MOTION-IN-DEPTH SHARPENING AND VERGENCE COROLLARY DISCHARGE

A thesis presented to the graduate faculty of
New England College of Optometry in partial fulfillment
of the requirements for the degree of Master of Science

Santye Chen

July 2021

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Abstract:

MOTION-IN-DEPTH SHARPENING AND VERGENCE COROLLARY DISCHARGE

Santye Chen

New England College of Optometry, 2021

Purpose:

Motion sharpening causes blurred images to appear sharper when moving than when stationary. Sharpening is stimulated by retinal image motion, but it is unclear whether vergence corollary discharge contributes to the sharpening of a pursued motion-in-depth stimulus. Previous findings in motion smear perception suggest that motor signals for convergence and divergence may provide additional sharpening of fine detail viewed in darkness. This study tested the hypothesis that corollary discharge from vergence eye movements contributes to motion sharpening of coarse blurred photopic images.

Methods:

14 naive, normally binocular, young adults viewed a 3D display at 1.069m. Subjects binocularly followed a fixation target moving in depth (crossed or uncrossed) at 1 or 3°/s. A 0.5°W x 2°H luminous test bar with 24' blurred edges was presented for 250ms 70' above or below fixation. The test bar moved with the fixation target (Exp 1) or at fixed stereoscopic depth (Exp 2). A comparison bar of variable blur determined by a PEST protocol was then presented for 250ms during steady fixation and the subject reported which bar was sharper. Eye movements were monitored by a ViewPoint^{TM} eye tracker to calculate the velocity of any retinal

image motion during the experimental trials. Subjects also performed control trials by fixating a stationary target while a blurred test bar moved in stereoscopic depth at the retinal image velocities measured during the experimental trials. Control trials revealed motion sharpening due to retinal image motion during the experimental trials. Total sharpening in experimental trials was then adjusted by the corresponding control values to correct for retinal image slippage.

Results:

Within-subjects ANOVAs measured the effect of velocity (1 or 3°/s) on match blur in experiments 1 and 2. No velocity effect was found in experiment 1 ($F=1.1$, $p=0.32$) which is consistent with the null hypothesis. As expected, experiment 2 showed significant sharpening ($F=17$, $p=0.001$), but the effect disappeared when control retinal image motion was subtracted from total sharpening ($F=2.8$, $p=0.12$). Convergence trials were found to appear sharper than divergence trials, but the effect is likely due to induced vergence micropsia.

Conclusions:

Our results suggest that the perceived sharpness of neither a fixated target moving in depth, nor a non-fixated background target, is affected by extra-retinal motion sharpening. Motion sharpening during motion-in-depth is caused by retinal image motion.

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General Introduction:

The prevalence of three-dimensional (3D) displays has dramatically increased over the past several decades. Their applications vary from Hollywood film releases to stereoscopic medical imaging. However, this gain of stereopsis is often accompanied by complaints of discomfort and fatigue (Shibata et al. 2011). A significant source of this discomfort is accommodation and convergence mismatch (ACM) which is caused by changes in vergence stimuli without the appropriate changes in accommodative demand (Hoffman et al. 2008).

"Motion sharpening" is a phenomenon that causes physically blurred images to be perceived sharper when in motion than when stationary. Bex et al. (1995) distinguished motion sharpening as a separate mechanism from the previously established "motion deblurring" models (Burr, 1980). It was demonstrated by Bex et al. (1995) that rather than sharp contours being preserved (motion deblurring), blurred contours in motion were perceived as sharper. Hammett et al. (2003) studied the relationship between blur perception, image speed, and contrast and found that the amount of motion sharpening increased with speed, independent of contrast. This showed that motion sharpening was more than just contrast enhancement. These studies were all concerned with laterally moving stimuli.

McCormack & Hogan (2019) found that subjects' convergence limits of clear and single binocular vision when viewing 3D display motion-in-depth were much larger than the analogous clinical convergence limit. Kulowski & McCormack (2013) demonstrated that one reason for this finding was that blur perception thresholds are significantly elevated during 3D convergence. This led McCormack et al. (2014) to investigate whether motion sharpening might have played a role in elevating blur thresholds. They revealed motion sharpening in stereoscopic motion-in-depth during fixed convergence and found that for images moving at the same retinal

velocity, motion sharpening was stronger for physical blurs moving in depth than in lateral motion. Inspired by Marinovic & Arnold's (2013) discovery of an asymmetry of motion sharpening between the leading and trailing edges of blurred moving objects, Ferrucci (2018) examined whether the increased 3D sharpening found in McCormack's study could be explained by additive asymmetric sharpening of the left and right eye images in stereoscopic motion-in-depth. It was found that stereoscopic motion-in-depth still produced more motion sharpening than lateral motion even when the asymmetric sharpening was neutralized. Ferrucci's findings suggested that a retinal mechanism was responsible for asymmetrically sharpening the trailing edges of moving images while a cortical mechanism sharpened both edges equally. If motion sharpening contributes to the enhanced clear and single vision in 3D display viewing observed by McCormack & Hogan (2019), then understanding the mechanisms of motion sharpening is imperative to manage ACM so as to minimize symptoms.

The application of motion sharpening effects has been investigated for the development of new video and display technologies. Fujibayashi & Boon (2008) exploited the phenomenon to improve video coding efficiency without sacrificing subjective quality. Tokimoto et al. (2019) proposed a method for high-speed LED displays to produce a subjective "super-resolution" which the authors attributed to processing mechanisms responsible for motion sharpening. Identifying additional mechanisms involved in motion-in-depth sharpening may provide applications to increasingly common 3D display technologies.

This study hypothesizes that there exists an extra-retinal oculomotor mechanism of motion sharpening by means of corollary discharge. A corollary discharge is a copy of an efferent motor signal that is sent to other brain regions to communicate impending movements, sometimes affecting perception. Vergence corollary discharge is known to alter perceived size,

distance, and depth (Howard & Rogers, 2002). It is conceivable that such a mechanism exists to assist accommodation and pupillary constriction with maintaining clarity of rapidly approaching or receding objects. For example, an object such as a projectile or predator approaching at 50 miles per hour has an instantaneous accommodation velocity demand of 5.6 D/sec at 2 meters, 22.4 D/sec at 1 meter, and 89.4 D/sec at 0.5 meters from the observer; young adults have an average peak accommodation velocity of 1.9 D/sec, far slower than needed to maintain optical focus in this scenario (Lockhart & Shi, 2011). A low latency neural sharpening mechanism could improve perceived clarity to the optically blurred objects moving quickly through depth.

We hypothesize that vergence corollary discharge may also sharpen blurred images moving in depth. We named this potential motion sharpening mechanism "motor sharpening". Bedell et al. (2004) found that observers performing vergence eye movements had a reduced perception of the motion smear of small luminous spot stimuli that could not be explained by retinal motion alone. They also observed a similar reduction of motion smear during smooth pursuit. Their experiment suggested the presence of a motion deblurring mechanism but did not necessarily establish motion sharpening due to motor sharpening. Our experiments use large, luminous, physically blurred greyscale stimuli to determine whether corollary discharge also tells the brain to sharpen blurred images – a motion sharpening process – during convergence and divergence tracking. If vergence eye movements alone are found to induce motion sharpening in the absence of a sufficient retinal image motion stimulus to induce motion sharpening, then the existence of motor sharpening would be demonstrated.

Specific Experimental Aims:

Experiment 1: Test for motor sharpening of a blurred parafoveal test target moving with a pursued fixation cross moving in depth. This condition is similar to clinical vergence testing and should determine if motor sharpening causes subjects to not notice ACM blur in 3D display fixation targets.

Experiment 2: Test for motor sharpening of a blurred stationary parafoveal test target when the observer pursues a foveal fixation cross moving in depth. This setup binocularly simulates the study of Bedell et al. (2004) which also used non-fixated targets moving across the retina.

Methods:

Apparatus

An Asus Windows desktop computer (M32AD-US033S) and Asus 278HE monitor with stereo glasses (Nvidia 3D Vision 2) runs our MATLAB psychophysics program and receives subjects' keyboard responses. A second Dell Windows laptop runs the Arrington Research ViewPoint EyeTracker software and sends subjects' vergence data to the main Asus computer. A Macintosh G4 computer running Labview software controls the psychophysics protocol of the MATLAB program and records the psychophysical data. The ViewPoint eye tracking sensors are installed on the stereo glasses. A chin/forehead rest is installed 1069mm in front of the Asus 3D monitor. The monitor has a resolution of 1920 by 1080, pixel pitch of 0.311mm, and a refresh rate of 120Hz. Viewing is performed in dim room illumination.

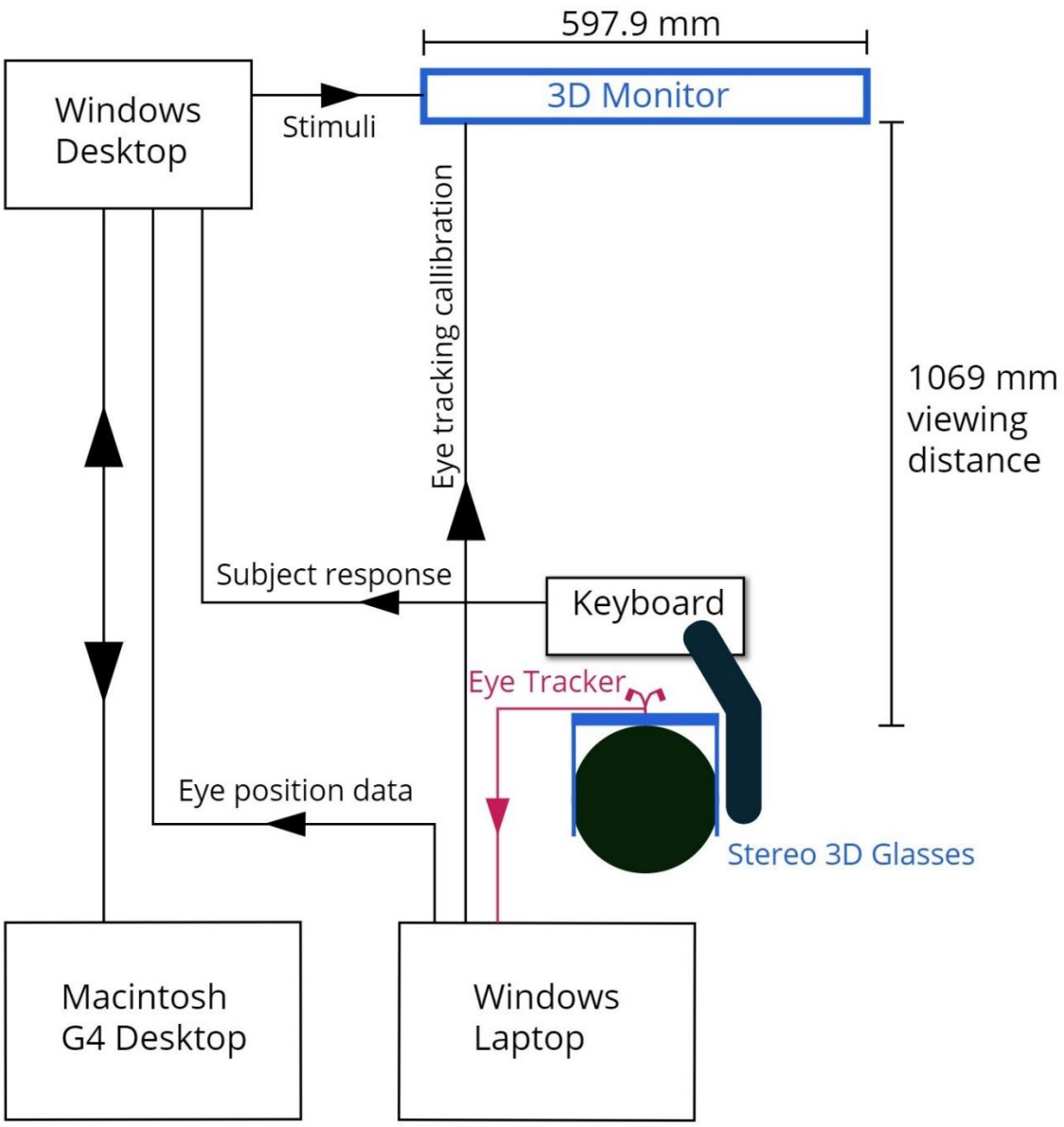


Figure 1: Schematic of apparatus setup (not to scale). The researcher controls the experimental protocol via the Macintosh. The subject views the 3D display wearing stereo shutter glasses fitted with eye tracking cameras and provides keyboard responses to the MATLAB program. Final experimental data is sent to the Macintosh computer.

Subjects

Students from the New England College of Optometry aged 18 to 35 years were recruited with the goal of a completed study population of 15 subjects. Candidates were screened for our inclusion criteria:

1. Normal ocular health (by subject report).
2. Normal general health (by subject report).
3. At least 20/20 visual acuity in each eye by emmetropia or corrected by contact lenses.
4. At least 40" stereoacuity measured by Borish Vectographic Nearpoint Card II™ contour clusters at 40cm.
5. Normal cover test and Von Graefe phorias (far: 2 EP to 3 XP; near: 2 EP to 8 XP).
6. Near point of convergence closer than 6cm from the nose.
7. Amplitude of accommodation meeting Hofstetter's minimum accommodation formula for age (Scheiman & Wick, 2015).

Subjects wore their full refractive contact lens correction (spectacle lenses tended to interfere with our eye tracking apparatus) during testing. Each subject was required to demonstrate an ability to fuse our vergence stimuli. Accepted subjects participated in three sessions: a 20-minute screening and two experimental sessions of 1.5 hours each.

16 subjects passed our screening criteria and participated in the first experimental session. All subjects scored better than 20" on the stereoacuity testing. One subject was unable to accurately track the vergence stimuli throughout their session and was discontinued from the study. Another subject that completed the full study provided unusable psychometric data (see

Figure 5B) and their results were not included in the final analysis. This left a final study population of 14 ethnically diverse subjects (7 males, 7 females) aged 22 to 32.

Stimuli

The stimuli are presented at 120 frames per second alternating between the eyes to produce stereoscopic depth. The blurred test stimuli are luminous 30’ width by 2° height bars of 50% contrast viewed against a uniform grey background of 14.5 cd/m^2 mean luminance. Blur is defined by the width of a half-cosine contrast envelope centered on each vertical bar edge. The blurred edges of test targets are set to 24’ while the blur of static comparison target edges is varied as needed, from trial to trial, for blur matching by way of a PEST adaptive staircase psychophysical method (below). For experiment #1 (moving test stimulus), the blurred test stimulus is presented either 70’ above or below the center fixation point for 250ms moving at the same binocular disparity velocity as the fixation cross and rings. The blur stimulus is presented as the eyes cross the screen surface to keep optical defocus from confounding our image blurs. For experiment #2 (stationary test stimulus), the blurred stimulus is presented either 70’ above or below the center fixation point for 250ms at the physical depth of the display screen.

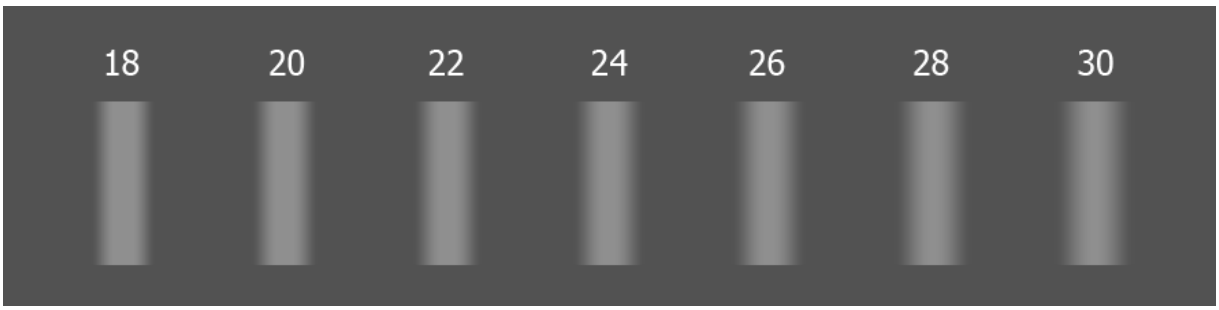


Figure 2: Blurred test bars labelled with the corresponding blur values in minutes of arc. Blur can be increased or decreased by increments of 2’ with a maximum of 30’ and minimum of 0’ (not pictured).

Subjects' fixation and vergence during trials are controlled by a 34' x 34' foveal fixation cross (when at screen depth) supported by three peripheral (7.6°, 8.4°, and 9.2° diameter at the screen depth) rings surrounding the cross. These vergence stimuli are programmed to change size according to their binocular disparity which produces a realistic looming effect that we found dramatically helps maintain fusion during trials stimulating more accurate vergence.

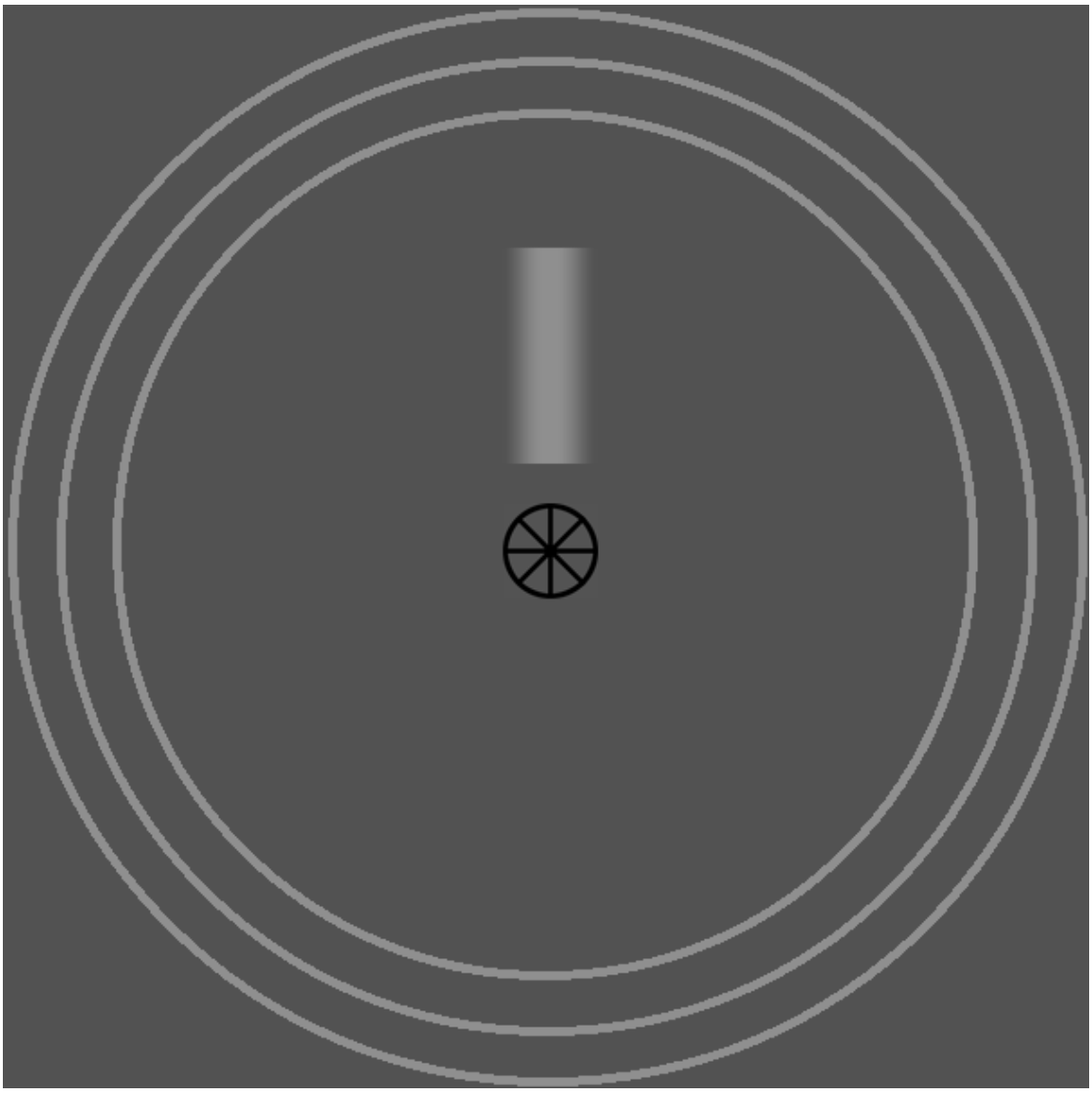


Figure 3: Fixation cross and peripheral rings (not to scale). Cross and rings change size according to stereoscopic depth. Blurred bar stimuli briefly appear 70' above or below the center of the fixation cross.

Experimental Design

Experimental and control trials are run for both experiments 1 and 2. The experimental trials measure the total motion sharpening occurring in each experiment while the control trials measure the amount of "sensory" sharpening caused by retinal image motion in the experiment. The motor sharpening in each experiment is defined as the difference between the total sharpening and the sensory sharpening. Each experiment utilizes four vergence stimulus conditions defined by direction and rate of vergence change: increasing disparity (convergence) or decreasing disparity (divergence), and 0.5°/sec or 1.5°/sec monocular target velocity (1°/sec and 3°/sec binocular) – a total of 4 conditions for each experiment.

In all conditions, a two-interval forced-choice matching method is used to measure the perceived blur of test targets. Each trial presents the test target interval (fixed 24' blur value) followed by the comparison target interval (variable blur value) in close temporal proximity. The blur of the comparison target is adjusted in 2' steps by a PEST psychophysical method to match the test target blur.

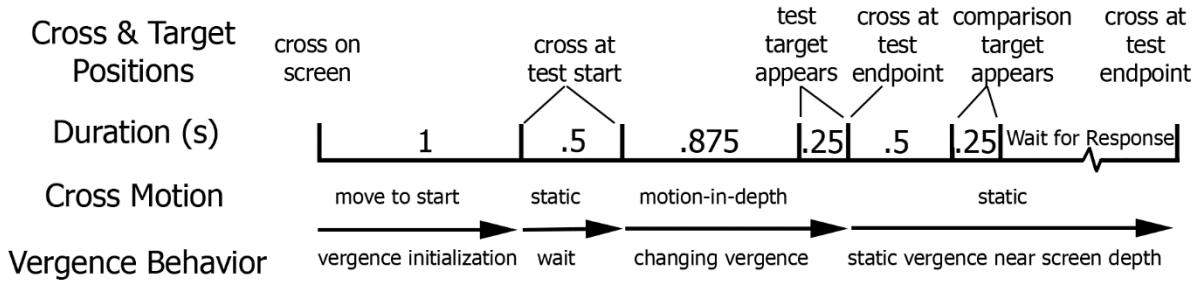


Figure 4. Timeline of a single two-interval forced-choice experimental trial. Control trials follow the same timeline but with static cross and vergence motion throughout.

The sequence of events in a single trial is depicted in Figure 4. The subject presses a key to start each trial. The test interval starts with the presentation of the fixation cross at its starting depth for one second, after which the fixation cross moves in depth at the condition's disparity rate for two seconds. The blurred test target is presented for 250ms in total – appearing 125ms before the target reaches the depth of the screen and disappearing 125ms after the target has passed the screen. Motion-in-depth stops immediately after the target presentation. The comparison target with blur selected by PEST is then presented for 250ms after a 500ms static interval. The subject then uses a keyboard to report whether the first or second target was perceived as sharper.

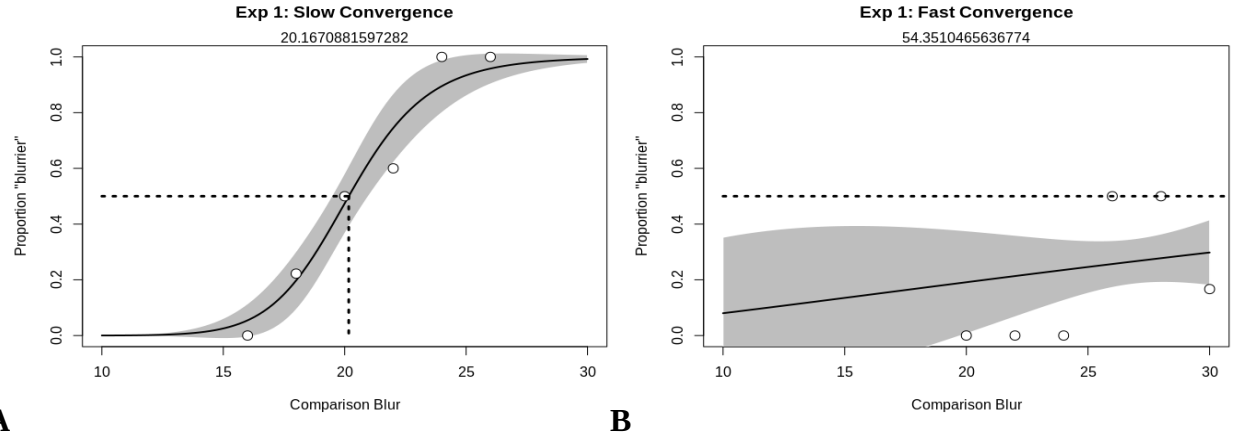
Subjects' vergence is monitored by eye tracking during both test and comparison intervals of each trial. Trials in which there is poor tracking, or the subject fails to maintain steady fixation of the stimulus are repeated. The eye tracker is calibrated with a 25-point calibration protocol before the experiment. Misalignment of the eye tracker during experiments is corrected by recalibrating the 25-point array position on the basis of its center point position, as needed, between trials. This Arrington Research method is termed a "slip correction". Frequency of recalibration was highly variable between subjects and depended on each subject's ability to maintain their head position throughout the session.

Control trials measure the sensory sharpening occurring in each of the 8 experimental conditions by recreating the mean retinal image motions caused by convergence/divergence-induced retinal image slip and using them as stereoscopic sensory sharpening stimuli during static fixation. The velocities of the control blur targets are the averaged retinal slip from 30 trials of each experimental condition. Subjects maintain static fixation on the same fixation stimuli used in the experimental conditions while the targets of constant 24' blur move in

stereoscopic depth at their calculated velocities. A 9th control condition of 0 velocity is used to measure bias toward the first or second interval in the absence of any motion sharpening. Steady fixation is verified by eye tracker monitoring. The timing of stimulus presentation is the same as in the experimental conditions except that the only motion is of the test target (Figure 4).

Analysis

Data analysis was performed using RStudio. Data for each 30-trial condition (both experimental and control) were fit to a logit psychometric function and plotted (Figure 5). The match blur for a condition is defined by the comparison blur value at the 50% response level.



A **B**

Figure 5. (A) Example of a psychometric curve fit for a 30-trial condition a typical subject. The y-axis represents the proportion of comparison blurs perceived as blurrier than the 24' test blurs. The vertical dotted line represents the "match blur" for the condition. (B) Example of unworkable data from the one subject that was removed from our final analysis. Even with the largest presentable blur amounts, the comparison blur was not reported to be blurrier in more than 50% of the trials.

Eye movement data during the stimulus presentation from each of the 8 experimental conditions were averaged and fit by linear regression. These average vergence velocities were subtracted from the corresponding velocities of the blur targets to calculate the average retinal slippage that occurred in each condition. The slippage velocities were used as velocity inputs for the control trials. The amount of sensory sharpening measured from each control condition (difference between match blur from 24') was subtracted from the match blur of the corresponding experimental condition to calculate the amount of motor sharpening. Comparison of total sharpening between velocities was performed by comparing the respective experimental match blur values. To visually illustrate motor sharpening in a directly comparable way to total sharpening, a "motor match blur" value was also calculated by subtracting the motor sharpening from 24 minutes of arc. This is the match blur value that would denote the amount of motor sharpening observed.

Experimental Match Blur (Total Sharpening)	**Control Match Blur**	**Motor Sharpening**	**Motor Match Blur**
18.89'	19.02'	0.13'	23.87'

Table 1. Example calculation of motor sharpening from experimental and control match blurs. Motor match blur values represent relative motor sharpening from the physical blur value of 24 arcmin.

Results:

Vergence Accuracy:

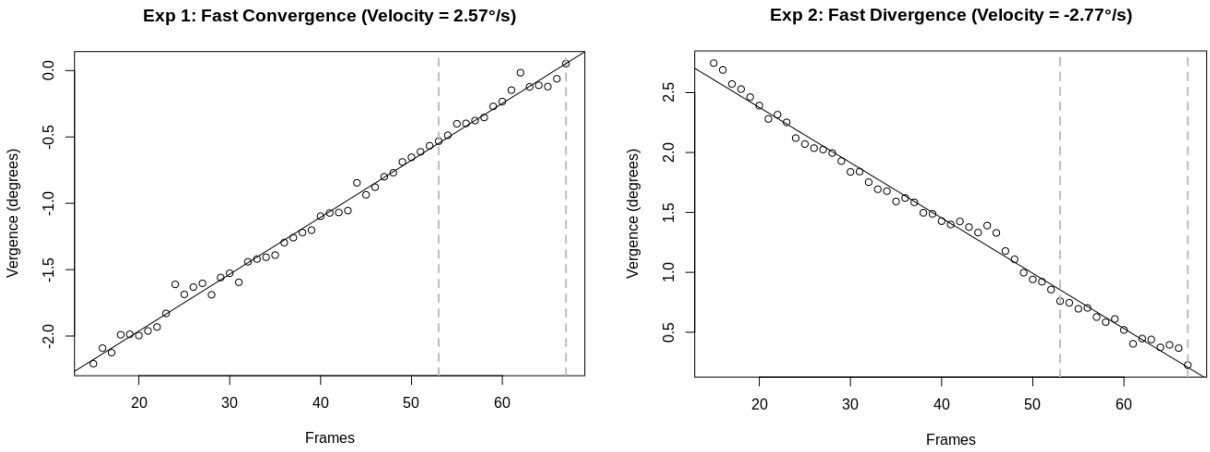


Figure 6. Plots of subject JRD's average convergence (left) and divergence (right) over time for two of the 3°/s conditions. Solid lines represent linear regressions of the data points. The x-axis represents the frames captured by our 60hz eye tracker (60 frames = 1s). The interval between the dotted vertical lines denotes the 250ms presentation of the test stimuli.

Motion-in-depth eye movements during accepted trials were found to be highly accurate and linear. Figure 6 plots JRD's average vergence over time. Our subjects' convergence was 0.096°/s (0.048°/s/eye) slower than the stimulus for the 1°/s condition, and 0.32°/s (0.16°/s/eye) slower for the 3°/s condition. Similarly, divergence was on average 0.11°/s (0.053°/s/eye) slower than the stimulus for 1°/s and 0.26°/s (0.13°/s/eye) for 3°/s. Our looming fixation stimuli were effective at inducing the desired vergence eye movements.

Effect of Vergence Velocity

		Sharpening (arcmin)	F-statistic	p-value (*<0.05)
Experiment 1	Total Sharpening	0.388	1.05	0.324
	Motor Sharpening	0.503	1.07	0.321
Experiment 2	Total Sharpening	2.21	16.8	* 0.00126
	Motor Sharpening	-0.697	2.81	0.117

Table 2: Within-subjects ANOVA using vergence velocity (0.5°/sec or 1.5°/sec) as the main effect. A positive sharpening value represents more sharpening with the faster velocity compared to slower.

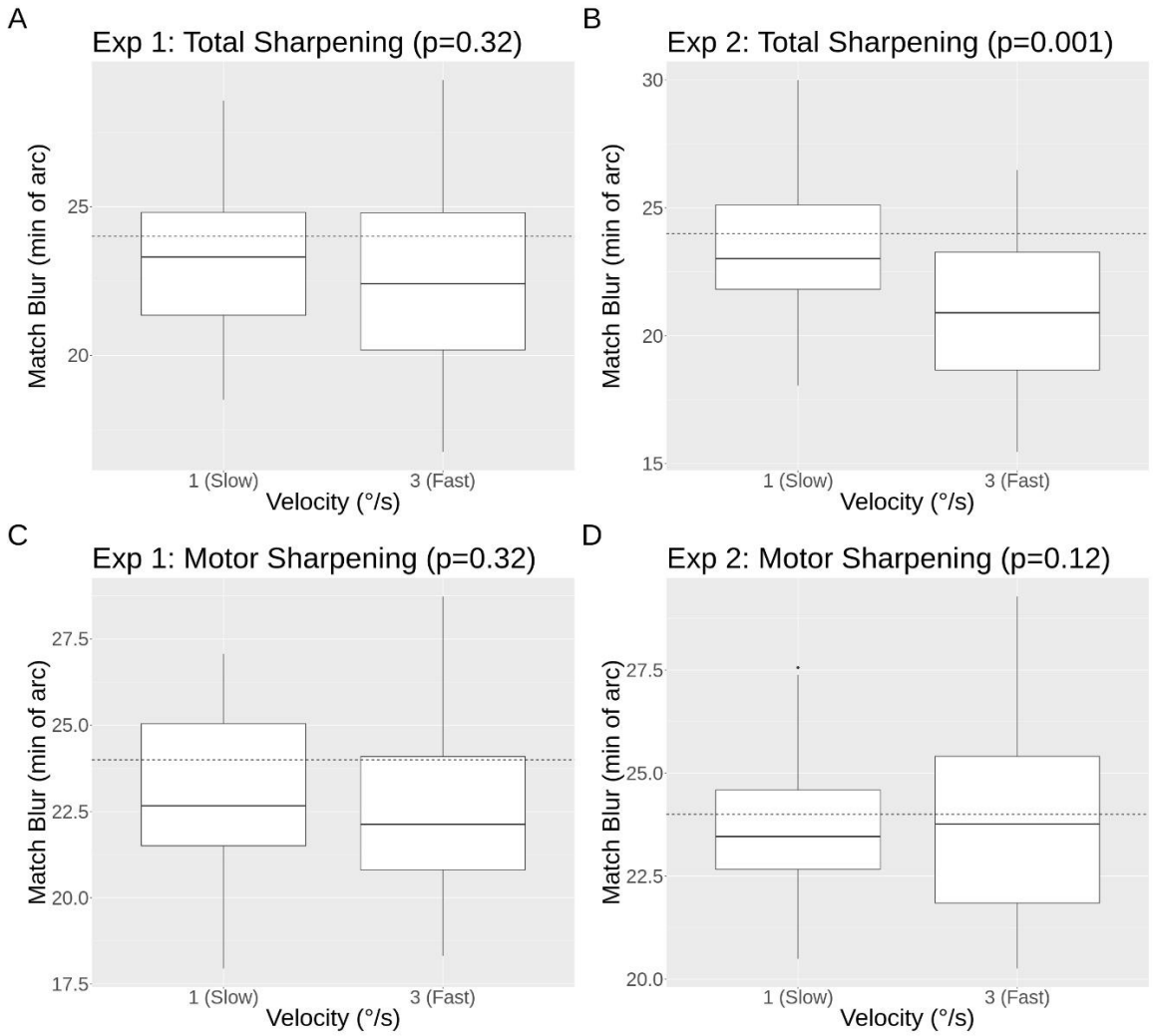


Figure 7. The effect of vergence velocity on match blurs in experiments 1 and 2 before (A, B) and after (C, D) correcting for retinal image motion. The horizontal dashed lines show the physical blur of the bar target – 24 arcmin. Boxplots represent the dataset quartiles.

It has been well-established that motion sharpening scales with speed (Bex 1995, Hammett 2003, Ferrucci 2018), thus any motion sharpening induced by vergence corollary discharge is expected to produce stronger effects during faster vergence eye movements. Within-subjects ANOVAs (Table 2) compared the amount of sharpening between 1°/s and 3°/s vergence

velocity in each experiment. An insignificant amount of both total and motor sharpening was found in experiment 1. This is consistent with the null hypothesis and does not support the existence of a corollary discharge component to motion sharpening.

Vergence velocity was found to have a highly significant (p=0.00126) effect on total sharpening in experiment 2. This was expected as the retinal motion stimulus for sensory sharpening was roughly equal to the speed of eye turn as the eyes pass over the targets. After controlling for retinal image motion (Figure 7D), the total sharpening effect disappeared, showing no evidence of motor sharpening.

Effect of Vergence Direction

	Convergence Match Blur	Divergence Match Blur	Directional Difference	F-statistic	p-value (*<0.05)
Experiment 1	22.52345	23.37185	0.848399	4.74	* 0.0485
Experiment 2	21.91595	22.78353	0.867579	6.57	* 0.0236

Table 3: Within-subjects ANOVA using vergence eye movement direction as the main effect. Match blur values (arcmin) are compared between convergence and divergence experimental trials irrespective of the velocity factor.

Within-subjects ANOVA (Table 3) indicates that our subjects perceived the blur stimuli as sharper during convergence eye movement trials than divergence trials, independent of velocity. This effect was statistically significant in both experiment 1 (p=0.0485) and experiment 2 (p=0.0236).

Discussion:

No Evidence of Extra-retinal Motion Sharpening

We suspected that corollary discharge during dysjugate eye movements produces perceived sharpening of physically blurred images. Such a mechanism would help explain the reduced motion smear observed during vergence conditions in Bedell et al. (2004). This study aimed to identify the existence of extra-retinal signals that produce motion sharpening.

Our looming fixation target successfully initiated smooth and accurate vergence eye movements in our subjects while tracking the through motion-in-depth. Analysis of our eye movement data revealed that convergence and divergence velocity was on average around 10% slower than the fixation cross velocity. This suggests that minimal retinal image slip was induced by our Experiment 1 protocol which presented the blurred test stimuli at the same stereoscopic velocity as fixation. For experiment 1, no significant difference in sharpness was found between the 1°/s and 3°/s conditions and thus no statistically significant motor sharpening was demonstrated. Correcting for the minimal amount of image slip using our control data, motor sharpening continued to be insignificant. Our findings from experiment 1 failed to provide any evidence that motion sharpening from vergence corollary discharge is responsible for the enhanced clear and single vision in 3D display viewing compared to clinical vergence testing.

Experiment 2 presented stationary blurred test stimuli at fixed depth. Vergence eye movements across the stimuli produced significant motion sharpening as expected. Our control experiment which presented stimuli moving through stereoscopic depth while the eyes steadily fixated showed that this sharpening was entirely attributable to the retinal image slip present in

these trials. No evidence of extra-retinal motion sharpening was found. This runs contrary to our initial suspicion that motor sharpening may have contributed to the effects observed in Bedell et al. (2004), the study that our experiment 2 replicated with several key differences. Bedell's study used a small luminous dot presented to the left eye only and their subjects were tasked with observing the length of motion smear. In contrast, our experiment used stereoscopic bars with blurred edges and our subjects judged the perceived sharpness of the edges. Motion sharpening, as described by Bex et al. (1995), specifically applies to physically blurred images and not the perceived blur of moving sharp images caused by the limited temporal processing speed of our visual system. The observations in Bedell's motion smear research (2004, 2005, 2010) fall under the latter category, and thus our findings ruling out motion sharpening via vergence corollary discharge do not conflict with his proposal that extra-retinal eye movement signals reduce perceived motion smear.

Significance of Vergence Direction

Our results (Table 3) consistently showed more change in match blur in convergence conditions compared to divergence. Previous studies of motion sharpening in stereoscopic motion-in-depth (McCormack 2014, Ferrucci 2018) found the direction of retinal stimulus motion on sharpening to be insignificant. This points toward an extra-retinal explanation but given that no extra-retinal motion sharpening was established in our study, it cannot be due to directional differences in our hypothesized mechanism.

We suspect that this unexpected finding was a product of the known vergence corollary discharge mechanisms of convergence micropsia and divergence macropsia. A stimulus of

constant visual angle appears to minify with increasing convergence and magnify with increasing divergence (Ross & Plug, 2002). During the early pilot trials for this experiment, SC and GM both observed that the test stimuli appeared to subtly decrease or increase in size while the eyes moved through depth. We identified these effects as potential confounds if motor sharpening was found to be significant. Our experiment shares many similarities to optometric clinical subjective refraction. Both use a two-interval forced choice procedure wherein the patient is asked to select the sharper version of two sequential presentations of a stimulus. Determining the correct refractive endpoint in non-presbyopes is often a challenge due to patients misinterpreting the minification of the visual acuity chart letters from excessive minus lens power as improved clarity or sharpness (Benjamin, 2006). Likewise, it is conceivable that our subjects misinterpreted minification during convergence trials as sharpness.

McCormack (2014) and Ferrucci (2018) did not encounter this phenomenon as their subjects maintained steady fixation at a constant depth. Although similar motion-in-depth vergence eye movements were used in Bedell et al. (2004), their results did not show a difference between vergence directions. We suspect that vergence micropsia was an undetected contaminant to the corollary discharge effects measured in their vergence trials. Our experiments utilized a two-interval forced choice response rather than a method of adjustment and was designed to detect differences in much smaller units of measurement. For any future studies involving both vergence eye movements and stereoscopic stimuli, vergence micropsia should be factored into the design and analysis.

Conclusions:

This study found no evidence to support the existence of motor sharpening. All motion sharpening effects observed could be explained by retinal image motion. Vergence micropsia during motion-in-depth pursuit at our tested velocities likely affects the judgement of stereoscopic stimulus sharpness when compared in a two-interval forced choice procedure due to the conflation of minification with clarity. Our implementation of realistically looming fixation targets was an effective method for helping untrained subjects maintain fusion during rapid vergence pursuit.

Appendix:

Design Choices and Pilot Trials

Our experiments underwent numerous design changes and iterations over its development. The incorporation of vergence eye movements for this study introduced several obstacles.

Optical blur during trials needed to be minimized in our study so as not to confound the perception of our physically blurred test stimuli. Our inclusion criteria selected for subjects with normal best-corrected visual acuity and accommodation, but their performance could be compromised by several factors. Vergence-induced errors in accommodation could conceivably

cause optical blur. We programmed the test stimulus to be presented ±125ms from when vergence is at the depth of the screen. Assuming that accommodation is accurate to the screen when fixation is at screen depth, then accommodation will only be in error for the 125ms before and after screen fixation. The accommodative error in diopters in our worst-case fast vergence condition is calculated by the equation:

$$Accommodative\ Error = Vergence\ Velocity \times Target\ Duration\ \times CA/C\ Ratio$$

$$= 3 \times\ 0.125\ \times 0.21\ (Hirani\ \&\ Firth, 2009)$$

$$= 0.08$$

This value of ±0.08D is well below the depth of focus, ±0.3D (Benjamin, 2006), as well as the normal and imperceptible accommodative lag in near vision, up to 0.75D (Benjamin, 2006). Thus, convergent accommodation was unlikely to induce noticeable blur in our protocol.

Ocular surface instability was another potential source of optical blur. The use of eye tracking in our experiment required contact lenses to be worn instead of spectacles. We found that our eye tracker could not reliably determine eye position through spectacle lenses as they obscured the first Purkinje images. Contact lens use is frequently implicated in ocular surface dryness which can cause intermittent blur. Furthermore, our subjects were required to keep their eyes held open during each trial presentation. The combination of these factors over a 1.5-hour long experiment was likely have some effects on clarity and comfort. Our design attempted to minimize these effects by avoided this by allowing the subject to control trial initiation, allotting as needed time for blinking and rest between trials. Subjects were also instructed to alert us immediately if they felt that their optical clarity was compromised during any trial so that it could be discarded and repeated.

Interval bias was a difficult confound to remove as subjects will always be aware of their eye movements during the experimental interval versus the steady fixation of the comparison interval. Early pilot trials randomized the order of the experimental and comparison intervals. This resulted in long trial durations and long intervals between test stimuli presentation. By only presenting the experimental interval first and trimming unnecessary motion-in-depth sequences, we were able to reduce the trial duration from 7s to just 3.375s each. We attempted to control for interval bias caused by this non-random presentation order by including an additional 9th condition to our control experiment that presented the same test stimulus in both intervals. We did not use the interval bias control data in our final analysis because the value cancels itself out arithmetically when applied to both experimental and control conditions. This does however, mean that we could not measure the absolute sharpening effects of each condition.

In our early pilot trials, the test stimuli could not be presented to the foveal centers as their sudden appearance disrupted the motion-in-depth tracking of the fixation cross. By placing the test target just above or below the fixation cross, their onset did not perturb vergence and subjects could maintain a constant tracking velocity. Randomized placement of the test target above or below fixation discouraged anticipation and attempted fixation of the test target.

Our fixation stimuli originally changed in binocular disparity only. Our pilot trials found that of the seven normally binocular subjects recruited, only two were able to maintain fusion when the target moved at 4°/s (2°/s/eye). This problem was not encountered in Bedell et al. (2004) which used the same rate of vergence change, however the experiment was conducted on the authors themselves who are expected to have more training and experience with following these stimuli. Our solution was to add a looming effect to the fixation cross and rings as they changed in binocular disparity. The fixation stimuli were programmed to increase or decrease in

image size congruently with the level of stereoscopic depth. The image size at any given binocular disparity was calculated by assuming an average pupillary distance of 60mm and 1069mm viewing distance to the screen. When performing these calculations, we realized that at 4°/s, the endpoint of divergence would be beyond infinity with a size smaller than a pixel. Conversely, in convergence the ring size would have exceeded the height of the display. We reduced the fast condition speed from 4°/s to 3°/s. This along with the looming effect resulted in 3 out of 5 pilot subjects and 15 out of 16 study subjects being able to track our fixation stimuli smoothly and accurately in all conditions.

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