 5 letter presentations in 0.1 logMAR steps. Dynamic visual acuity was determined for horizontal, vertical, oblique, and random walk motion and was measured at five target speeds (1, 3, 6, 9, and 12 m/s, which are approximately equal to constant angular velocities of 14, 37, 56, 66, and 72 °/s). These speeds were chosen with the intention to include speeds which were both relatively easy to pursue and some that exceeded the typical capabilities of the ocular pursuit system. These tests are summarized in Fig. 4.1.

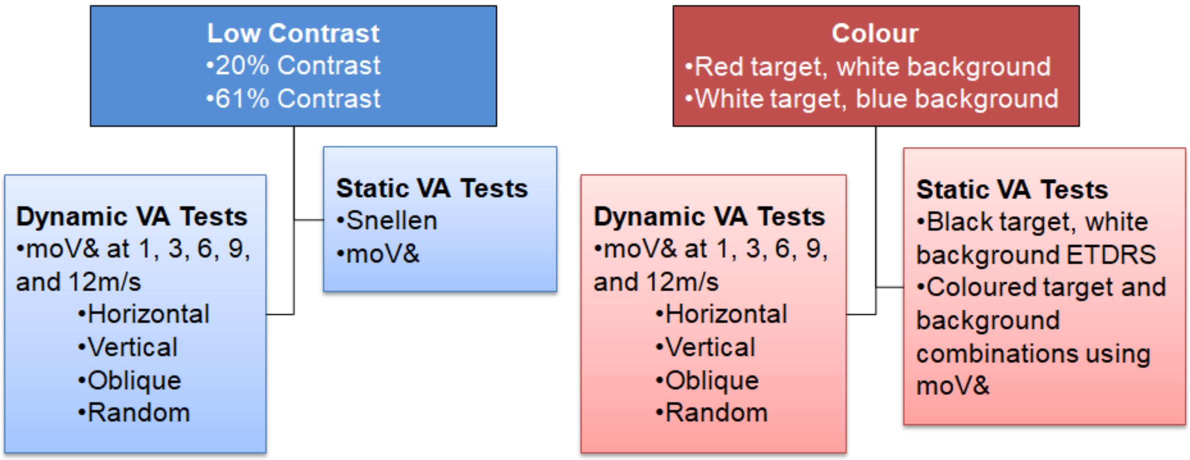

Figure 4.1: Summary of tests completed by each participant for the low contrast and colour study blocks.

All visual acuities were measured monocularly, with the viewing eye randomly selected for each participant. The same eye was used for all tests on both visits. Static visual acuity measures were always measured before dynamic visual acuity. The orders of the dynamic visual acuity tests (trajectory and target speed) were randomized for each subject at each visit.

4.3.1 Statistical Analysis

All data analysis was conducted using R (v 3.0.2).[80]

Although no gold standard test currently exists for low contrast or coloured static visual acuity, the convergent validity of the low contrast static moV& test can be determined by comparison with the low contrast Snellen chart, and the coloured moV& targets can be compared with the standard ETDRS chart.

Preliminary descriptive statistics looked at the central tendencies and distribution of the data obtained from each optotype. The mean difference in static visual acuity between visits 1 and 2 was used when determining repeatability in order to account for the intra-subject variation of visual acuity and refractive error. Repeated measures ANOVA was used to determine if the mean differences in static visual acuity between visits 1 and 2 significantly differed from zero. Statistical significance was defined as $p \leq 0.05$. Pairwise post hoc comparisons were conducted using the Bonferroni correction if there was a significant difference between static visual acuity tests, or if there was a significant difference between visits 1 and 2 for the same test. Clinically, tests were considered significantly different if there was a three-letter difference in acuity (0.06 logMAR) as this is the stopping criteria of acuity tests in common clinical practice.

For participants in some trials, a dynamic visual acuity value could not be obtained due to a floor effect – the participants could not correctly guess any letters at the first speed and size presented, therefore an acuity measure could not be determined. Due to a programming error by the clinical investigator, one data point is missing in the coloured block (red optotype on a white background, random motion at 12m/s for visit 1). Calculations comparing data between visits excluded those trials which had no comparison data available, and calculations involving averages used all available data points.

Agreement between static visual acuity tests as well as the repeatability (agreement between two measures of the same test) of both the static and dynamic visual acuity tests was determined using Lin's concordance correlation coefficient (CCC). Agreement between visits was also represented graphically using Bland-Altman plots.

4.4 Results

All 21 participants in each of the contrast and colour blocks of the experiment completed both study visits.

4.4.1 Static Visual Acuity

LogMAR mean (±standard deviation) static visual acuities for the low contrast targets are as follows: 20% contrast Snellen=0.13 ± 0.09; 20% contrast moV&=-0.01 ± 0.14; 61% contrast Snellen=-0.01 ± 0.09; 61% contrast moV&=-0.08 ± 0.12 (Fig. 4.2). The difference between the low contrast Snellen and moV& static visual acuity tests was statistically ($p \leq 0.001$) and clinically (>0.06 logMAR) significant at both 20% and 61%. Lin's CCC showed a poor concordance between the low contrast Snellen and moV& static visual acuity tests, with 20% contrast having a worse CCC value compared to 61% contrast (20% contrast $CCC_{\text{Snellen vs moV\&}}$=0.294, 61% contrast $CCC_{\text{Snellen vs moV\&}}$=0.490).

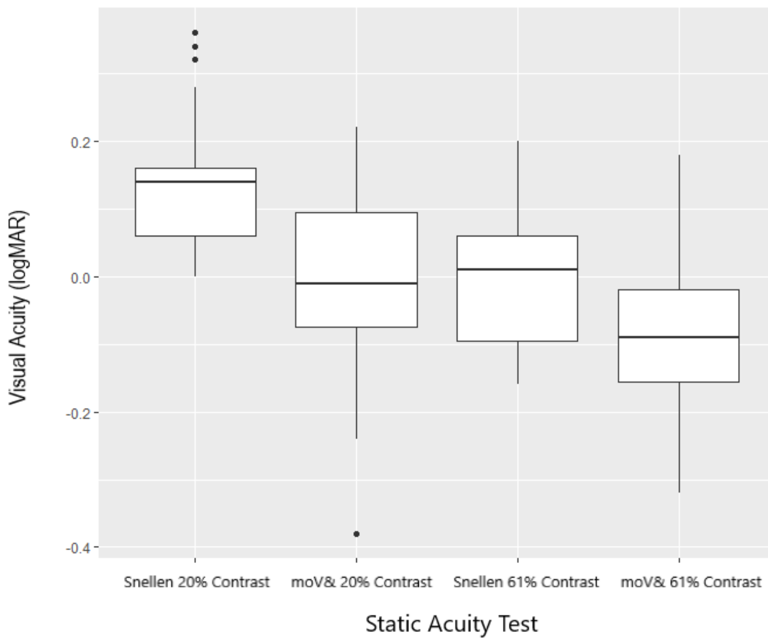

Figure 4.2: Boxplots comparing low contrast static visual acuity tests. The median result is shown, with the lower and upper hinges corresponding to the 1st and 3rd quartiles and whiskers being 1.5 x IQR.

For the coloured optotype and background combinations, the logMAR mean (±standard deviation) static visual acuities were as follows: black optotype on a white background ETDRS=-0.02 ± 0.15; red optotype on a white background moV&=-0.09 ± 0.18; white optotype on a blue background moV&=-0.11 ± 0.17 (Fig. 4.3). The difference in static acuity between the ETDRS chart and both coloured optotype/ background combinations in moV& was both clinically (>0.06 logMAR) and statistically ($p \leq 0.001$) significant. The two colour combinations in moV& (red optotype/ white background and white optotype/ blue background) were not significantly different from each other (p=0.210). Lin's CCC showed good concordance between the ETDRS chart and both colour combinations ($CCC_{ETDRS\ vs\ Red/White}$=0.792; $CCC_{ETDRS\ vs\ White/Blue}$=0.747).

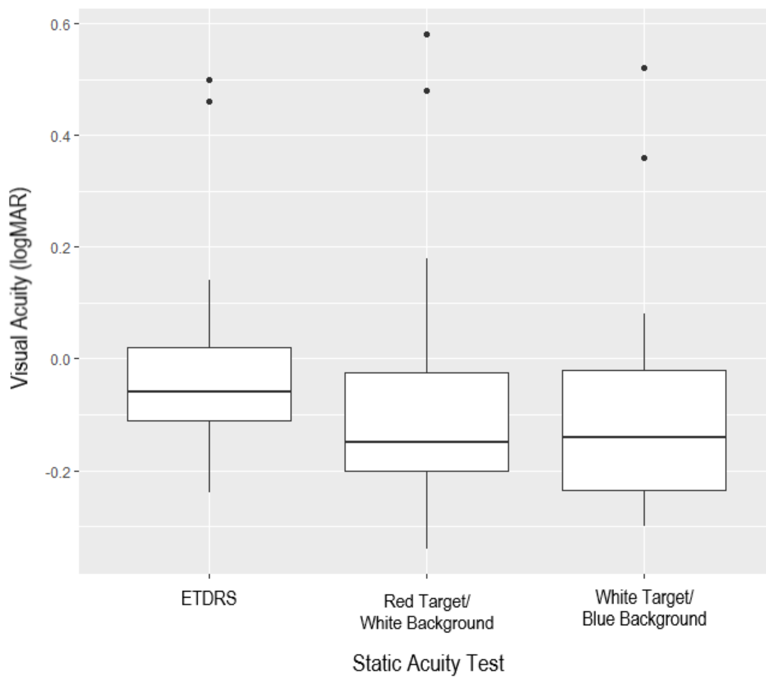

Figure 4.3: Boxplots comparing the ETDRS with the moV& coloured static visual acuity test combinations. The median result is shown, with the lower and upper hinges corresponding to the 1st and 3rd quartiles and whiskers being 1.5 x IQR.

4.4.2 Static Visual Acuity Test-Retest Repeatability

moV& showed fair to good test-retest repeatability between visits 1 and 2 for both low contrast values tested, and had better repeatability than the low contrast Snellen chart. At 20% contrast, Lin's $CCC_{moV\&}$=0.60, and $CCC_{Snellen}$=0.51. For the 61% contrast targets, $CCC_{moV\&}$=0.80 and $CCC_{Snellen}$=0.71.

For both of the coloured optotype and background combinations, moV& showed good test-retest repeatability between visits comparable to that of the standard ETDRS chart. Lin's CCC_{ETDRS}=0.88, which is similar to that of the red target on a white background (CCC=0.85) and the white target on a blue background (CCC=0.88) using moV&.

There was no significant difference in low contrast static visual acuities measured using moV& on visit 1 compared to visit 2 at either 20% contrast (p=0.105) or 61% contrast (p=0.912). Similarly, there was not a significant difference between visits for moV& static visual acuities measured using a red target on a white background (p=0.932) or a white target on a blue background (p=0.760).

4.4.3 Dynamic Visual Acuity

All measures of dynamic visual acuity were worse than static visual acuities measured under the same conditions (i.e. all moV& dynamic visual acuities at 20% contrast were worse than moV& static visual acuities at 20% contrast; this was also true for the 61% contrast target and the red target/white background and white target/ blue background colour combinations). The mean dynamic visual acuities for both the static and dynamic visual acuity tests are summarized in Table 4.1.

Table 4.1: Mean (±SD) dynamic visual acuity (logMAR) for each direction and speed on the moV& software measured, averaged across two visits (static visual acuities are shown for comparison).

	Speed				
	1m/s	**3m/s**	**6m/s**	**9m/s**	**12m/s**
20% contrast					
Horizontal	0.407 ± 0.097	0.789 ± 0.181	0.780 ± 0.154	0.800 ± 0.173	0.820 ± 0.170
Vertical	0.541 ± 0.102	0.780 ± 0.175	0.800 ± 0.147	0.800 ± 0.169	0.880 ± 0.141
Oblique	0.770 ± 0.128	0.790 ± 0.148	0.840 ± 0.160	0.820 ± 0.123	0.928 ± 0.135
Random	0.652 ± 0.088	0.745 ± 0.168	0.690 ± 0.154	0.707 ± 0.162	0.687 ± 0.150
	Snellen	**moV&**			
Static VA	0.133 ± 0.091	-0.01 ± 0.136			
61% contrast					
Horizontal	0.224 ± 0.118	0.461 ± 0.163	0.435 ± 0.155	0.453 ± 0.169	0.480 ± 0.149
Vertical	0.459 ± 0.105	0.465 ± 0.196	0.429 ± 0.139	0.470 ± 0.136	0.525 ± 0.143
Oblique	0.518 ± 0.145	0.427 ± 0.143	0.486 ± 0.146	0.553 ± 0.153	0.583 ± 0.106
Random	0.418 ± 0.124	0.376 ± 0.181	0.340 ± 0.154	0.369 ± 0.140	0.341 ± 0.150
	Snellen	**moV&**			
Static VA	-0.01 ± 0.087	-0.08 ± 0.122			

Red target/ White background					
Horizontal	0.209 ± 0.138	0.363 ± 0.217	0.350 ± 0.201	0.370 ± 0.188	0.400 ± 0.180
Vertical	0.418 ± 0.168	0.360 ± 0.187	0.380 ± 0.199	0.400 ± 0.166	0.430 ± 0.163
Oblique	0.460 ± 0.201	0.388 ± 0.191	0.430 ± 0.174	0.486 ± 0.176	0.514 ± 0.181
Random	0.330 ± 0.149	0.324 ± 0.142	0.300 ± 0.139	0.267 ± 0.163	0.271 ± 0.161
	ETDRS	**moV&**			
Static VA	-0.02 ± 0.151	-0.09 ± 0.181			
White target/ Blue background					
Horizontal	0.197 ± 0.159	0.329 ± 0.204	0.280 ± 0.182	0.310 ± 0.186	0.360 ± 0.180
Vertical	0.376 ± 0.162	0.280 ± 0.205	0.320 ± 0.187	0.380 ± 0.167	0.410 ± 0.160
Oblique	0.390 ± 0.178	0.337 ± 0.198	0.400 ± 0.164	0.444 ± 0.171	0.521 ± 0.179
Random	0.287 ± 0.138	0.281 ± 0.176	0.260 ± 0.148	0.240 ± 0.143	0.243 ± 0.147
	ETDRS	**moV&**			
Static VA	-0.02 ± 0.151	-0.11 ± 0.166			

4.4.4 Test-Retest Repeatability

Low contrast dynamic visual acuity had poor test-retest repeatability (Table 4.2), especially at 20% contrast (Lin's CCCs ranging from 0.056 to 0.65) compared to 61% contrast (Lin's CCCs range from 0.25 to 0.75). Both coloured target/ background combinations had good test-retest repeatability, with Lin's CCCs for the red target/ white background ranging from 0.60 to 0.88, and Lin's CCCs for the white target/ blue background ranging between 0.50 and 0.85 (Table 4.3).

Table 4.2: Lin's CCCs between visits 1 and 2 for low contrast dynamic visual acuities at each speed for 20% and 61% contrast.

	1m/s	3m/s	6m/s	9m/s	12m/s
20% Contrast					
Horizontal	0.46	0.34	0.39	0.61	0.60
Vertical	0.28	0.32	0.38	0.30	0.26
Oblique	0.48	0.56	0.33	0.53	0.056
Random	0.33	0.64	0.65	0.56	0.43
61% Contrast					
Horizontal	0.51	0.65	0.72	0.68	0.60
Vertical	0.27	0.63	0.67	0.25	0.29
Oblique	0.40	0.57	0.71	0.41	0.39
Random	0.38	0.73	0.50	0.70	0.74

Table 4.3: Lin's CCCs between visits 1 and 2 for coloured dynamic visual acuities at each speed for red target/ white background and white target/ blue background.

	1m/s	3m/s	6m/s	9m/s	12m/s
Red target on a white background					
Horizontal	0.73	0.74	0.88	0.87	0.71
Vertical	0.61	0.76	0.83	0.82	0.60
Oblique	0.71	0.70	0.82	0.72	0.78
Random	0.66	0.76	0.62	0.81	0.77
White target on a blue background					
Horizontal	0.71	0.80	0.84	0.79	0.81
Vertical	0.73	0.78	0.85	0.80	0.50
Oblique	0.68	0.67	0.80	0.72	0.67
Random	0.55	0.58	0.59	0.80	0.73

The number of completed trials (trials in which the subject was able to correctly respond at the largest letter size or smaller) is outlined in Table 4.4. For horizontal, vertical, and oblique motion, the number of successfully completed trials decreases as optotype speed increases, especially for the low contrast trials. Although the coloured target combinations also show this trend, it is to a much smaller extent compared to the low contrast trials. Almost all participants were able to complete the random motion trials regardless of optotype speed, contrast, or colour. This may be due to the fact that for random motion, optotypes were presented for 16 seconds. This gave participants more time to identify each random motion target compared to the one-pass presentation of horizontal, vertical, and oblique motion.

Table 4.4: Number of completed trials for dynamic visual acuities at each speed and visit for (a) 20% contrast, (b) 61% contrast, (c) red target, white background and (d) white target, blue background.

(a)	1m/s	3m/s	6m/s	9m/s	12m/s
Horizontal	Visit 1 = 21 Visit 2 = 21	Visit 1 = 19 Visit 2 = 21	Visit 1 = 19 Visit 2 = 21	Visit 1 = 17 Visit 2 =18	Visit 1 = 17 Visit 2 = 18
Vertical	Visit 1 = 21 Visit 2 = 21	Visit 1 = 18 Visit 2 = 19	Visit 1 = 16 Visit 2 = 19	Visit 1 = 13 Visit 2 = 16	Visit 1 = 13 Visit 2 = 12
Oblique	Visit 1 = 20 Visit 2 = 21	Visit 1 = 18 Visit 2 = 19	Visit 1 = 15 Visit 2 = 17	Visit 1 = 15 Visit 2 = 14	Visit 1 = 11 Visit 2 = 12
Random	Visit 1 = 21 Visit 2 = 21	Visit 1 = 21 Visit 2 = 21	Visit 1 = 20 Visit 2 = 21	Visit 1 = 20 Visit 2 = 21	Visit 1 = 20 Visit 2 = 20

(b)	1m/s	3m/s	6m/s	9m/s	12m/s
Horizontal	Visit 1 = 21 Visit 2 = 21	Visit 1 = 21 Visit 2 = 21	Visit 1 = 21 Visit 2 = 20	Visit 1 = 21 Visit 2 = 21	Visit 1 = 21 Visit 2 = 21
Vertical	Visit 1 = 21 Visit 2 = 21	Visit 1 = 21 Visit 2 = 21	Visit 1 = 21 Visit 2 = 21	Visit 1 = 20 Visit 2 = 21	Visit 1 = 18 Visit 2 = 18
Oblique	Visit 1 = 21 Visit 2 = 21	Visit 1 = 21 Visit 2 = 21	Visit 1 = 21 Visit 2 = 21	Visit 1 = 19 Visit 2 = 20	Visit 1 = 20 Visit 2 = 21
Random	Visit 1 = 21 Visit 2 = 21	Visit 1 = 21 Visit 2 = 21	Visit 1 = 21 Visit 2 = 21	Visit 1 = 21 Visit 2 = 21	Visit 1 = 21 Visit 2 = 21

(c)	1m/s	3m/s	6m/s	9m/s	12m/s
Horizontal	Visit 1 = 21 Visit 2 = 21	Visit 1 = 21 Visit 2 = 21	Visit 1 = 21 Visit 2 = 21	Visit 1 = 19 Visit 2 = 20	Visit 1 = 21 Visit 2 = 21
Vertical	Visit 1 = 21 Visit 2 = 21	Visit 1 = 21 Visit 2 = 21	Visit 1 = 20 Visit 2 = 21	Visit 1 = 21 Visit 2 = 21	Visit 1 = 21 Visit 2 = 21
Oblique	Visit 1 = 21 Visit 2 = 21	Visit 1 = 21 Visit 2 = 21	Visit 1 = 21 Visit 2 = 21	Visit 1 = 21 Visit 2 = 21	Visit 1 = 17 Visit 2 = 20
Random	Visit 1 = 21 Visit 2 = 21	Visit 1 = 21 Visit 2 = 21	Visit 1 = 21 Visit 2 = 21	Visit 1 = 21 Visit 2 = 21	Visit 1 = 20 Visit 2 = 21

(d)	1m/s	3m/s	6m/s	9m/s	12m/s
Horizontal	Visit 1 = 21 Visit 2 = 21	Visit 1 = 21 Visit 2 = 21	Visit 1 = 21 Visit 2 = 21	Visit 1 = 21 Visit 2 = 20	Visit 1 = 21 Visit 2 = 21
Vertical	Visit 1 = 21 Visit 2 = 21	Visit 1 = 21 Visit 2 = 21	Visit 1 = 21 Visit 2 = 21	Visit 1 = 19 Visit 2 = 21	Visit 1 = 21 Visit 2 = 19
Oblique	Visit 1 = 21 Visit 2 = 21	Visit 1 = 21 Visit 2 = 21	Visit 1 = 21 Visit 2 = 21	Visit 1 = 21 Visit 2 = 20	Visit 1 = 15 Visit 2 = 18
Random	Visit 1 = 21 Visit 2 = 21	Visit 1 = 21 Visit 2 = 21	Visit 1 = 21 Visit 2 = 21	Visit 1 = 21 Visit 2 = 21	Visit 1 = 21 Visit 2 = 21

The between-visit repeatability for each of the low contrast and colour combinations tests with horizontal motion at 6m/s is outlined in Fig. 4.4. The mean differences (±SD) for horizontal motion at 6m/s with a 20% contrast target, 61% contrast target, red target on a white background, and white target on a blue background are 0.109 (±0.146), -0.002 (±0.118), 0.0209 (±0.0954), and 0.0486 (±0.0935) respectively.

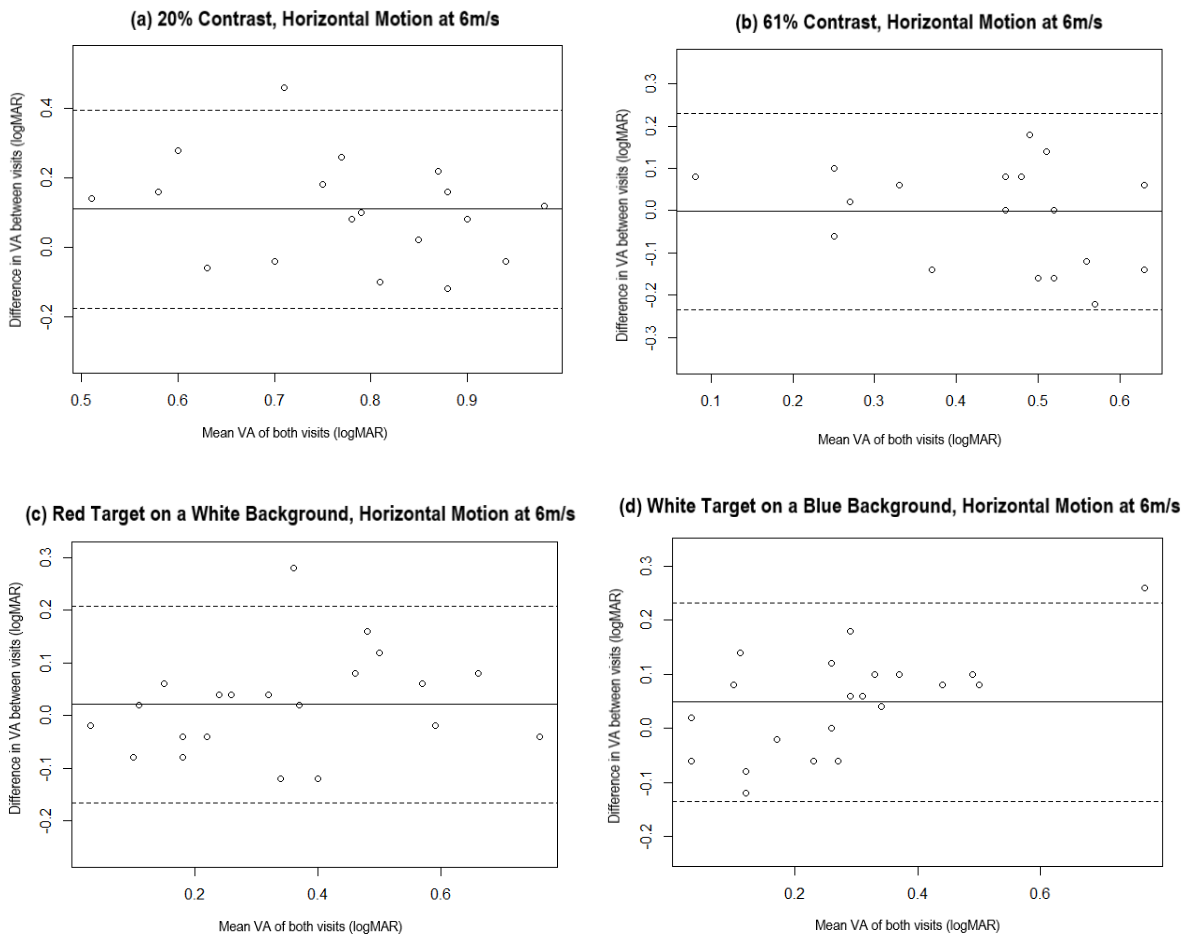

Figure 4.4: Bland-Altman plots for visual acuity (logMAR) between visits 1 and 2 for horizontal motion at 6m/s for (a) 20% contrast, (b) 61% contrast, (c) a red target on a white background and (d) a white target on a blue background.

4.5 Discussion

In this paper, we determined the repeatability of two low contrast (20% and 61% contrast) and two coloured optotype and background combinations (red target on a white background and white target on a blue background) of the moV& software's static and dynamic visual acuity capabilities. As there is not currently a "gold standard" test with which to compare low contrast and coloured visual acuity, the test-retest repeatability was determined. The low contrast Snellen chart is not a standardized chart for the measurement of low contrast visual acuity, but was used for comparison with the low contrast moV& software due to its prevalence in clinical practice and easy accessibility. Similarly, the black and white high-contrast ETDRS chart was compared to the coloured moV& software since there are no standardized coloured visual acuity tests available. Although the ETDRS chart is the "gold standard" test for static visual acuity, it differs from the coloured moV& targets in optotype and background colour as well as contrast. The contrast between the target and background of the ETDRS chart was 100%, while both colour combinations for the moV& software had a contrast of 83%.

Low contrast static visual acuity was better when measured using moV& compared to the Snellen chart. At 20% contrast, moV& static visual acuity was approximately 1 line (0.10 logMAR) better than Snellen acuity. The difference was less at 61% contrast, with moV& acuity being approximately 3 letters (0.06 logMAR) better than Snellen acuity. Since the clinical endpoint for visual acuity is incorrectly identifying three out of five letters of a given size, the difference in acuity between low contrast moV& and low contrast Snellen is clinically significant for both low contrast values. This difference was also shown to be statistically significant ($p \leq 0.001$) at both 20% and 61% contrasts.

The difference between low contrast Snellen and low contrast moV& static visual acuity may be due to the variation in targets and testing methods – moV& acuity was determined by identifying one letter on the screen at a time, and selecting the letter from a keypad containing 10 choices. Snellen acuity was determined by presenting the participants with a chart of five lines of letters decreasing in size, and asking the participant to read as much of the chart as possible, starting with the largest line which they could easily read all 5 letters. This means that moV& did not have the crowding effects which were present in the Snellen task, and participants may have had an easier time guessing letters on moV& as they had 10 letter options compared to the unrestricted 26 letter options available when completing the Snellen task. It has been demonstrated that crowded visual acuity is approximately 1.2x worse compared to non-crowded visual acuity in adults with high contrast targets, although more research on this effect in adults is needed as most of the work regarding crowded visual acuity has been done in children.[86] The crowding effect has also been shown to be more prominent with high contrast targets compared to low contrast targets, therefore the effect of crowding on visual acuity measures may vary between the 20% and 61% contrast targets.[87] In order to make the static visual acuity tasks in this experiment more comparable, a single letter presentation Snellen visual acuity should be used with the same letter choices between the two tasks. Additional research may benefit from comparing the low contrast static visual acuity capabilities of moV& with the low contrast

Sloan letter chart, which is a grey-on-white version of the gold standard ETDRS chart and allows for the measurement of low contrast visual acuity at 1.25%, 2.5%, 5%, 10%, and 25% contrast.[24,25] The low contrast Sloan letter chart uses the same font as the moV& software and has been shown to be both valid and reliable, although the crowding problem would still remain, making task comparison difficult.[24,25]

The static visual acuity measures for both of the low contrast (20% and 61% contrast) and coloured optotype and background combinations (red on white and white on blue) of moV& demonstrated good repeatability. Repeated measures ANOVA revealed no significant difference between static visual acuity measured at visit 1 compared to visit 2 for the 20% contrast, 61% contrast, red optotype on a white background or the white optotype on a blue background conditions. The 20% contrast task had a lower CCC values between visits 1 and 2 (0.60) compared to the 61% contrast (0.80), red optotype on a white background (0.85), and white optotype on a blue background (0.88) static visual acuities. This is consistent with literature which has shown that repeatability of low contrast acuity is poorer than high contrast measures.[26] This also holds true for the low contrast Snellen chart, which had a lower CCC value between visits 1 and 2 for 20% contrast (CCC=0.51) compared to 61% contrast (CCC=0.71). Both moV& low contrast static visual acuity tests had better repeatability compared to the same contrast values measured on the low contrast Snellen chart, and the 61% contrast task had a repeatability that resembled the repeatability of the gold standard ETDRS chart (CCC=0.88). The coloured static visual acuities also had repeatability similar to that of the ETDRS chart. Although they are not comparable in the colour or contrast of the targets, the similarity in test-retest repeatability between the ETDRS chart and the 61% contrast and the coloured optotype and background moV& charts demonstrate good reliability of the moV& software.

All low contrast and coloured optotype and background measures of dynamic visual acuity yielded worse results compared to the static visual acuity measured under similar conditions using moV&. At 20% contrast, dynamic visual acuity was approximately 7.5 lines (0.75 logMAR) worse than static visual acuity. This difference decreased with the other conditions – 61% contrast dynamic visual acuity was ~5 lines (0.5 logMAR) worse, dynamic visual acuity with a red target on a white background was ~4.5 lines (0.45 logMAR) worse, and dynamic visual acuity with a white target on a blue background was ~4 lines (0.4 logMAR) worse. Due to the increased number of factors required in order to recognize a moving object (eye movements, shorter exposure time, fixation and tracking), dynamic visual acuity tasks are more difficult than static visual acuity, hence leading to worse visual acuity. In agreement with our results, previous research has found low to no correlation between high contrast static visual acuity and dynamic visual acuity, which worsens as target velocity increases.[4,6]

Test-retest repeatability for low contrast moV& dynamic visual acuity was poor, with 20% contrast having worse repeatability ranges compared to 61% contrast. The difference in Lin's CCC values may be because low contrast targets yielded a worse dynamic visual acuity compared to high contrast targets, and measurements were more variable. This shows that it was more difficult for the observers to track and visualize the low contrast targets. Due to the large range of Lin's CCC values seen at both 61% contrast and 20% contrast moV& dynamic visual acuity, low contrast dynamic visual acuity can be measured with different levels of confidence in repeatability for specific speed and trajectory combinations. For example, at 61% contrast, horizontal motion at 6m/s had a CCC of 0.72 which indicated good repeatability. The same contrast with oblique motion at 1m/s had a CCC of 0.40, resulting in less repeatable measures. Assessing the repeatability of moV& with a larger range of target contrast, especially at contrasts higher than 61%, would be beneficial in both assessing the reliability of the low contrast dynamic visual acuity of moV& as well as looking at the effect of contrast on dynamic visual acuity.

The coloured optotype and background combinations had good Lin's CCC for their dynamic visual acuity measures at all speed and trajectory combinations. They also had much higher CCC values and a smaller range compared to either of the low contrast settings. Both colour combinations tested had a contrast of 83%, which was higher than either of the low contrast targets (20% and 61%). This made the coloured acuity task easier due to the higher target contrast, although this explanation does not take into account the possible effects of colour on visual acuity (for example, longitudinal chromatic aberrations, although this effect would likely be small with the colour combinations tested). Future research is required to determine the effect of colour on both static and dynamic visual acuity.

Although a gold standard test does not exist with which to test low contrast or coloured static and dynamic visual acuity, the low contrast and coloured visual acuity functions of moV& could be validated against the standard black target on a white background as that is the current gold standard for visual acuity. As contrast has been shown to have a significant effect on both static and dynamic visual acuity, comparing the visual acuity of targets with different contrasts will not allow for additional assessment of the test accuracy of moV&.[10,12,14] Since the contrast of the low contrast targets (20% and 61%) as well as the coloured targets (83%) are not the same as a standard black target on a white background (100%), we are not able to compare these optotypes in order to determine accuracy, but these comparisons are still helpful in determining the construct and convergent validity of moV&. Future research comparing the dynamic visual acuity of a grey-on-white 83% contrast target with the coloured optotypes used in this study may allow for an additional assessment of convergent validity, and provide interesting data exploring the effect of colour on dynamic visual acuity.

The results of this study demonstrates that moV& has good repeatability for low contrast and coloured targets, which suggests that moV& has clinical utility for static visual acuity measures at 61% contrast, 20% contrast, with a red optotype on a white background, and with a white optotype on a blue background. Clinically, moV& could also be used to determine coloured dynamic visual acuity with other colour combinations, although further research is needed to determine the effect of other colours on test repeatability as well as to assess the possible effects of different colour combinations on dynamic visual acuity. The two colour combinations used in this study were selected to represent common colours seen in sports – the red target was similar to the RGB value of a cricket ball, and the blue background was similar to the RGB value of a blue sky on a sunny day. The validation of these two colour combinations would allow for moV& to be used in specific sports vision scenarios.

4.6 Dissertation Progress II

Fig. 3.7 from Chapter 3 has been expanded to include the findings of Experiment 2 (Fig. 4.5). Experiment 2 demonstrates that moV& is repeatable for low contrast and coloured targets when measuring static visual acuity. The repeatability of moV& for DVA measures vary based on contrast – the low contrast targets have worse repeatability compared to both the high contrast and the coloured targets; repeatability of DVA varied with both target speed and trajectory, with the greatest variability demonstrated in the low contrast targets.

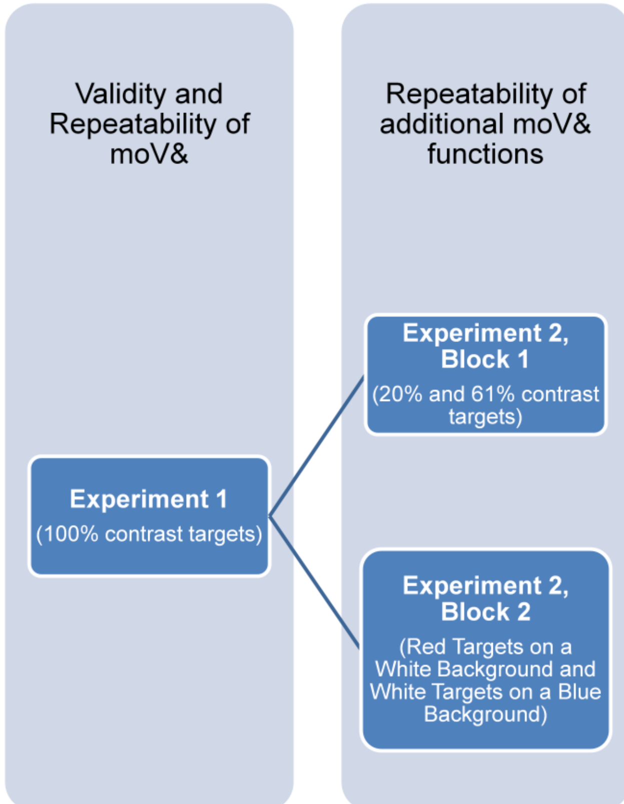

Figure 4.5: Dissertation Progress II, outlining the purpose of Experiments 1 and 2.

The data collected during Experiments 1 and 2 allow for us to analyze the effect of optotype characteristics such as size, speed, and trajectory on the targets validated in Experiments 1 and 2 (20%, 61%, and 100% contrast black targets on a white background, 83% contrast red targets on a white background, 83% contrast white targets on a blue background). This was done in Experiment 3.

Chapter 5 – The Effect of Optotype Trajectory, Velocity, and Size on Dynamic Visual Acuity and Speed Thresholds in High Contrast, Low Contrast, and Coloured Targets

5.1 Chapter Summary

Purpose: To successfully navigate the visual world, humans must be able to resolve targets in motion. Dynamic visual acuity or speed threshold can be determined when relative motion exists between a target and observer. Many different factors can influence dynamic visual acuity and speed threshold, including target trajectory, velocity, size, contrast, and colour. A novel test has recently been developed (moV&, V&MP Vision Suite) with which to measure dynamic visual acuity and speed thresholds using different motion trajectories, speeds, and sizes. The purpose of this study is to examine the effect of optotype trajectory, velocity, and size on dynamic visual acuity and speed thresholds using five optotypes: 100%, 61%, and 20% contrast black targets on a white background, and 83% contrast red targets on a white background, and white targets on a blue background. *Methods*: Participants were separated into three study blocks: 1) High Contrast (n=25, 100% contrast targets), 2) Low Contrast (n=21, 61% and 20% contrast targets), 3) Colour (n=21, red on white and white on blue targets). Each block consisted of 2 study visits a minimum of 2 weeks apart. At each visit, DVA was measured using moV&. Dynamic visual acuity was measured at five target speeds (1, 3, 6, 9, and 12m/s), and speed threshold was measured at three target sizes (+0.2, +0.4, and +0.6 logMAR above static VA for High Contrast block; +0.4, +0.6, and +0.8 logMAR above static VA for Low Contrast and Colour blocks). Horizontal, vertical, oblique, and random walk motion trajectories were used, and the effects of trajectory, speed, and size on dynamic visual acuity and speed threshold were determined. *Results*: Trajectory

had a significant effect on dynamic visual acuity for all contrast and colour combinations, and a significant effect on speed threshold for all optotypes except the white target on a blue background (p=0.153). Target speed had a significant effect on dynamic visual acuity for all contrast and colour combinations tested except the red target on a white background (p=0.112), while target size had a significant effect on speed threshold for all optotypes. *Discussion:* Target trajectory, speed, and size have effects on dynamic visual acuity and speed threshold, with the exception of a few optotype colour combinations. Further research is needed to explore the role of target colour on dynamic visual acuity and speed threshold.

5.2 Introduction

In order to successfully navigate the visual world, humans must be able to resolve targets while either they or the targets are in motion. For example, a driver must be able to read a street sign while travelling at a fast speed in order to successfully navigate to their destination. Athletes also depend on vision to quickly move and respond during sport. Recognition of moving targets is crucial in these situations, as motion occurs at relatively high speeds and target recognition is imperative to safety and performance.

Research on visual skills used by ice hockey players has shown that dynamic visual acuity plays an important role in successfully passing and shooting a puck.[2] Dynamic visual acuity is the smallest size at which one can recognize a target when relative motion exists between the target and observer.[4] It requires an observer to detect a target in their field of view, use saccadic and smooth pursuit eye movements to visually acquire it, and be able to resolve critical detail for recognition in a relatively brief exposure time.[12] Dynamic visual acuity differs from traditional measures of static visual acuity (such as those conducted at routine oculovisual assessments) as target movement requires the observer to make continuous eye movements in order for the target to remain on the fovea. The added challenge of tracking a moving target results in dynamic visual acuity measures being more variable compared to static visual acuity, even at speeds as slow as 20°/s.[12] In larger heterogeneous populations, a significant correlation has been shown between static and dynamic visual acuity which decreases as target velocity increases.[4] However, in more homogeneous populations (such as the population of healthy young adults used by Long & May, 1992) the correlation between static and dynamic visual acuity is not significant.[6] In all cases, static targets yield better visual acuity (observers are able to resolve detail of smaller sized targets) compared to dynamic targets.[12] Dynamic visual acuity can significantly improve with training and is more indicative of performance on everyday tasks compared to static acuity; therefore, clinical applications for dynamic vision training exist for patients who rely on good dynamic visual acuity in their daily activities.[11,55,88–90]

5.2.1 Dynamic Visual Acuity and Speed Thresholds

When a target is in motion, one of two different thresholds can be measured – dynamic visual acuity or speed threshold. Dynamic visual acuity is measured at a constant target speed, and is the smallest size which an observer can resolve target detail. Speed threshold is the fastest speed at which an observer can resolve detail of a constant target size. It is important to distinguish between these two threshold measures as they are different variables. Dynamic visual acuity is reported as a measurement in size, while speed threshold is a velocity. The term “dynamic visual acuity” has been used to refer to both thresholds in past research, although it has always been defined appropriately for its use in each instance.[35,40,41]

5.2.2 Methods of Measuring Dynamic Visual Acuity

In dynamic visual acuity research, relative motion between the observer and optotype has been achieved two ways – by having an optotype move across a screen (either using a motorized turntable and a front surface mirror or a computer program) or by having the observer's head rotate while viewing a static target.[7] These methods require the observer to use different oculomotor mechanisms in order to visualize the target. When a target is in motion, smooth pursuits can be used to accurately track up to a speed of approximately 50°/s, above which catch-up saccades are required.[5] The observer's head can be fixed (the moving target is tracked by eye movements only) or free (the observer can use both eye and head movements to track the target) depending on the experimental set up and purpose.[8,42] When viewing a static target during head rotation the vestibular system activates the vestibulo-ocular reflex, which maintains the target on the fovea during head movement.[5] Since the vestibulo-ocular reflex is a reflex, it uses different neural processing in order to generate the appropriate motor response compared to voluntary ocular tracking.[34] This results in each assessment method measuring a different aspect of dynamic visual acuity. This study uses a dynamic object task, whereby the object moves across the screen, with free head movement in order to measure dynamic visual acuity and speed threshold. This allows the observers to use a combination of eye and head movements reflective of real-world tracking strategies.

5.2.3 Factors Which Effect Dynamic Visual Acuity

Many different physiological and neural processes must function together for an observer to resolve detail of a moving target; therefore there are many different optotype characteristics with the potential to influence dynamic visual acuity. These include exposure time, velocity and target size, trajectory, contrast, and colour.

5.2.3.1 Exposure Time

Exposure time is the amount of time a target is presented to an observer. When a target is in motion, exposure time can vary depending on experimental set up. For example, if a target is moving in a linear trajectory, faster moving targets will have a shorter exposure time compared to slower moving targets. Additionally, exposure time will vary for targets presented at the same speed but on different screen sizes or moving in different trajectories on a rectangular screen. It has been shown that longer target exposure results in better dynamic visual acuity.[6,44] Exposure time can be controlled in an experimental set up by having the target repeatedly travel across a screen or by limiting the presentation time of slower moving targets to match that of the fastest speed. However, both of these methods do not reflect the conditions of dynamic visual acuity in real-life scenarios and vary the visual tracking strategies used by the observer.

5.2.3.2 Velocity and Target Size

Target speed and the size influence an observer’s ability to visualize a moving target. Dynamic visual acuity improves as target velocity decreases, allowing smaller targets to be visualized at slower speeds (speeds ranging between 1 – 100 °/s).[4,6,9,13,33] This relationship has been shown to be approximately linear.[14] The variance and standard deviation of dynamic visual acuity measures also increase linearly at faster target speeds.[12,14]

This relationship between target speed and target size is also seen in research on speed thresholds. Speed thresholds are affected by target size – as size decreases, speed thresholds are worse (i.e. performance is poor at a slower speeds).[40] Therefore, target speed and size affect the visualization of a moving target. It is important to keep either the speed or the size of the target constant when the other is the dependent variable, as varying both will not provide a useful measure of either dynamic visual acuity or speed threshold. The target speed should be specified when reporting dynamic visual acuity measures and the target size should be specified when reporting speed thresholds, as they play an important factor in the experimental results.

5.2.3.3 Trajectory

The above definitions of dynamic visual acuity and speed threshold describe a target moving across the visual field in a "walking" motion (i.e. the target moves along a path across a screen). Walking motion can be applied to a number of trajectories – predictable horizontal, vertical, and oblique motion, or random motion. Trajectory influences dynamic visual acuity, as dynamic visual acuity improves when a target is moving in a left-to-right horizontal trajectory compared to right-to-left horizontal motion or an oblique trajectory.[9,35] Since the majority of the literature on dynamic visual acuity and speed thresholds creates target motion using a mirror mounted on a variable speed turntable, there has been limited trajectory research conducted. Computer software has made it easier to vary target trajectory, and allows for both linear and non-linear motion patterns to be examined, which will expand our understanding of this stimulus characteristic.

5.2.3.4 Contrast

In addition to features of target motion, characteristics of the targets themselves can influence dynamic visual acuity and speed thresholds. Static visual acuity, dynamic visual acuity, and speed thresholds have all been shown to worsen with low contrast between the target and background.[8,12,14,15] Dynamic visual acuity and speed threshold are also more sensitive to changes in target speed and size with low contrast targets compared to high contrast.[44] Furthermore, target contrast has been found to influence the eye movements used to track moving targets – low target contrast results in a larger initial deviation of pursuit eye movements.[84]

5.2.3.5 Target and Background Colour

Due to the difference in temporal processing between the different retinal cone types, it has been hypothesized that target wavelength may affect dynamic visual acuity and speed threshold. Research exploring the impact of target colour on static visual acuity has shown that acuity measured using coloured sinusoidal gratings is worse with a blue and yellow combination compared to a red and green combination.[27] Colour can also affect static acuity when letter optotypes are used – black letters on a white background yield similar static visual acuities to a yellow letter on a red background, while both yield a 40% higher acuity than a blue letter on a red background.[16] At this time, one study (Long and Garvey, 1988) has been published which looks at the impact of target wavelength on dynamic visual acuity – it found that target wavelength significantly effects dynamic visual acuity under scotopic and mesopic light levels in dark-adapted viewers, but not under photopic conditions.[17] However, Long and Garvey's experiment only had two participants; therefore further investigation is required before any solid conclusions can be drawn. It is likely that no further research has been done on this topic because a validated, standardized test with which to measure coloured static or dynamic visual acuity does not currently exist. Once again, computer software has opened up new avenues of research, especially for coloured visual acuity as computer software and displays make it simple to change the colour of both the target and background.

5.2.4 moV&, A Novel Dynamic Visual Acuity Test

When examining research on dynamic visual acuity and speed thresholds, a common limitation is that there is no widely accepted, validated, standardized method with which to assess either measure. The Vision & Motor Performance (V&MP) Lab at the University of Waterloo School of Optometry & Vision Science has recently developed and validated a new test (moV&, V&MP Vision Suite) with which to measure distance static visual acuity, dynamic visual acuity, and speed thresholds using different motion trajectories, speeds, and sizes.[38] moV& also allows for the contrast and colour of the target and background to be varied by specifying the Alpha (target contrast), and R, G, and B values of the target and background. The moV& software allows for the influence of different dynamic visual acuity and speed threshold characteristics to be explored.

5.2.5 Purpose

The purpose of this study is to examine the relationship between optotype velocity, trajectory, and size on dynamic visual acuity and speed thresholds using the high contrast (100% Weber contrast), low contrast (61% and 20% Weber contrast), and coloured target-background (red target on a white background, white target on a blue background) functions of the moV& software.

5.2.6 Hypothesis

It is predicted that for all targets (high contrast, low contrast, and coloured optotype-background combinations) dynamic visual acuity will become worse as the velocity of the target increases, and speed thresholds will become worse as optotype size decreases. The horizontal walking motion is hypothesized to result in better dynamic visual acuity and speed thresholds compared to vertical, oblique, or random walking trajectories.

5.3 Methods

This study followed the tenants of the Declaration of Helsinki and has been reviewed and received ethics approval through a University of Waterloo Research Ethics Committee. Prior to study enrollment all participants were given an explanation of the nature and possible consequences of the study and signed an informed consent form.

This study was conducted in 3 blocks: a high contrast target block, a low contrast target block, and a coloured target block. For the high contrast block, twenty-five adult participants (age range 20-55 years, mean 26.5 ± 9.9 years; 8 males, 17 females) were recruited and attended two separate 1-hour study visits. Both the low contrast and the coloured blocks had twenty-one adult participants. The low contrast block participants were between 20-28 years old, mean 22.0 ± 1.97 years, with 7 males and 14 females. The coloured block participants had an age range of 20-25 years, with a mean of 22.3 ± 1.18 years and 8 males, 13 females. Participants in the low contrast and coloured target blocks attended two separate 1.5-hour study visits; study visits for all three blocks were separated by a minimum washout period of 14 days.[79] Participants consisted of adults at the University of Waterloo who self-reported no binocular vision defects or ocular issues with the potential to impact visual acuity in either eye. The participant's habitual distance refractive correction was worn for all testing at both visits. The same trained clinical investigator (M.H.) took all visual acuity and speed threshold measurements, and to the best of her abilities used the same psychophysical methods and stopping rules for each trial and participant. All measures of acuity were scaled logarithmically into 0.1 logMAR steps (anchored at 0.0 logMAR) and speed threshold was measured in m/s. Testing was stopped when at least three of the five letters presented at the same contrast, colour, speed, size, and motion type were incorrectly identified.

Each subject was randomly assigned to complete all tests for both visits using either their left or right eye, with the non-tested eye occluded with an opaque eye patch. For the high contrast and low contrast blocks, static visual acuity was measured at each visit using a computerized Snellen chart with targets set to the same contrast as that being tested on the moV& software (100%, 61%, and 20% Weber contrast). The participant's Snellen static visual acuity was used as a reference to determine the starting letter size for dynamic visual acuity measurements. The participant's Snellen acuity was converted into logMAR by taking the log of the reciprocal of the threshold value in 20/20 notation and attributing a value of -0.02 logMAR for each additional correctly identified letter, and +0.02 logMAR for each incorrectly identified letters. The starting size for high contrast dynamic visual acuity measures was determined by adding 0.3 logMAR to the Snellen acuity at 100% contrast (in logMAR) unless otherwise specified. For low contrast dynamic visual acuity, the starting size was set by adding 1.0 logMAR to the low contrast Snellen static acuity (in logMAR) unless otherwise specified. For the coloured block, static visual acuity was assessed using a standard (high contrast black target on a white background) ETDRS paper chart, and the starting size for dynamic visual acuity measurements was obtained by adding 1.0 logMAR to their static visual acuity.

moV& (V&MP Vision Suite, Waterloo, Ontario), a computerized distance static and dynamic visual acuity chart, was used to measure all dynamic visual acuities and speed thresholds. moV& is a single-letter test in which participants identify a letter on a screen and indicate their response by selecting one of 10 possible Sloan letters from a key pad. For each optotype size and speed combination, 5 of the 10 possible letters were randomly presented in descending (for dynamic visual acuity, starting with the largest size) or ascending (for speed threshold, starting with the slowest speed) order. If three or more of the five letters were correctly identified, the next smallest size or the next fastest speed was presented until three of the five letters could not be correctly identified. Dynamic visual acuities were measured using a per letter scoring system in logMAR by assigning each letter a value of 0.02 logMAR, and speed thresholds were measured in m/s rounding to the nearest 1m/s. moV& has the option to specify the optotype contrast (target A value) as well as the colour of both the optotype and the background (target and background RGB values). The Weber contrast of the displays for both the moV& and the Snellen tests were determined using a spotmeter (Konica

Minolta Sensing Americas, Inc, Ramsey, New Jersey). For the low contrast block, the target A values tested were 30 (20% Weber contrast) and 81 (61% Weber contrast). For the coloured block, two optotype-background colour combinations were tested – a red target on a white background (target RGB values 160, 34, 34; target A value 210; background RGB values 255, 255, 255) and a white target on a blue background (target RGB values 255, 255, 255; target A value 255; background RGB values 54, 109, 181). These colour combinations were chosen to reflect common colours observed in sports – a white ball against a blue sky on a sunny day, and the red and white detailing of a cricket ball or baseball. Both colour combinations had a Weber contrast of 83% between the target and background.

The following tests were randomized at each visit for all study blocks: dynamic visual acuity for horizontal, vertical, oblique, and random walk motion at five target speeds (1, 3, 6, 9, and 12m/s, which are approximately equal to constant angular velocities of 14, 37, 56, 66, and 72°/s) and speed thresholds for horizontal, vertical, oblique, and random walk motion at three target sizes (+0.2 logMAR, +0.4 logMAR, and +0.6 logMAR above static visual acuity for the high [100%] contrast block, +0.4 logMAR, +0.6 logMAR and +0.8 logMAR above static visual acuity for the low contrast and coloured blocks). These values were chosen with the goal of incorporating speeds that were relatively easy to track as well as speeds that exceeded the capacity of the ocular pursuit system. Larger sizes were required for testing speed threshold in the low contrast and coloured target blocks as pilot testing showed that the decrease in contrast in both these conditions made the task too difficult to complete at a size of +0.2 logMAR above static visual acuity. The +0.8 logMAR above static visual acuity size was not tested for the speed threshold of high contrast targets as most participants reached the maximum speed of 10m/s at the +0.6 logMAR above static visual acuity size. This testing procedure is summarized in Fig. 5.1.

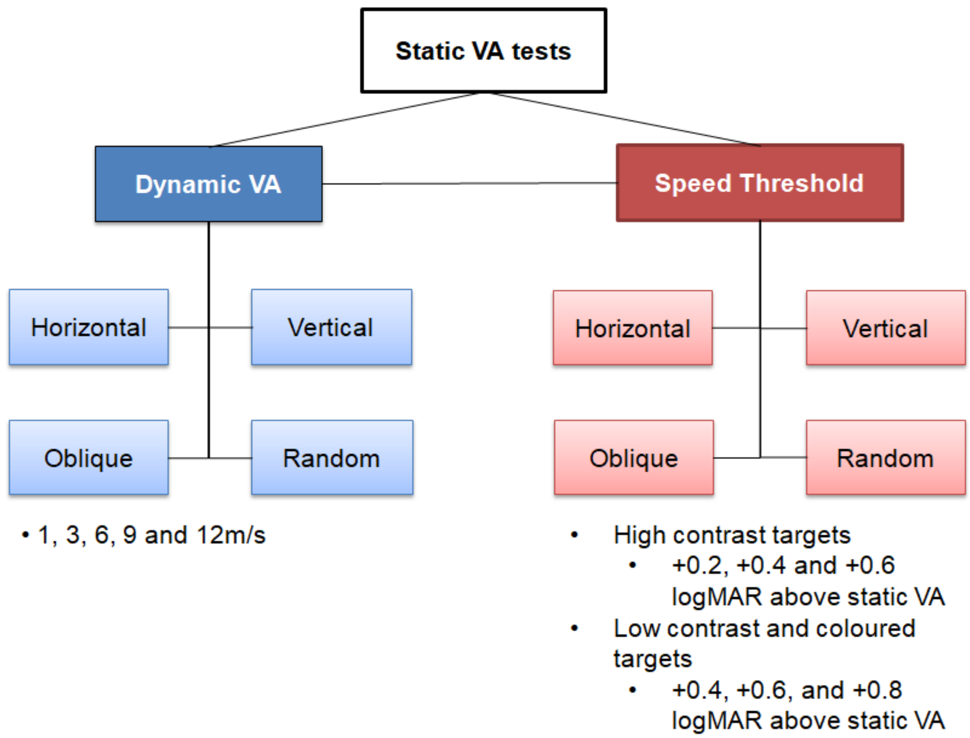

Figure 5.1: Summary of tests completed by each participant in all study blocks.

Predictable linear motion targets (horizontal, vertical, and oblique) only moved across the screen once at a constant speed. Random walk motion involved the target moving continuously in a Brownian particle motion pattern, with each subsequent position being randomly determined. If the letter exited the screen during random motion, it would re-enter at a random location and continue its motion for up to 16 seconds. Due to the unpredictable nature of the random walk motion, observers must use a combination of eye movements such as fixations, pursuits, and saccades in order to successfully track and identify these letters.

Data analysis was conducted using R (v 3.0.2).[80] The relationship between visit, optotype speed and optotype size was estimated using a three-way ANOVA, with significance defined as $p \leq 0.05$. The influence of the variability across subjects (subjects as a random factor) was explored by determining the effect of visit, speed, size, and trajectory as fixed effects through linear mixed modeling.

For some trials, a threshold value could not be obtained as the participant was unable to correctly identify any letters at the first speed and size combination presented. Three data points (high contrast random walk dynamic visual acuity at 6m/s in visit 2, 20% contrast oblique speed threshold at +0.6 logMAR above static visual acuity in visit 1, and red target/ white background random walk dynamic visual acuity at 12m/s in visit 1) were missed for three different participants due to a programming error by the clinical investigator. Calculations requiring comparison between two visits (ANOVAs) excluded data points where no comparison data was available, while calculations involving averages used all available data points.

5.4 Results

All participants successfully completed both study visits for each block.

5.4.1 Mean Dynamic Visual Acuity

The logMAR mean dynamic visual acuities (±standard deviation) for all target contrast and colour combinations are summarized in Table 5.1, and the mean dynamic visual acuity is plotted for all trajectories, target contrasts, and colour combinations in Figure 5.2. Linear predictable dynamic visual acuity (horizontal, oblique, and vertical motion) displayed similar trends as target speed increased, while random walk motion did not significantly change.

Table 5.1: Mean (±SD) dynamic visual acuity (logMAR) for each direction and speed on the moV& software measured, averaged across two visits.

	Speed				
	1m/s	**3m/s**	**6m/s**	**9m/s**	**12m/s**
100% contrast					
Horizontal	0.15 ± 0.12	0.29 ± 0.15	0.30 ± 0.14	0.33 ± 0.14	0.33 ± 0.12
Vertical	0.28 ± 0.13	0.25 ± 0.16	0.30 ± 0.14	0.33 ± 0.14	0.33 ± 0.13
Oblique	0.34 ± 0.14	0.30 ± 0.15	0.35 ± 0.15	0.38 ± 0.15	0.39 ± 0.13
Random	0.24 ± 0.16	0.23 ± 0.16	0.21 ± 0.14	0.23 ± 0.16	0.20 ± 0.16
61% contrast					
Horizontal	0.22 ± 0.12	0.46 ± 0.16	0.43 ± 0.15	0.45 ± 0.17	0.48 ± 0.15
Vertical	0.46 ± 0.10	0.46 ± 0.20	0.43 ± 0.14	0.47 ± 0.14	0.52 ± 0.14
Oblique	0.52 ± 0.14	0.43 ± 0.14	0.49 ± 0.15	0.55 ± 0.15	0.58 ± 0.11
Random	0.42 ± 0.12	0.38 ± 0.18	0.34 ± 0.15	0.37 ± 0.14	0.34 ± 0.15
20% contrast					
Horizontal	0.41 ± 0.10	0.79 ± 0.18	0.78 ± 0.15	0.80 ± 0.17	0.82 ± 0.17
Vertical	0.54 ± 0.10	0.78 ± 0.17	0.80 ± 0.15	0.80 ± 0.17	0.88 ± 0.14
Oblique	0.77 ± 0.13	0.79 ± 0.15	0.84 ± 0.16	0.82 ± 0.12	0.93 ± 0.13
Random	0.65 ± 0.09	0.74 ± 0.17	0.69 ± 0.15	0.71 ± 0.16	0.69 ± 0.15

Red target/ White background					
Horizontal	0.21 ± 0.14	0.36 ± 0.22	0.35 ± 0.20	0.37 ± 0.19	0.40 ± 0.18
Vertical	0.42 ± 0.17	0.36 ± 0.19	0.38 ± 0.20	0.40 ± 0.17	0.43 ± 0.16
Oblique	0.46 ± 0.20	0.39 ± 0.19	0.43 ± 0.17	0.49 ± 0.18	0.51 ± 0.18
Random	0.33 ± 0.15	0.32 ± 0.14	0.30 ± 0.14	0.27 ± 0.16	0.27 ± 0.16
White target/ Blue background					
Horizontal	0.20 ± 0.16	0.33 ± 0.20	0.28 ± 0.18	0.31 ± 0.19	0.36 ± 0.18
Vertical	0.38 ± 0.16	0.28 ± 0.20	0.32 ± 0.19	0.38 ± 0.17	0.41 ± 0.16
Oblique	0.39 ± 0.18	0.34 ± 0.20	0.40 ± 0.16	0.44 ± 0.17	0.52 ± 0.18
Random	0.29 ± 0.14	0.28 ± 0.18	0.26 ± 0.15	0.24 ± 0.14	0.24 ± 0.15

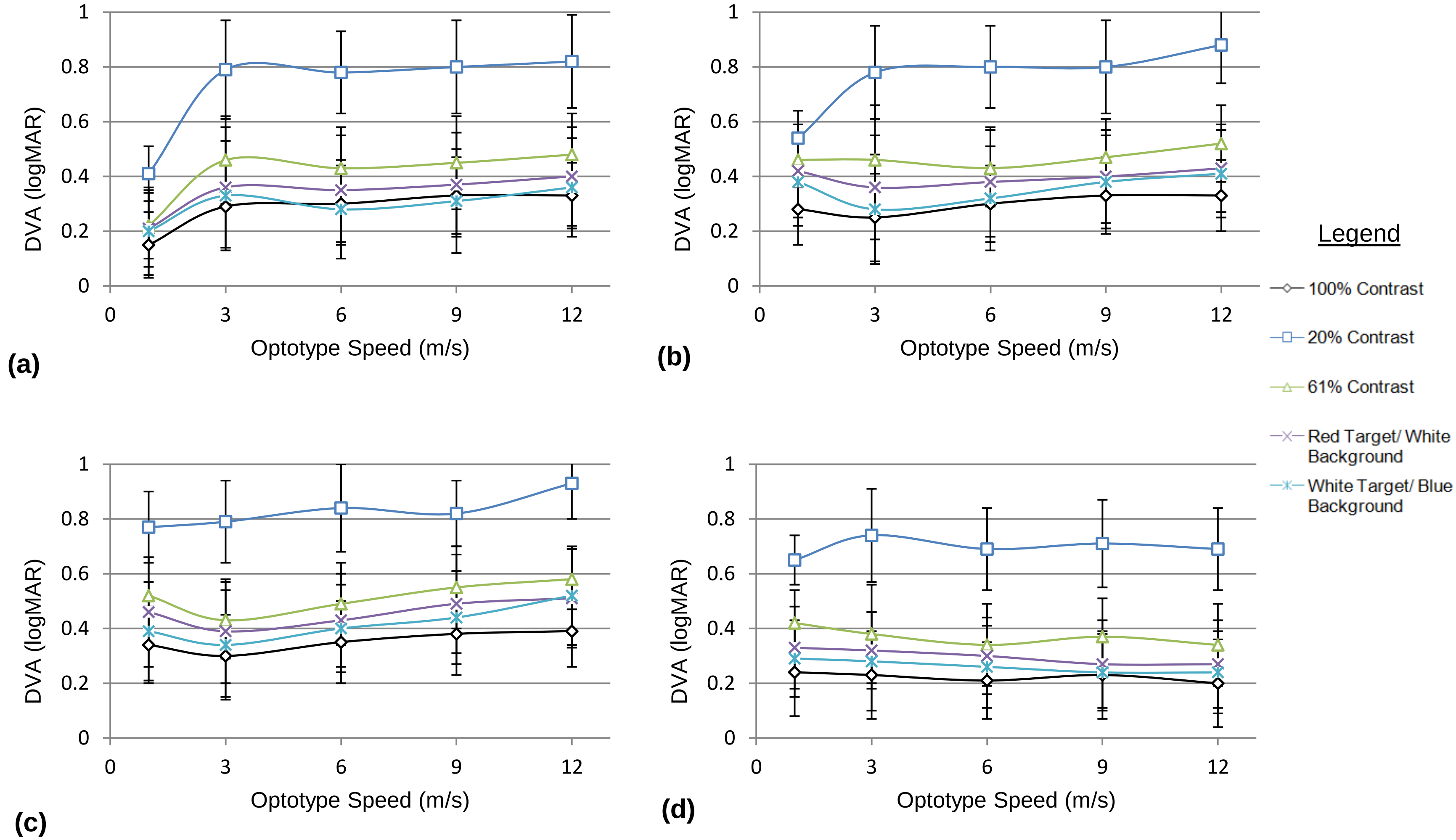

Figure 5.2: Mean (±SD) dynamic visual acuity (logMAR) for each optotype in (a) horizontal (b) vertical (c) oblique and (d) random walk motion.

At 100% contrast, horizontal dynamic visual acuity was 1.5 lines worse ($p<0.0001$) when speed increased from 1m/s to 3m/s, but was only 1-2 letters worse as speed increased stepwise from 3m/s to 6m/s to 9m/s and to 12m/s ($p>0.05$). Vertical dynamic visual acuity at 1m/s was approximately one line worse than 12m/s ($p=0.004$); however, there was not a significant difference in dynamic visual acuity as speed increased ($p>0.05$), except between 1m/s and 3m/s ($p=0.008$). Oblique dynamic visual acuity was 3 letters worse from 1m/s to 12m/s, which was clinically significant (a 3 letter difference is the stopping rule generally used by clinicians for visual acuity measurements) but not statistically significant ($p=0.377$). The difference in oblique dynamic visual acuity as speed increased was neither statistically nor clinically significant. Random walk dynamic visual acuity varied by 1-2 letters between speeds, but there was not a significant difference in dynamic visual acuity as speed increased.

At 61% contrast there was a significant difference in horizontal dynamic visual acuity between 1m/s and all other speeds ($p<0.0001$), but not between 3, 6, 9, and 12m/s. Vertical motion showed no significant difference in dynamic visual acuity for speeds between 1m/s and 9m/s, but did clinically significantly increase (worsening of dynamic visual acuity by ≥3 letters) between all speeds and 12m/s. This difference was only statistically significant between 6m/s and 12m/s ($p=0.001$). Oblique dynamic visual acuity improved from 1m/s to 3m/s ($p=0.020$), then a worsened as the speed increased up to 12m/s. However, the only significant difference was between 6m/s and 9m/s ($p=0.035$). Random walk dynamic visual acuity was not significantly different between speeds except 1m/s and 6m/s ($p=0.001$) and 1m/s and 12m/s ($p<0.0001$).

Horizontal dynamic visual acuity at 20% contrast significantly worsened as speed increased, except from 3m/s to 6m/s (p=0.999) and 6m/s to 9m/s (p=0.893). Vertical dynamic visual acuity worsened as speed increased, but this was only significant between 1m/s and 3m/s (p=0.003), and 9m/s and 12m/s (p=0.029). Oblique dynamic visual acuity worsened when comparing 1m/s to 12m/s (p<0.0001), but there were no significant differences as speed increased by step (from 1m/s to 3m/s, 3m/s to 6m/s, 6m/s to 9m/s, and 9m/s to 12m/s, p>0.05). Random walk dynamic visual acuity worsened as speed increased from 1m/s and 3m/s (p=0.001), and improved as speed increased from 3m/s to 6m/s (p=0.001); however, no statistically or clinically significant difference was found between 6, 9, and 12m/s nor between 1m/s and 12m/s.

The red target on a white background horizontal dynamic visual acuity worsened between 1m/s and 3m/s (p<0.0001), after which acuity changes were not clinically or statistically significant (less than a 3 letter difference, p>0.05). Vertical motion showed a clinically significant improvement in dynamic visual acuity as speed increased from 1m/s to 3m/s, although it was not statistically significant (3 letter improvement, p=0.99). As speed increased from 3m/s to 12m/s dynamic visual acuity became worse, although not significantly (p>0.05). Oblique motion showed a similar trend as vertical motion, although the improvement in dynamic visual acuity as speed increased from 1m/s to 3m/s was both statistically and clinically significant (1 line improvement, p=0.002). As speed increased from 3m/s to 12m/s acuity became worse, although not significantly (p>0.05). Random walk dynamic visual acuity improved when comparing 1m/s to 9m/s (p=0.019), and 1m/s and 12m/s (p=0.044); however, there was no significant change between 1m/s, 3m/s, and 6m/s (p>0.05).

Horizontal dynamic visual acuity for the white target on a blue background was better at 1m/s compared to all other speeds (p≤0.001). There was no significant difference between the other speeds tested except between 9m/s to 12m/s (p=0.038) and 6m/s to 12m/s (p<0.0001), with 12m/s yielding the worse dynamic visual acuity in both cases. Vertical motion showed a 1 line improvement in dynamic visual acuity from 1m/s to 3m/s (p=0.004), and a 2-3 letter worsening of dynamic visual acuity at each step increase in speed from 3m/s to 12m/s (only statistically significant from 6m/s to 9m/s, p=0.003). Oblique dynamic visual acuity was significantly worse at 12m/s compared to all other speeds except 9m/s (p=0.060), but there was not a significant difference between each step increase of speed (p>0.05). Mean random walk dynamic visual acuity did not significantly differ with speed (<3 letter difference, p > 0.05).

5.4.2 Mean Speed Thresholds

The mean speed thresholds in m/s (±standard deviation) are shown in Table 5.2. As target size increased, speed threshold increased for all trajectories and optotypes; that is to say that as target size got larger, participants were able to complete the tasks at faster speeds. This increase was statistically significant for all trajectories at 100% contrast, 61% contrast, 20% contrast, red targets on a white background, and white targets on a blue background with one exception: it was not statistically significant between +0.6 logMAR and +0.8 logMAR above static visual acuity for a white target on a blue background in a random walk motion. Similar to the mean dynamic visual acuity results, mean speed thresholds are displayed graphically in Figure 5.3. The increase in speed threshold as target size increases follows a similar trend for horizontal, oblique, vertical, and random walk motion. For all optotypes, many participants reached the maximum speed (10m/s) at the largest target sizes.

Table 5.2: Mean (±SD) speed thresholds (m/s) for each direction and size on the moV& software measured, averaged across two visits.

	Size above static visual acuity			
	+0.2 logMAR	**+0.4 logMAR**	**+0.6 logMAR**	**+0.8 logMAR**
100% contrast				
Horizontal	1.50 ± 1.50	6.88 ± 3.84	9.84 ± 1.00	-
Vertical	1.92 ± 3.28	6.76 ± 4.30	9.88 ± 0.85	-
Oblique	1.14 ± 2.17	5.54 ± 3.90	9.66 ± 1.27	-
Random	2.90 ± 3.85	8.78 ± 2.93	9.82 ± 1.27	-
61% contrast				
Horizontal	-	3.05 ± 3.39	6.93 ± 3.85	9.52 ± 1.74
Vertical	-	1.71 ± 3.16	6.12 ± 4.19	9.12 ± 2.09
Oblique	-	1.14 ± 2.31	5.81 ± 4.32	9.24 ± 2.46
Random	-	3.19 ± 3.93	8.12 ± 3.73	9.57 ± 1.61
20% contrast				
Horizontal	-	0.91 ± 1.30	2.57 ± 2.80	5.24 ± 3.91
Vertical	-	0.48 ± 1.15	1.83 ± 2.52	5.43 ± 3.72
Oblique	-	0.14 ± 0.52	0.95 ± 2.08	3.26 ± 3.76
Random	-	0.35 ± 1.57	2.04±3.38	6.57 ± 4.13

Red target/ White background				
Horizontal	-	4.26 ± 4.17	7.40 ± 3.63	9.43 ± 2.08
Vertical	-	3.26 ± 4.02	7.21 ± 4.07	9.33 ± 2.08
Oblique	-	2.38 ± 3.04	7.38 ± 3.63	9.00 ± 2.42
Random	-	4.50 ± 4.49	8.43 ± 3.30	9.81 ± 0.74
White target/ Blue background				
Horizontal	-	3.88 ± 3.87	8.05 ± 3.55	9.74 ± 0.94
Vertical	-	4.02 ± 3.76	8.33 ± 3.31	9.50 ± 1.80
Oblique	-	3.14 ± 3.64	7.79 ± 3.76	9.52 ± 2.15
Random	-	5.17 ± 4.38	8.57 ± 3.02	9.48 ± 1.92

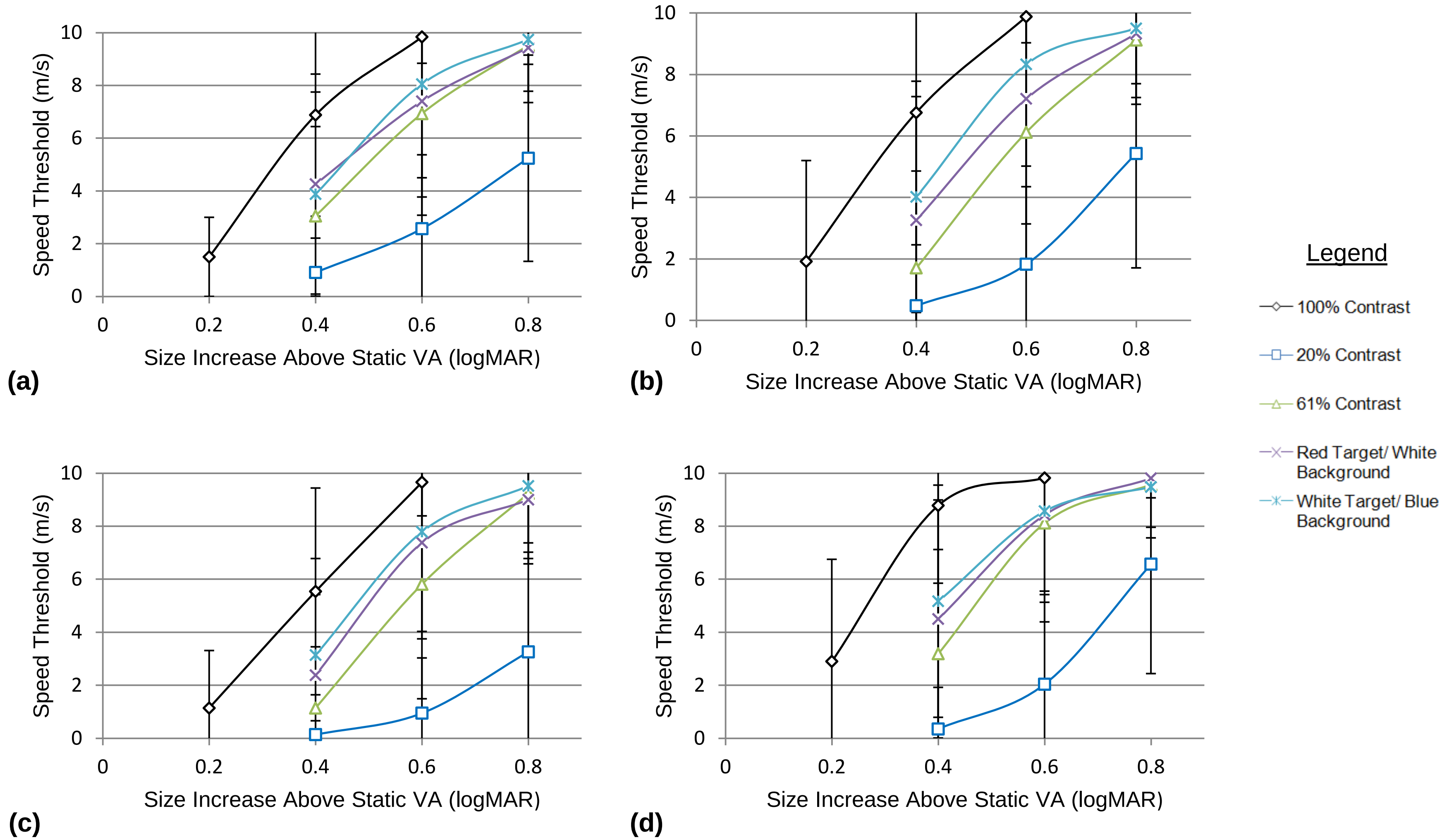

Figure 5.3: Mean (±SD) speed threshold (m/s) for each optotype in (a) horizontal (b) vertical motion (c) oblique and (d) random walk.

At 100% contrast, the mean speed threshold for all sizes at random motion was significantly better (faster) than for any of the predictable linear trajectories ($p<0.05$). Although the speed thresholds for predictable linear motion was best for vertical motion, followed by horizontal and oblique motion respectively, there was no significant difference between any of the predictable linear trajectories ($p>0.05$).

At 61% contrast, the mean speed threshold for random motion was best, followed by horizontal, vertical, and oblique motion in that order. However, random motion was not significantly better than horizontal motion ($p=0.550$), and vertical motion was not significantly better than oblique motion ($p=0.999$). Horizontal motion was also significantly better than vertical motion ($p=0.016$). At 10% contrast, the same trend in mean speed threshold was found – random motion had the best speed threshold, followed by horizontal, vertical, and oblique. However, there was not a significant difference between random and horizontal motion ($p=0.999$), or horizontal and vertical motion ($p=0.846$). There was a significant difference between vertical and oblique motion ($p<0.0001$).

This same trend was seen with red targets on a white background – the speed threshold was best for random motion followed by horizontal, vertical and oblique motion. There was not a significant difference between random and horizontal motion ($p=0.587$), horizontal and vertical motion ($p=0.999$) or vertical and oblique motion ($p=0.999$). For white targets on a blue background, random motion had better speed thresholds than vertical, followed by horizontal and oblique motion. However, the difference was not significant between any of the trajectories except random and oblique motion ($p=0.036$).

5.4.3 Effect of Visit

The mean dynamic visual acuity measured at visit 2 was significantly better than the mean dynamic visual acuity measured at visit 1 for all optotype contrasts ($p \leq 0.05$ for 100%, 61%, and 20% contrast); however, this difference was not clinically significant (was less than a 3 letter difference) except at 20% contrast (difference in mean dynamic visual acuity of 4 letters, $p<0.0001$). At 100% contrast, visit had a main effect on dynamic visual acuity [$F(1, 768)=4.971$, $p=0.026$], although it did not interact with target trajectory [$F(3, 768)=0.075$, $p=0.973$], speed [$F(4, 768)=0.341$, $p=0.850$], or both trajectory and speed [$F(12, 768)=0.270$, $p=0.993$]. At 61% contrast, visit also had a main effect on dynamic visual acuity [$F(1, 685)=11.546$, $p=0.001$], but did not interact with trajectory [$F(3, 685)=0.439$, $p=0.725$], speed [$F(4, 685)=0.229$, $p=0.922$], or both [$F(12, 685)=0.213$, $p=0.998$]. Visit had a main effect at 20% contrast [$F(1, 682)=54.33$, $p<0.0001$], but did not interact with trajectory [$F(3, 682)=0.536$, $p=0.658$], speed [$F(4, 682)=1.071$, $p=0.370$], or trajectory and speed [$F(12, 682)=0.198$, $p=0.999$].

The mean dynamic visual acuity on visit 2 was better than visit 1 for both the red target on a white background ($p=0.004$) and the white target on a blue background ($p=0.006$); however, this difference was not clinically significant for either colour combination (less than a 3 letter difference between mean dynamic visual acuities).

However, unlike with the contrast targets, visit did not have a main effect on dynamic visual acuity for either colour combination tested. For the red target on a white background, the main effect of visit was $F(1, 777)=1.270$, $p=0.260$, and visit did not interact with trajectory [$F(3, 777)=0.089$, $p=0.966$], speed [$F(4, 777)=0.164$, $p=0.956$] or trajectory and speed [$F(12, 777)=0.205$, $p=0.998$]. For the white target on a blue background, the main effect of visit was $F(1, 777)=0.629$, $p=0.428$, and visit did not interact with trajectory [$F(3, 777)=0.033$ $p=0.992$], speed [$F(4, 777)=0.137$, $p=0.969$], or both [$F(12, 777)=0.258$, $p=0.995$].

Visit did not have a main effect on speed threshold at 100% contrast [$F(1, 576)=0.937$, $p=0.333$], nor did it interact with trajectory [$F(3, 576)=0.560$, $p=0.641$], target size [$F(2, 576)=0.052$, $p=0.950$], or trajectory and size [$F(6, 576)=0.294$, $p=0.940$]. At 61% contrast, visit had a main effect on speed threshold [$F(1, 479)=14.375$, $p<0.0001$], but did not interact with trajectory [$F(3, 479)=0.120$, $p=0.948$], size [$F(2, 479)=0.807$, $p=0.447$], or trajectory and size [$F(6, 479)=0.140$, $p=0.991$]. Visit had a main effect on speed threshold at 20% target contrast, $F(1, 479)=30.281$, $p<0.0001$. Although visit did not interact with trajectory [$F(3, 479)=0.393$, $p=0.758$] or trajectory and size [$F(6, 479)=0.801$, $p=0.569$], it did interact with target size [$F(2, 479)=6.499$, $p=0.002$]. There was no significant difference in mean speed threshold between visit 1 and 2 for targets at 100% contrast (speed threshold at visit 1 was 0.2 m/s faster than visit 2, $p=0.234$). The mean speed threshold at visit 2 was better than that at visit 1 at 61% contrast (speed threshold at visit 2 was 1.1 m/s faster than visit 1, p<0.0001), and 20% contrast (speed threshold at visit 2 was 1.4 m/s faster than visit 1, p<0.0001).

Analysis of the red target on a white background data showed that visit did not have a main effect on speed threshold [$F(1, 480)=0.397$, p=0.529] and did not interact with trajectory [$F(3, 480)=1.437$, p=0.231], target size [$F(2, 480)=0.935$, p=0.393], or trajectory and size [$F(6, 480)=0.661$, p=0.681]. The white targets on a blue background demonstrated a similar trend – visit did not have a main effect on speed threshold [$F(1, 480)=3.304$, p=0.070], nor did it interact with trajectory [$F(3, 480)=0.772$, p=0.510], target size [$F(2, 480)=0.201$, p=0.818], or trajectory and size [$F(6, 480)=0.328$, p=0.922]. There was no significant difference in speed threshold between visits 1 and 2 for red targets on a white background (mean speed threshold at visit 1 was 0.2 m/s faster than at visit 2, p=0.443). For white targets on a blue background, mean speed threshold at visit 1 was significantly faster than at visit 2 (speed threshold at visit 1 was 0.5 m/s faster than at visit 2, p=0.018).

5.4.4 Effect of Trajectory

At 100% contrast, trajectory had a main effect on dynamic visual acuity [$F(3, 768)=22.985$, p<0.0001] and interacted with target speed [$F(12, 768)=3.868$, p<0.0001]. Trajectory also had a main effect at 61% contrast [trajectory had a main effect, $F(3, 685)=32.369$, p<0.0001, and interacted with speed, $F(12, 685)=8.806$, p<0.0001]. The same was seen at 20% target contrast [$F(3, 682)=33.23$, p<0.0001]; interaction with speed [$F(12, 682)=11.30$, p<0.001]; and for both colour combinations [red target on a white background main effect $F(3, 777)=30.553$, $p<0.0001$, interaction with speed, $F(12, 777)=3.550$, $p<0.0001$; white target on blue background main effect $F(3, 777)=29.830$, $p<0.0001$, interaction with speed, $F(12, 777)=3.243$, $p<0.0001$]. When trajectory was compared across all speeds, the same trend was found for all optotype contrasts and colours tested: horizontal and random motion did not significantly differ from each other ($p>0.05$) and had the best mean dynamic visual acuity scores, vertical motion had the next best scores and oblique motion had the worst scores. Vertical and oblique motions were significantly different from both horizontal and random motion as well as each other ($p<0.05$).

Trajectory had a main effect on speed threshold at 100% contrast [$F(3, 576)=9.499$, $p<0.0001$], and interacted with target size [$F(6, 576)=2.695$, $p=0.014$]. Although trajectory had a main effect at 61% contrast [$F(3, 479)=6.363$, $p<0.0001$], it did not interact with target size [$F(6, 479)=1.067$, $p=0.382$]. At 20% contrast, trajectory had a main effect [$F(3, 479)=8.507$, $p<0.0001$] and interacted with size [$F(6, 479)=2.642$, $p=0.016$]. For the red target on a white background, trajectory had a main effect, $F(3, 480)=3.732$, $p=0.011$; however, trajectory and target size did not interact [$F(6, 480)=0.738$, $p=0.619$]. Trajectory did not have a main effect on speed threshold for the white target on a blue background [$F(3, 480)=1.764$, $p=0.153$], nor did it interact with target size [$F(6, 480)=0.328$, $p=0.542$]. When trajectory was compared across all target sizes, it was found that random motion yielded the best (fastest) speed thresholds, followed by horizontal, vertical, and oblique motion in that order.

However, the significance of the difference in speed threshold varied based on the optotype contrast and colour and those optotypes which did not follow the aforementioned trend are as follows: At 100% contrast, horizontal and vertical motion speed thresholds were not significantly different (p=0.999), nor were vertical and oblique (p=0.076) or horizontal and oblique (p=0.090). At 61% contrast, there was no significant difference between random and horizontal motion (p=0.550) or between vertical and oblique motion (p=0.999). At 20% contrast, random, horizontal, and vertical motion did not significantly differ from each other (p>0.05), but all were significantly better than oblique motion (p<0.0001). For the coloured optotypes, the only significant difference in speed thresholds was between oblique and random motion (p>0.0001 for the red target on a white background, p=0.036 for the white target on a blue background) and between random and vertical motion for the red target on a white background (p=0.011).

5.4.5 Effect of Target Velocity on Dynamic Visual Acuity

Speed had a main effect on dynamic visual acuity at 100% contrast [*F*(4, 768)=5.613, p<0.0001], 61% contrast [*F*(4, 685)=5.680, p<0.0001], 20% contrast [*F*(4, 682)=62.635, p<0.0001], and with the white target on a blue background [*F*(4, 777)=4.453, p=0.001]. Speed did not have a significant main effect on dynamic visual acuity when the red target on a white background colour combination was used, *F*(4, 777)=1.882, p=0.112. Significant interactions between target speed, trajectory, and visit are stated in the previous two sections.

5.4.6 Effect of Target Size on Speed Thresholds

Target size had a main effect on speed threshold for targets at 100% contrast [$F(2, 576)=405.494$, $p<0.0001$], 61% contrast [$F(2, 479)=213.535$, $p<0.0001$], 20% contrast [$F(2, 479)=128.861$, $p<0.0001$], with the red target on a white background [$F(2, 480)=133.998$, $p<0.0001$], and with the white target on a blue background [$F(2, 480)=135.936$, $p<0.0001$]. Any interactions between target size, trajectory, and visit are stated in the previous sections addressing the effects of target trajectory and visit on speed thresholds.

5.4.7 Variability across Subjects

Using an ANOVA to analyze the data for this experiment does not take into account inter-subject variability. This is a limitation, as dynamic visual acuity and speed threshold may vary between subjects, but display similar trends. Therefore, a linear mixed-effects model was used to determine the effect of variability across subjects and the possible influence of this variability on how visit, trajectory, speed, and size affect dynamic visual acuity and speed threshold. The linear mixed-effects model was analyzed using the lmer package in R.[80]

In the models for both dynamic visual acuity and speed threshold, subjects were included as a random factor in order to control for variability between subjects. A random intercept model was used. The model for dynamic visual acuity (DVA) was “DVA ~ Trajectory*Speed + Visit + (1|Subject),” and the model for speed threshold was “Speed Threshold ~ Trajectory*Size + Visit + (1|Subject).” When the linear mixed model for dynamic visual acuity was applied to the 100% contrast data, the null hypothesis ($H_{0\text{-}1}$ = the variable had no effect on dynamic visual acuity) could be rejected for visit, trajectory, and speed (Table 5.3). Therefore, all three of the variables can be said to have an effect on dynamic visual acuity. Additionally, the model was determined to be the best fit for the data as removing any of the variables significantly decreased the goodness of fit as shown by the AIC values: when visit was removed, $X^2(1, n=25)=17.236$, $p<0.0001$; when trajectory was removed, $X^2(6, n=25)=292.46$, $p<0.0001$; when speed was removed, $X^2(4, n=25)=147.49$, $p<0.0001$. The speed threshold model showed that speed threshold was significantly affected by target size, horizontal motion, and random walk motion; however, the null hypothesis could not be rejected for visit, oblique motion, or vertical motion as their confidence intervals contained zero (Table 5.4). When looking at how these variables affected the goodness of fit of the model, the following AIC values were found – when visit was removed, $X^2(1, n=25)=1.0808$, $p=0.298$; when trajectory was removed, $X^2(6, n=25)=37.223$, $p<0.0001$; when size was removed, $X^2(4, n=25)=547.86$, $p<0.0001$. Therefore, visit did not have a significant effect on the goodness of fit when removed as a variable, but the goodness of fit became worse when trajectory and target size were removed.

This process was repeated for all optotype contrasts and colours tested. At 61% contrast, visit, trajectory, and speed all had an effect on dynamic visual acuity (Table 5.3) and significantly decreased the goodness of fit of the model when removed.

When visit was removed, $X^2(1, n=21)=23.083$, $p<0.0001$; when trajectory was removed, $X^2(6, n=21)=261.95$, $p<0.0001$; and when speed was removed, $X^2(4, n=21)=120.07$, $p<0.0001$. The speed threshold model showed speed threshold was affected by visit, target size, horizontal and oblique motion; however, the null hypothesis ($H_{0\text{-}2}$ = the variable has no effect on speed threshold) could not be rejected for random walk and vertical motion as their confidence intervals contain zero, meaning that it is possible that these trajectories have an effect on speed threshold (Table 5.4). Visit, target trajectory, and size all reduced the goodness of fit of the model when removed – when visit was removed, $X^2(1, n=21)=20.553$, $p<0.0001$; when trajectory was removed, $X^2(6, n=21)=32.572$, $p<0.0001$; when size was removed, $X^2(4, n=21)=386.55$, $p<0.0001$.

At 20% contrast, the linear mixed model showed that visit, trajectory, and speed all had an effect on dynamic visual acuity (Table 5.3). The goodness of fit of the model worsened if any of the variables were excluded – when visit was removed, $X^2(1, n=21)=70.496$, $p<0.0001$; when trajectory was removed, $X^2(6, n=21)=236.73$, $p<0.0001$; and when speed was removed, $X^2(4, n=21)=280.4$, $p<0.0001$. The speed threshold model showed that speed threshold was not affected by oblique and vertical optotype motion, but was affected by visit, target size, horizontal, and random walk motion (Table 5.4). Visit, trajectory, and size all significantly decreased the goodness of fit when removed from the model – when visit was removed, $X^2(1,$

n=21)=39.192, p<0.0001; when trajectory was removed, $X^2(6, n=21)=50.656$, $p<0.0001$; when size was removed, $X^2(4, n=21)=260.51$, $p<0.0001$.

Dynamic visual acuity for the red target on a white background was affected by visit, trajectory, and speed (Table 5.3). All three variables reduced the goodness of fit of the linear mixed model when removed – when visit was removed, $X^2(1, n=21)=4.807$, $p=0.0283$; when trajectory was removed, $X^2(6, n=21)=315.76$, $p<0.0001$; when speed was removed, $X^2(4, n=21)=96.328$, $p<0.0001$. Target size and oblique motion were the only two variables which had a significant effect on speed threshold (Table 5.4). When excluded, trajectory and target size significantly reduced the goodness of fit of the model; however, visit did not. When visit was excluded, $X^2(1, n=21)=0.5538$, $p=0.4568$; when trajectory was excluded, $X^2(6, n=21)=18.916$, $p=0.00431$; and when size was excluded, $X^2(4, n=21)=268.96$, $p<0.0001$.

For the white target on a blue background, speed and trajectory had an effect on dynamic visual acuity, but not visit (Table 5.3). This was reflected in the variables' significance in being included in the model – when trajectory was removed, $X^2(6, n=21)=294.71$, $p<0.0001$; when speed was removed, $X^2(4, n=21)=111.9$, $p<0.0001$; but when visit was removed, $X^2(1, n=21)=3.0522$, $p=0.0806$. Speed threshold was significantly affected by visit, target size, and random motion; however, the null hypothesis could not be rejected for the effect of horizontal, oblique, and vertical motion (Table 5.4). Visit, target trajectory, and size all significantly reduced the model's goodness of fit when removed – when visit was removed, $X^2(1, n=21)=4.3928$, $p=0.0261$; when trajectory was removed, $X^2(6, n=21)=13.3$, $p=0.0385$; when size was removed, $X^2(4, n=21)=258.31$, $p<0.0001$.

<u>Table 5.3</u>: Linear mixed modeling results for dynamic visual acuity (* = cannot reject null hypothesis).

	Slope	**Standard Error**	**2.5% confidence interval**	**97.5% confidence interval**
		100% Contrast		
Visit	-0.023	0.00544	-0.0332	-0.0120
Speed	0.015	0.00133	0.0121	0.0173
Horizontal	0.225	0.0278	0.170	0.280
Vertical	0.070	0.0134	0.0437	0.0958
Oblique	0.121	0.0139	0.0941	0.148
Random	0.050	0.0131	0.0249	0.0759
		20% Contrast		
Visit	-0.074	0.00871	-0.0915	-0.0575
Speed	0.029	0.00214	0.0251	0.0335
Horizontal	0.652	0.0309	0.591	0.712
Vertical	0.067	0.0219	0.0249	0.110
Oblique	0.218	0.0220	0.175	0.261
Random	0.151	0.0214	0.110	0.193

61% Contrast				
Visit	-0.035	0.00727	-0.0492	-0.0208
Speed	0.017	0.00182	0.0132	0.0203
Horizontal	0.360	0.0298	0.301	0.418
Vertical	0.132	0.0190	0.0948	0.169
Oblique	0.146	0.0189	0.109	0.183
Random	0.095	0.0189	0.0586	0.132
White target on a blue background				
Visit*	-0.012	0.00685	-0.0253	0.00146
Speed	0.011	0.00171	0.00725	0.0139
Horizontal	0.247	0.0360	0.176	0.318
Vertical	0.082	0.0178	0.0471	0.117
Oblique	0.104	0.0179	0.0686	0.138
Random	0.060	0.0178	0.0255	0.0951
Red target on a white background				
Visit	-0.015	0.00681	-0.0282	-0.00158
Speed	0.014	0.00171	0.0104	0.0171
Horizontal	0.277	0.0363	0.205	0.349
Vertical	0.129	0.0178	0.0944	0.164
Oblique	0.152	0.0178	0.117	0.187
Random	0.082	0.0178	0.0471	0.116

<u>Table 5.4</u>: Linear mixed modeling results for speed threshold (* = cannot reject null hypothesis).

	Slope	Standard Error	2.5% confidence interval	97.5% confidence interval
		100% Contrast		
Visit*	-0.223	0.216	-0.645	0.198
Size	20.85	1.32	18.26	23.43
Horizontal	-1.93	0.696	-3.29	-0.576
Vertical*	0.493	0.809	-1.08	2.07
Oblique*	-0.807	0.809	-2.38	0.771
Random	2.51	0.809	0.936	4.09
		20% Contrast		
Visit	1.34	0.212	0.932	1.76
Size	10.8	1.30	8.30	13.4
Horizontal	-5.61	0.925	-7.41	-3.81
Vertical*	-1.25	1.14	-3.48	0.970
Oblique*	0.354	1.14	-1.87	2.58
Random	-2.73	1.14	-4.96	-0.51
		61% Contrast		
Visit	1.09	0.241	0.626	1.56
Size	16.2	1.48	13.3	19.1
Horizontal	-4.86	1.05	-6.91	-2.81
Vertical*	-2.24	1.30	-4.77	0.286
Oblique	-3.53	1.30	-6.06	-1.00
Random *	0.603	1.30	-1.92	3.13

White target on a blue background				
Visit	-0.516	0.248	-0.998	-0.0336
Size	14.6	1.52	11.7	17.6
Horizontal*	-0.790	1.08	-2.88	1.30
Vertical*	0.635	1.33	-1.96	3.23
Oblique*	-1.19	1.33	-3.79	1.41
Random	2.84	1.33	0.240	5.43

Red target on a white background				
Visit*	-0.186	0.253	-0.678	0.305
Size	12.9	1.55	9.90	15.9
Horizontal*	-0.438	1.11	-2.59	1.71
Vertical*	-1.79	1.36	-4.43	0.864
Oblique	-2.96	1.36	-5.61	-0.307
Random*	0.333	1.36	-2.32	2.98

Finally, the random intercept linear mixed model was compared to a linear model in which all variables were fixed effects (assuming the intercept is the same for all subjects) to determine which model was a better fit for the data (Table 5.5). Since the goodness of fit significantly worsened (X^2) when subject was removed as a random factor for all optotype contrast and colour combinations tested (p<0.0001), the random intercept model was determined to be a better fit for the data as variability exists between subjects.

<u>Table 5.5</u>: Results of random intercept and fixed slope linear mixed model compared to a general linear model (i.e. not accounting for subject variability).

Target Type	**Threshold**	**Degrees of freedom**	**Sample size**	**Log Likelihood for GLM**	**Log Likelihood for Mixed Model**	X^2	**p-value**
100% contrast	Dynamic visual acuity	1	25	418	875	913	<0.0001
	Speed Threshold	1	25	-1481	-1452	57	<0.0001
61% contrast	Dynamic visual acuity	1	21	394	659	531	<0.0001
	Speed Threshold	1	21	-1295	-1237	115	<0.0001
20% contrast	Dynamic visual acuity	1	21	315	499	369	<0.0001
	Speed Threshold	1	21	-1224	-1170	109	<0.0001
Red and White	Dynamic visual acuity	1	21	267	706	878	<0.0001
	Speed Threshold	1	21	-1320	-1261	118	<0.0001
White and Blue	Dynamic visual acuity	1	21	275	700	849	<0.0001
	Speed Threshold	1	21	-1300	-1249	101	<0.0001

5.5 Discussion

In this paper, we explored the effect of target trajectory, speed, and size on dynamic visual acuity and speed thresholds using five different optotypes: 100%, 61%, and 20% contrast black targets on a white background, and two colour combinations at 83% contrast (red target on a white background, and white target on a blue background). The results of these explorations will be discussed below.

5.5.1 Mean Dynamic Visual Acuity and Speed Threshold

Previous research has shown that target size and speed effect dynamic visual acuity and speed thresholds – larger target sizes can be viewed at faster target speeds.[4,6,7,9,13] This study confirms this finding for a number of different optotype contrasts and colour combinations, as well as different target trajectories. Target size had a significant effect on speed threshold for all contrast and colour combinations tested – as target size increased, speed thresholds improved. Likewise, target speed had an effect on dynamic visual acuity (as target speed increased, dynamic visual acuity became worse) for all contrast and colour combinations tested except the red target on a white background, where dynamic visual acuity did not significantly change as target speed increased. This was most likely due to the improvement in vertical and oblique dynamic visual acuity as speed increased from 1m/s to 3m/s for the red target on a white background optotype. Possible explanations for this phenomenon will be discussed in the *Effect of Trajectory* section which follows. Further research on the visual tracking of coloured optotypes is needed in order to determine why speed did not have a significant main effect on dynamic visual acuity for the red target on a white background optotype only.

5.5.2 Effect of Visit

Dynamic visual acuity measured at visit 2 was better than that measured at visit 1 for targets at 100% contrast, 61% contrast, and 20% contrast, but not for red targets on a white background or white targets on a blue background. This indicates that there may be a learning effect with the dynamic visual acuity task. Previous research has shown good test-retest repeatability of moV& for targets at 100% contrast, however this does not exclude the possibility that a learning effect is present.[38] Additionally, at 20% contrast moV& test-retest repeatability was poor compared to 61% contrast, and both low contrast levels had worse repeatability than the colour combinations at 83% contrast (see Chapter 4). The red target on a white background and white target on a blue background used in this study showed good test-retest repeatability for dynamic visual acuity measured using moV& (see Chapter 4). Good test-retest repeatability is not necessarily indicative of the effect of visit on dynamic visual acuity measures, as is demonstrated with the 100% contrast target.

Visit only had a main effect on speed thresholds for targets at 61% and 20% contrast, with the speed threshold measured at visit 2 being better (faster) than those measured at visit 1. It is logical that the effect of visit would be present for both dynamic visual acuity and speed thresholds measurements, as the tasks are similar in that they both require the visualization of moving targets and only differ in the variable measured. However, there was no main effect of visit present for targets at 100% contrast, while visit did have a main effect on dynamic visual acuity at this target contrast. Visit also did not have a main effect on red targets on a white background or white targets on a blue background. The presence of this effect at certain target contrast levels may be indicative that a learning effect is only present when the task is more difficult, as it can be hypothesized that it is more difficult to visualize a low contrast moving target compared to a higher contrast. However, this hypothesis requires further investigation.

5.5.3 Effect of Trajectory

Target trajectory had an effect on dynamic visual acuity, and trajectory interacted with target speed for all contrast and colour combinations. This supports previous literature which shows that trajectory has a significant effect on dynamic visual acuity.[9,35] However, past literature only explored horizontal and oblique motion due to limitations of the instrumentation. This experiment used horizontal, vertical, oblique and random walk motion, and showed that all trajectories have a significant effect on dynamic visual acuity. Similarly, trajectory had an effect on speed thresholds for all contrast and colours except the white target on a blue background. Trajectory and size interacted for targets at 20% and 100% contrast only.

Overall, random and horizontal motion had better dynamic visual acuity and speed threshold measurements compared to vertical and oblique motion. Past literature has shown that horizontal dynamic visual acuity is superior to oblique, possibly due to the increased prevalence of horizontal motion in daily life.[9] When comparing the predicable linear trajectories to random motion, it is important to remember that a difference in exposure time was present – random walk motion targets could enter and exit the screen for up to 16s, while predictable linear motion targets only travelled across the screen once. Longer exposure times result in better dynamic visual acuity measurements, therefore it can be hypothesized that exposure time is a contributing factor towards random walk dynamic visual acuity and speed threshold being superior to most linear trajectories.[6]

5.5.4 Effect of Velocity on Dynamic Visual Acuity

Dynamic visual acuity became worse as velocity increased for most optotypes and trajectories with the exception of random walk motion, which remained relatively consistent for all of the contrasts and colours tested. Some exceptions to this trend were present for specific optotype, speed, and trajectory combinations. For example, vertical dynamic visual acuity improved from 1m/s to 3m/s for targets at 100% contrast, white targets on a blue background, and red targets on a white background. Additionally, there was a significant improvement in oblique dynamic visual acuity at 3m/s for targets at 61% contrast and with the red target on a white background, and random walk dynamic visual acuity improved at 61% contrast and with the red target on a white background between 1m/s and 12m/s.

This improvement in visual acuity from 1m/s to 3m/s for predictable linear trajectories may be due to a change in visual tracking strategy. Smooth pursuit eye movements are typically used to track objects moving at speeds up to 50°/s – at faster speeds, catch-up saccades are needed in order to keep the image on the fovea,[5] and there is a brief moment of low position error and low retinal slip at the end of an accurate catch-up saccade, during which a target may be perceived with high acuity.[5] Given that 1, 3, 6, 9, and 12m/s are approximately equal to constant angular velocities of 14, 37, 56, 66, and 72°/s, it would be expected that a significant change in visual acuity would be present between 3m/s and 6m/s as a result of a change in visual tracking strategies, however in this study, we noticed that dynamic visual acuity improved from 1m/s to 3m/s in this study instead of from 3m/s to 6m/s as would be expected and further investigation is needed to determine why this the change in dynamic visual acuity between 1m/s and 3m/s occurred.

Random walk dynamic visual acuity did not significantly change as target speed increased for all optotypes tested. This may be due to the fact that, as previously mentioned, random motion targets were presented for a longer amount of time compared to targets moving in a predictable linear trajectory. Additionally, since subjects are unable to predict the path of the target in random walk motion, they must use a combination of fixations, pursuits, and saccades to visualize the target. These factors may contribute to the lack of effect that speed has on random walk dynamic visual acuity, but further investigation of tracking strategies is needed in order to fully understand these differences.

5.5.5 Effect of Target Size on Speed Thresholds

Target size had a significant effect on speed thresholds. Speed thresholds were worse for smaller target sizes in all optotypes (100% contrast, 61% contrast, 20% contrast, red targets on a white background, and white targets on a blue background). At the largest target size for all optotypes, the majority of participants reached the maximum speed of 10m/s. Additionally, some participants were unable to view 3 out of 5 of the letters at the first speed presented (1m/s) for the smallest target size, especially at 20% contrast, resulting in a speed threshold of 0 m/s. The presence of a floor and ceiling effect for speed threshold demonstrates that certain target sizes, trajectories, contrasts, and colours were more difficult or easy to visualize.

5.5.6 Variability across Subjects

It is important to determine if the change in dynamic visual acuity with target speed (and the change in speed threshold with target size) is influenced by variability between subjects, since an ANOVA does not take into account inter-subject variability. The random intercept (fixed slope) linear mixed model was a better fit for the data compared to a general linear model which excluded subject as a random variable; therefore the dynamic visual acuity of all subjects worsened at a similar rate as speed increased, regardless of their dynamic visual acuity at the slowest speed (which varied between subjects). A similar trend was found for speed thresholds – since the random intercept (fixed slope) linear mixed model was the better fit for the data, it was shown that the speed thresholds of all subjects improved as target size increased. However, only linear mixed models were explored in this analysis – it is possible that a non-linear model may be a better fit for the data, therefore further analysis is needed exploring non-linear mixed models.

5.5.7 Reverse-Contrast

Although the contrast between the target and the background for both colour combinations was equal, the white letter on a blue background was reversed-contrast from the red letter on a white background. Reverse-contrast static acuity (white letters on a black background) is better when compared to normal static acuity (black letters on a white background) due to the effect of aberrations and light scatter.[91,92] It can therefore be hypothesized that reverse-contrast dynamic visual acuity would show a similar effect, and preliminary comparisons of the two colour combinations used in this study show that the white targets on a blue background had a significantly better overall mean dynamic visual acuity compared to red targets on a white background (0.32 logMAR for white targets on a blue background compared to 0.37 logMAR for red targets on a white background, $p<0.0001$). Mean speed threshold was also significantly better for white targets on a blue background (7.26 m/s) compared to red targets on a white background (6.87m/s, $p=0.015$). However, further investigation is needed in order to draw any solid conclusions regarding the effect of reverse-contrast on dynamic visual acuity and speed threshold.

5.6 Conclusion

This study explored the effect of different factors on dynamic visual acuity and speed threshold for targets at 100%, 61%, and 20% contrast as well as two colour combinations (red target on a white background and a white target on a blue background). It was shown that dynamic visual acuity measured at visit 2 was significantly better than that measured at visit 1 for targets at 100%, 61%, and 20% contrast, but not for either of the coloured targets. Visit number only had a significant effect on speed threshold for the low contrast targets (61% and 20% contrast). Target trajectory had a significant effect on dynamic visual acuity and speed thresholds for all optotypes except the speed thresholds of the white target on a blue background, and target size had a significant effect on speed thresholds for all optotypes. Target speed had a significant effect on dynamic visual acuity for targets at 100%, 61%, and 20% contrast as well as white targets on a blue background, but not for red targets on a white background. Further research looking at the effect of a wider range of contrast and colour combinations would allow for the influence of contrast and colour on dynamic visual acuity and speed thresholds to be determined. As we continue to expand our understanding of how we visualize moving targets and the different factors which can affect this ability, dynamic visual acuity and speed threshold measurements will become more clinically useful in areas such as binocular vision, low vision, contact lens, sports vision, and traumatic and acquired brain injury.

5.7 Dissertation Progress III

Figure 4.4 from Chapter 4 has been expanded to include the findings of Experiment 3. This final figure (Fig.5.4) illustrates how each experiment built off of the conclusions drawn from the previous one. For example, it had to be demonstrated that moV& was valid and/ or repeatable for the targets used in Experiment 3 in order for useful conclusions to be drawn.

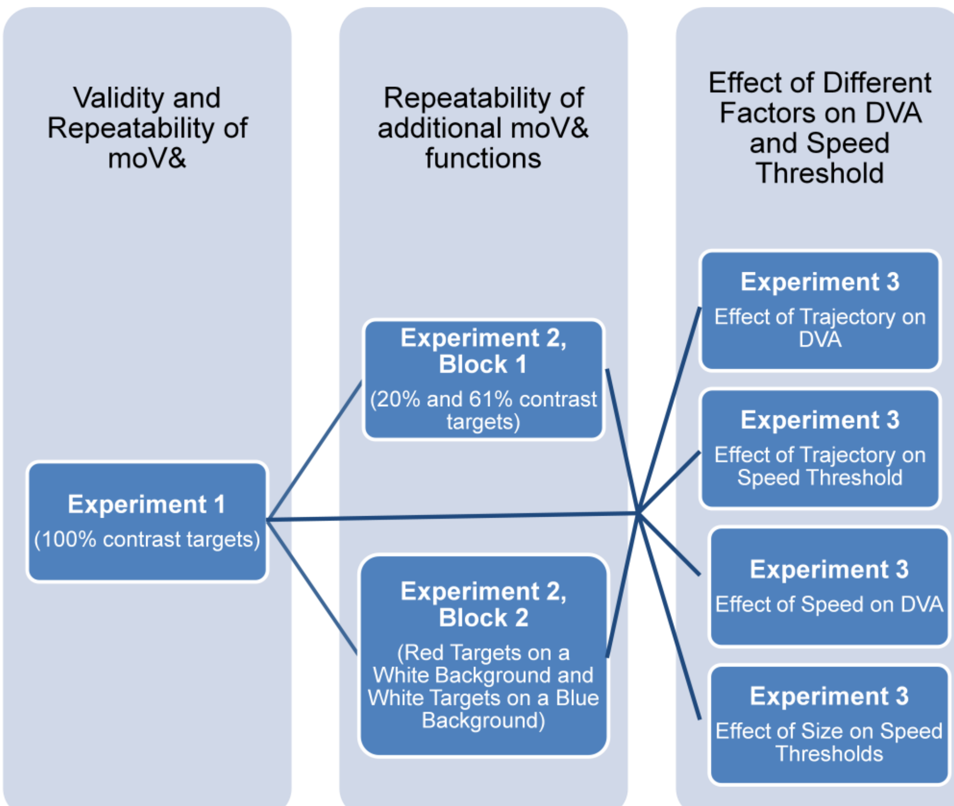

Figure 5.4: Dissertation Progress III, outlining the purposes of Experiments 1-3.

Chapter 6 – Summary, Conclusions, and Future Directions

6.1 Summary of Findings

In order to visualize a moving target for measurements of DVA or speed threshold, an observer must visually acquire the target and resolve critical detail for recognition while the target is within their field of view.[12] There are many variables of both target motion and the target itself which can affect an observer's ability to visualize a moving target. Previous DVA research has shown that DVA improves when a target is moving in a horizontal trajectory compared to oblique, and that DVA improves as optotype velocity decreases.[9,13] Similarly, speed threshold improves when target size increases.[40]

A problem with literature is that there is not a standardized, validated, readily available tool with which to measure DVA or speed thresholds. This makes direct comparisons of results between experiments difficult. Tools that have been used to measure DVA and speed threshold in the past were limited in their available trajectories, speeds, or optotypes. With the development of computerized software for visual acuity measurements, a need arose for a test with the capacity to measure both static and dynamic visual acuity as well as the ability to customize features such as optotype and background colour and contrast. Therefore, the Vision & Motor Performance Lab at the University of Waterloo School of Optometry & Vision Science developed the moV& software – a computerized test with the capability to measure distance static visual acuity, DVA, and speed thresholds while allowing the specification of optotype contrast, colour, speed, size, and trajectory.

As with any novel test, moV& had to demonstrate that it can yield repeatable and valid measures of both static and dynamic visual acuity before it could be accepted as a useful tool in research and clinical practice. The primary objective of this dissertation, through multiple experiments, was to determine a measure of repeatability and validity for all of the features available in moV&. Once the reliability and validity of the targets was established, the data could be analyzed to determine the effect of trajectory, size, and speed on dynamic visual acuity and speed threshold (the secondary objective of the dissertation). Both the primary and secondary objectives were achieved, the details of which are explained in subsections 6.1.1 to 6.1.3.

6.1.1 Validity and Repeatability of High Contrast Optotypes

The purpose of Experiment 1 was to determine the validity and repeatability of the static and dynamic visual acuity features of moV& using high (100%) contrast black letter targets on a white background. moV& static visual acuity was compared to static visual acuity measured with the clinical standard high contrast Snellen chart and the gold standard ETDRS chart. The test-retest repeatability was also determined for both static and dynamic visual acuity through Lin's correlation coefficients of concordance. The results of Experiment 1 show that static high contrast moV& visual acuity is valid and repeatable, comparable to the Snellen and ETDRS chart.

As there is no gold standard DVA test, it was not possible to compare the accuracy of the moV& DVA tests to an existing standard. However, the repeatability of the moV& DVA test was determined for all moV& trajectories (horizontal, vertical, oblique, and random walk) at five target speeds (1, 3, 6, 9, and 12m/s). The DVA for all trajectories and speeds tested demonstrated good test-retest repeatability comparable with that of the static tests. Additionally, jitter visual acuity was shown to be repeatable and comparable to static visual acuity, and moV& high contrast DVA demonstrated good construct validity in that DVA measurements became worse as target speeds got faster.

These results show that moV& can be used to measure static and dynamic visual acuity for high contrast black targets on a white background. Therefore, the validity and repeatability of other functions of moV& (such as low contrast and coloured target and background optotypes) can be determined. The repeatability of the low contrast and coloured optotype and background functions of moV& was determined in Experiment 2. Additionally, the results of Experiment 1 allow for moV& to be used in order to determine the effect of optotype trajectory, speed, and size on DVA and speed thresholds – this was done in Experiment 3.

6.1.2 Repeatability of Low Contrast Targets and Coloured Optotypes and Background Combinations

Once the validity and repeatability of moV& was determined for high contrast targets, the repeatability of the low contrast and coloured functions of moV& could be explored. Two contrast values for black targets on a white background (61% and 20% Weber contrast) and two target and background colour combinations at 83% Weber contrast (red target on a white background and white target on a blue background) were chosen. The contrast values were chosen so as to pick a low and mid contrast level compared to the 100% contrast targets used in Experiment 1. Additionally, low contrast levels ranging from 19%-23% Weber contrast, and intermediate contrast levels ranging from 51% to 70% contrast commonly appear in previous literature on low contrast visual acuity.[12,26,93] The colour combinations of red on white and white on blue were chosen based on their prevalence in sports – the colours mimic the red and white detailing on a cricket ball or baseball, and a white ball against a blue sky. The low contrast and coloured functions of moV& could not be compared to another standardized chart, as no such chart exists for low contrast or coloured static or dynamic visual acuity. However, the reliability of moV& could be demonstrated through the assessment of test-retest repeatability, and convergence validity could be evaluated through the examination of the impact of different contrast levels on test-retest repeatability.

The results of Experiment 2 showed that both contrast levels and colour combinations tested had good repeatability for static visual acuity measures using moV&. There was no significant difference in static visual acuity for any of the target contrasts or colours between visit 1 and visit 2, although Lin's correlation coefficient of concordance was higher (better) for 61% contrast and both colour combinations than it was for 20% contrast targets.

The same target trajectories and speeds used in Experiment 1 were also tested in Experiment 2 (horizontal, vertical, and oblique linear predictable motion; random walk motion; 1, 3, 6, 9, and 12m/s (all trajectories)). Jitter visual acuity was only tested in Experiment 1 as it was found to be comparable to static visual acuity, and the effects of dynamic visual acuity were the focus of Experiments 2 and 3. The repeatability of moV& DVA for targets at 61% contrast targets was fair, but the repeatability was poor for targets at 20% contrast. Both 61% and 20% contrast DVAs had a large range of repeatability values for the different trajectory and speed combinations tested. Both red targets on a white background and white targets on a blue background had good repeatability. Lin's coefficient of correlation for each speed, size, and optotype contrast or colour combination is specified in the Results sections of Chapters 3 – 5. Based on these results, moV& DVA can be measured with varying degrees of confidence depending on the repeatability of moV& found with the target contrast, trajectory, and speed combination to be tested. It is speculated that the poor repeatability for the low contrast DVA measures is due to an increased difficulty in task, thereby demonstrating convergent validity; however, further research is needed to assess the impact of task difficulty on DVA.

The results of this experiment demonstrate that moV& can be used to measure static visual acuity using targets at 61% and 20% contrast, red targets on a white background, and white targets on a blue background. moV& can also be used to measure low contrast and coloured DVA with varying amounts of confidence depending on target trajectory and speed. Therefore, the effect of optotype trajectory, speed, and size on DVA and speed thresholds with low contrast and coloured optotypes can be determined using moV&. This was done in Experiment 3, although conclusions were drawn with the awareness that the repeatability of some DVA measurements were poor, especially at the 20% contrast.

6.1.3 The Effect of Trajectory, Speed, and Size on Dynamic Visual Acuity and Speed Thresholds

Experiment 3 determined the effect of target trajectory, speed, and size on DVA and speed threshold using the different moV& optotypes shown to be repeatable in Experiments 1 and 2 (i.e. targets at 100%, 61%, and 20% contrast, red targets on a white background, and white targets on a blue background). The same four trajectories (horizontal, vertical, oblique, and random walk) and five speeds (1, 3, 6, 9, and 12m/s) were used, as well as three target sizes for speed thresholds (+0.2, +0.4, and +0.6 logMAR above static visual acuity for 100% contrast targets; +0.4, +0.6, and +0.8 logMAR above static visual acuity for 61% contrast targets, 20% contrast targets, red targets on a white background, and white targets on a blue background).

It was shown that, in agreement with previous literature, target speed had a significant effect on DVA for targets at 100%.[6,7,9,14] Additionally, speed had a significant effect on DVA for targets at 61% contrast, 20% contrast, and white targets on a blue background. Target speed did not have a significant effect on DVA for red targets on a white background. Also in agreement with previous research, trajectory had a significant effect on DVA and speed thresholds for all contrast and colours tested, with the exception of speed thresholds measured with white targets on a blue background.[9,35] Target size had a significant effect on speed thresholds for all contrast and colour combinations tested.

When looking at the interaction between target trajectory and speed, horizontal motion for all target contrast levels and colour combinations tested showed a significant worsening of DVA as speed increased from 1m/s to 3m/s, after which smaller non-significant changes in DVA were present from 3m/s to 12m/s. Vertical motion showed a significant worsening of DVA as speed increased from 1m/s to 12m/s at 20% contrast, but no significant change for either colour combination or 61% contrast. Oblique motion showed a worsening of DVA as speed increased from 1m/s to 12m/s for all target contrast and colour combinations, although it was not statistically significant at 100% contrast. Interestingly, there was an improvement in DVA from 1m/s to 3m/s (after which DVA worsened) for certain optotypes at the oblique (61% contrast and red targets on a white background) and vertical (100% contrast, white targets on a blue background, and red targets on a white background) trajectories. Unlike the linear motion trajectories, random walk motion did not demonstrate a significant worsening of DVA as speed increased for any of the contrast or colour combinations tested. At 61% contrast and with the red target on a white background, random walk DVA improved as speed increased from 1m/s to 12m/s. This may be due to a difference in tracking strategies used for medium contrast targets (61% and 83% contrast) compared to the low and high contrast targets (20% and 100% contrast respectively), but further investigation is needed.

The interaction between target size and trajectory had a similar relationship to target speed and trajectory. Speed thresholds were significantly worse at smaller target sizes for all optotypes and trajectories with one exception – speed threshold was not significantly worse for white targets on a blue background between +0.6 and +0.8 logMAR above static visual acuity when the target was moving in a random walk motion. This may be due to the reverse-contrast of white targets on a blue background compared to all other optotypes used, as it has been found that white letters on a black background yield better static visual acuity compared to visual acuity of black letters on a white background.[91,92] However, further research is needed to determine the effect of reverse-contrast and coloured optotypes on dynamic visual acuity.

Linear mixed modeling showed that threshold variability existed between subjects, but all subjects showed a similar trend of DVA worsening as target speed increased and speed threshold improving as target size increased. Therefore, the results of this experiment show that target trajectory, speed, and size have a significant effect on DVA and speed threshold. A few exceptions to this statement exist within specific optotype trajectory, speed, and size combinations and future research looking at visual tracking strategies are required to determine why these exceptions exist. It is also important to remember that the repeatability of some DVA measures using moV& were poor, especially at 20% contrast. Additional research focusing on the effect of optotype contrast and colour on DVA and speed thresholds is needed in order to determine if the results found in this dissertation are applicable across a wider range of optotypes.

6.2 Dissertation Conclusions

The findings from Experiments 1 and 2 show the repeatability of the static and dynamic visual acuity components of moV& for a variety of high contrast, low contrast, and coloured optotypes. Additionally, the static visual acuity for moV& with 100% contrast black targets on a white background was validated against the clinical standard Snellen and gold standard ETDRS static visual acuity charts. These findings allowed for moV& to be reliably used in order to determine the effects of different factors on DVA and speed thresholds in Experiment 3.

The results of Experiment 3 agree with previous literature looking at the effect of trajectory, speed, and size on DVA and speed thresholds. However, this dissertation looks at a wider variety of trajectories and the use of low contrast and coloured optotypes which has not been extensively explored in past literature, and never with a proven reliable test. It was concluded that DVA became worse as target speed increased for all trajectories except random walk motion, where DVA was either not affected or improved depending on the optotype contrast and colour used. Speed threshold improved as target size increased for all optotype contrasts and colours tested. Trajectory influenced DVA (with horizontal and random motion yielding the best DVA values, followed by vertical and oblique motion) and speed thresholds (random motion yields the best speed threshold values, followed by horizontal, vertical, and oblique motion respectively). Therefore, target trajectory, speed, and size all have an effect on DVA and speed threshold for all target contrast and colours tested.

The findings of Experiment 3 replicates those found in previous research, but do so using a novel system. This provides some additional proof of concept indications of validity, in that moV& appropriately measures DVA and speed thresholds. Although the validity of moV& as a tool with which to measure low contrast and coloured static and dynamic visual acuity for high contrast, low contrast, and coloured targets still needs to be demonstrated through comparison with another validated test, the fact that DVA and speed thresholds measured with moV& replicate data trends shown in previous research gives a strong indication that moV& is a valid test. It is possible that a systematic error is present which equally effects all measurements, resulting in similar trends in the data with all measurements skewed by the same margin of error. In order to rule out this type of error, comparison with a validated test is required, but unfortunately not possible at this time. However, moV& can be effectively used to determine trends in DVA and speed thresholds. This is useful clinically, as changes in DVA can aid in demonstrating visual improvement with a refractive correction in place or after completing a vision training program. Also, moV& high contrast static visual acuity is validated and can be used to determine if any deterioration in static visual acuity is present.

6.3 Limitations and Future Work

In the Discussion sections of Chapters 3 – 5, limitations of the research completed in this dissertation were discussed in detail, and suggestions for future areas of investigation required in order to fill these knowledge gaps were given. This section will summarize the major limitations of our research, and address possible future uses for moV& as a system with which to reliably measure DVA and speed thresholds.

In Experiment 1, the validity of moV& was determined for static high contrast targets through comparison with the gold standard and clinical standard for measures of high contrast static visual acuity (the ETDRS and Snellen chart, respectively). However, no such standard exists for DVA – therefore, repeatability was chosen as an indicator that moV& yielded useful measures. The external validity of moV& was also shown, as the results of the study demonstrated that DVA worsens as target speed increases, and that the horizontal trajectory yielded better DVA compared to vertical and oblique motion; both of these findings are in agreement with previous DVA research. The lack of a standard test with which to measure low contrast and coloured static visual acuity as well as high contrast, low contrast, and coloured DVA is a limitation to determining the accuracy of moV& in Experiments 1 and 2. However, this dissertation focused on aspects of test validity which could be demonstrated in a novel test, such as convergent validity, construct validity, and external validity.

The results of Experiment 2 suggest that the repeatability for a larger variety of target contrasts should be explored, especially contrasts higher than 61%. This would allow for the reliability of low contrast DVA to be determined and the utility of moV& to be confirmed for a larger range of contrast levels, making moV& more clinically useful. Determining the repeatability of moV& DVA for more colour combinations would also be beneficial, especially considering the large variety of colours seen in dynamic environments such as sport and driving. Additional research on contrast and colour combinations would allow for the effect of colour and contrast on static visual acuity, DVA, and speed thresholds to be explored in more detail than what could be done with analysis comparing two contrast and two colour values.

Experiment 1 showed that jittered visual acuity is more comparable to static visual acuity than DVA for 100% contrast targets. However, the effect of jittered acuity was not determined for the low contrast or coloured optotypes used in Experiment 2. It would be interesting to explore if contrast or colour affects the relationship between jittered and static visual acuity, as well as the effects of contrast and colour on jittered visual acuity in comparison to their effects on static and dynamic visual acuity.

The results of Experiments 1 and 2 allowed for the measurements taken using moV& to be used for Experiment 3. However, conclusions drawn from the results of Experiment 3 should be done with caution as the repeatability of moV& DVA varied depending on the target, trajectory and speed tested. For example, DVA for 20% contrast targets had low repeatability; therefore the effect of speed, size, and trajectory determined using moV& may not reflect the true relationship on DVA and speed thresholds for targets at this contrast. Determining the effect of DVA on a wider variety of low contrast levels and colour combinations would give us a better idea of the true nature of the relationship between target speed, size, and trajectory with DVA and speed thresholds. The results of Experiment 3 demonstrate the added value of examining the eye tracking strategies used by subjects when performing DVA tests and assessing how they differ at different target speeds and trajectories. This would show the effect of eye movements and visual tracking strategies on DVA and speed thresholds. Additional research exploring the sensory processes used to view fine detail of moving targets with varying contrast and colour properties would also be interesting to explore, as it would provide an objective method of validating the moV& software as well as give insight as to the link between the motor and sensory processing involved in DVA tasks.

Future uses of the moV& software are numerous, and DVA measurements can be useful in many different fields of optometry. moV& has been used to collect data for research on vision strategies used for DVA in video game players and athletes.[94] moV& has also been used to show the relationship between DVA and skiing performance in a population of low vision athletes.[95] Clinically, DVA measurements have possible applications in vision training, binocular vision issues, low vision issues, contact lens and sports vision, as well as traumatic and acquired brain injury, and assessing fitness to drive. DVA and speed threshold measurements have applications across many areas of research, and as the vision science and optometric community continues to expand their understanding of how the visual system resolves moving targets, further innovative uses for moV& will be created.

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