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What is dynamic visual acuity

Timothy C. Hain, MD • March 7, 2021 The VOR (vestibulo-ocular reflex) gain is most helpful for diagnosing ototoxicity and other bilateral vestibulopathies. There are several methods of quantifying it at the bedside. The Dynamic illegible 'E' test or DIE is a very helpful procedure (Longridge, 1987). One has a patient view a eye chart similar to that shown below with the head still. This measures visual acuity with the head in motion. Eye charts can be downloaded from the web here: . Persons with substantial function of their vestibular system have no loss in visual acuity with this procedure. Even persons with unilateral loss -- i.e. having lost 50% of their vestibular system -- will generally score normally. Rigorous psychophysical techniques can detect and lateral loss (Fian et al., 2001), but practically there are easier ways to detect unilateral loss (such as caloric testing). Patients with bilateral vestibular loss, especially acutely, often lose 6-8 lines of visual acuity. Vertical movement is not as sensitive or specific as the horizontal test (Schubert et al, 2002). As patients recover from bilateral loss, they perform better on this test. This is probably related to a combination of adaptive changes in the vestibuloocular reflex as well as predictive pre-programming of eye movements (Herdman et al, 2001). Figure 1: Eye chart similar to this can be downloaded from the web. We also have designed a similar eye chart that we think is superior that can be downloaded (see below). LogMar DIE testing The Snellen charts, which are designed to measure visual acuity, are not all that well suited to measure visual acuity, especially when quantified as "lines" of visual acuity, are not all that well suited to measure visual acuity. visual acuity, which might not matter, but would destroy the comparability of the DIE test done with a different chart. The Snellen chart is also designed (roughly) so that 3 lines is equivalent to a factor of 2 loss in visual acuity (i.e. 0.3 LogMar, or equivalently 6 dB). However, this doesn't always work, probably because the numbers of the Snellen chart generally are multiples of 10 feet -- this simplicity would be lost if the numbers scaled logarithmically. The graph below of LogMar is an acronym for the base-10 logarithm of the minimum angle of resolution. It is simply the log-10 of the inverse visual acuity (e.g. 20/20). Because 20/20=1, normal is a LogMar of 0. 20/200 corresponds to a LogMar of 1 (log of 10), so most of the eye chart can be expressed by LogMar's between from 0-1. The equivalence table between Snellen lines and LogMar (calculated using a simple Excel spreadsheet) is given below: Snellen Line Acuity LogMar 8 20/20 0 7 20/25 0.097 6 20/30 0.176 5 20/40 0.301 4 20/50 0.398 3 20/70 0.544 2 20/100 0.699 1 20/200 1 We have designed an eye chart more suitable for DIE testing, shown below. This chart uses Snellen Optotypes, it is sized for 10 ft viewing, and has LogMar values (times 10) shown on the right. This chart is used by simply recording the 10*LogMar value that a person can see with the head still, the value that a person can see with the head still the he conventional Snellen type chart is that the visual acuity differences are not affected by viewing distance or other conditions that affect visual acuity. Changing viewing distance will of course make the visual acuity measurements wrong, but because it simply adds an offset to the Logmar value, it will not (theoretically anyway), affect the visual acuity difference. This characteristic arises intentionally because the Logmar values are now accurate. We have used 10*LogMar, to make the numbers go in the opposite direction -- 1.0 on a conventional Snellen Chart is 20/200 vision, while on this chart, 10 is 10/100 (or 20/200). For this chart, if the viewing distance is different than it was designed for (lets say, 20 feet instead of 10), the visual acuities will actually be 20/100 rather than 10/100, and simply a factor of 2 different. This means that the LogMar values on this chart should be adjusted by subtracting 10 x log of 2 = (10 * 0.301), or simply 3. In general, the adjustment is: 10*Logmar = Measured 10*Logmar not be correct. References Herdman SJ and others. Role of central preprogramming in dynamic visual acuity with vestibular loss. Arch Oto HNS 2001:127:1205-1210 Longridge NS, Mallinson AI. The dynamic visual acuity with vestibular pathology. J Otolaryngol 1987;16:97-103, Acta Otol (Stockh) 103: 273-279, 1987; Otolarygol HNS 1984:92:671-7 Schubert MC, Herdman SJ, Tusa RJ. Vertical dynamic visual acuity in normal subjects and patients with vestibular hypofunction. Otol and Neurotol 23:373-377, 2002 Tian JR, Shubayev I, Demer JL. Dynamic visual acuity during yaw rotation in normal and unilaterally vestibulopathic humans. Annals NYAS Vol 942, 501-504, 2001 Thomson D. VA testing in optometric practice. Part 2: Newer chart designs. Optometry Today: 22-24, 06/05/05 [Skip to Navigation] This website uses cookies and how you can disable them visit our Privacy and Cookie Policy. Got it, thanks! Open Access Peer-reviewed Dynamic visual acuity (DVA) is the ability to resolve fine spatial detail in dynamic objects during head fixation, or in static objects during head or body rotation. This ability is important for many activities such as ball sports, and a close relation has been shown between DVA and sports expertise. DVA tasks involve eye movements, yet, it is unclear which aspects of eye movements contribute to successful performance. Here we examined the relation between DVA and the kinematics of smooth pursuit and saccadic eye movements in a cohort of 23 varsity baseball players. In a computerized dynamic-object DVA test, observers reported the location of the gap in a small Landolt-C ring moving at various speeds while eye movements were recorded. Smooth pursuit kinematics—eye latency, acceleration, velocity gain, position error—and the direction and amplitude of saccadic eye movements were linked to perceptual performance. Results reveal that distinct eye movement patterns—minimizing eye position error, tracking smoothly, and inhibiting reverse saccades—were related to dynamic visual acuity. The close link between eye movement quality and DVA performance has important implications for the development of perceptual training programs to improve DVA. Citation: Palidis DJ, Wyder-Hodge PA, Fooken J, Spering M (2017) Distinct eye movement patterns enhance dynamic visual acuity. PLoS ONE 12(2): e0172061. Nicholas Seow Chiang Price, Monash University, AUSTRALIAReceived: October 21, 2016; Accepted: January 30, 2017; Published: February 10, 2017Copyright: © 2017 Palidis et al. This is an open access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited. Data Available under the following link: This study was supported by a Discovery Grant from the Natural Sciences and Engineering Research Council Canada (NSERC RGPIN 418493) and Canada Foundation for Innovation (CFI) John R. Evans Leaders Fund to MS. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript. Competing interests: The authors have declared that no competing interests exist. Dynamic visual acuity (DVA) is the ability to resolve fine spatial detail in an object that moves relative to the observer. It is critical for sports performance involving visuo-motor action with fast moving objects. In baseball, for example, a batter must extract information about the moving ball's motion angle, speed and spin. A close relation has been shown between DVA and level of expertise in various ball sports such as baseball, basketball, volleyball, table tennis, seccer and water polo [1-9]. These studies show that athletes outperform non-athletes, and that experts exhibit better DVA than novices. Baseball players also show superior static visual acuity [10]. However, it is unclear which factors lead to such DVA advantages. DVA is typically tested in two different ways: by asking observers to identify or judge dynamic objects while their head is fixed ("dynamic-object DVA"), or static objects while their head or body moves ("static-object DVA"). DVA"). A classic test of dynamic-object DVA involves reporting the location of a small opening in a moving "Landolt-C" ring (see Fig 1a). This type of task measures minimum resolvable acuity, i.e., the ability to separate two features in space. It requires a combination of different types of eye and head movements to stabilize the image of interest close to the fovea, the small area on each eye's retina where photoreceptor density and visual acuity are maximal [11,12]. Smooth pursuit eye movements aim to match the speed of gaze with that of small, moving visual angle per second. At higher target speeds, when gaze lags behind the target, the eyes use fast catch-up saccades to compensate for position and velocity errors [13]. A classic static-object test involves recognizing stationary letters or numbers on a visual acuity chart while the observer's head is being rotated. This test is widely used clinically [14] and requires use of the vestibulo-ocular reflex (VOR), an eye movement induced by activation of the vestibular system. The VOR compensates for head rotation to keep stationary objects of interest close to the fovea. Download: PowerPoint slide larger image original image Fig 1. Experimental timeline and set-up.A. Trial timeline of computer-based DVA test. Each trial starts with peripheral fixation, followed by step-ramp stimulus motion; target is a Landolt-C ring. Observers performed a judgment about the location of the gap in the "C" (one of 4 locations) at the end of each trial via button press. B. Set-up for computerized dynamic-object DVA test and eye tracking. C. Set-up for clinical static-object DVA test. movements and visual perception are closely related [15,16]. We reason that superior DVA could be attributed to better eye movement control. For example, more effective smooth pursuit enables the viewer to keep a moving object closer to the fovea, thus reducing motion blur [17,18], and pursuit enhances motion prediction [19,20]. In general, image position relative to the fovea and retinal image motion—two factors modulated by pursuit—predict DVA [21,22]. Indeed, recent studies in baseball players have linked better dynamic-object DVA to eye movements [7,8]. However, these studies did not investigate detailed pursuit kinematics or catch-up saccade properties in relation to DVA. Catch-up saccades seem an important factor, given that the speeds of most balls in sports are too high to be tracked smoothly. It is thus unknown which aspects of the eye movement patterns that relate to DVA performance. The current study also compares performance in a staticobject and dynamic-object DVA test to assess the relation between both types of tasks. Participants were 23 males (mean age 19.5 yrs, SD = 1.2), members of the varsity baseball team at the University of British Columbia (UBC), Vancouver, Canada. The research described here was conducted according to the principles expressed in the Declaration of Helsinki, and the UBC Behavioral Research Ethics Board approved experimental protocols. All participants gave written informed consent prior to participants had normal or corrected-to-normal visual acuity; those with refractive errors wore their regular glasses or contact lenses during the study. Normal visual acuity was confirmed using the ETDRS visual acuity chart at 4-meter test distance (Original Series Chart "R", Precision Vision, La Salle, IL, USA). Average visual acuity was 20/15 and observers' acuity ranged from 20/35 to 20/12.5 monocularly, and 20/20 to 20/10 binocularly. We developed a computer-based dynamic-object DVA task in which stimuli were black Landolt-C rings (Fig 1a; luminance 1.1 candela per square meter; cd/m2), with a gap in one of four locations, either top right (as shown in Fig 1a), top left, bottom left, or bottom right. Stimulus diameter was 0.40 deg, gap size varied between 1-8 pixels from trial to trial. In each trial, the target moved horizontally to the left or to the right at a constant speed of 50 or 70 degrees per second (deg/s). Target motion direction was randomized from trial to trial. The fixation target was a black cross of 0.40 deg diameter presented 5 deg to the left or right of screen centre. Stimuli were presented on a white background with a luminance of 107 cd/m2. Participants were seated in front of a computer monitor (Fig 1b; 18-inch CRT, 40.6×30.5 cm, 1600×1200 pixels, refresh 85 Hz; ViewSonic, Walnut, CA, USA) at a viewing distance of 71.5 cm. With this setup, 1 pixel is equivalent to 0.0204 degrees of visual angle. Stimulus display and data collection were controlled by a PC (NVIDIA GeForce GT 430 graphics card) and the experiment was programmed in Matlab 7.8 (The MathWorks Inc., Natick, MA, USA) using Psychtoolbox 3.0.8 [23]. A combined chin- and forehead rest stabilized participants' head. Each trial started with a fixation cross (Fig 1a), and observers were instructed to keep their eyes on the cross until the moving target appeared. To prevent anticipatory eye movements, the fixation cross was displayed for a variable time interval (500-1000 ms). Target motion began simultaneously with the offset of the cross. We used a "step-ramp task"-a paradigm widely employed in laboratory pursuit studies [24]. Because smooth pursuit typically occurs with a latency of 100-150 ms in humans, the sudden appearance of a moving target would cause the eye to jump (saccade) to the target and then track it smoothly. In order to produce a smooth onset of pursuit, the target (a closed circle) initially jumped away from fixation (step) and then moved back towards the fovea, akin to the path of a baseball in the pitcher's hand. The target reached the fovea after 120 ms, just in time for the eye to start tracking it, and changed from a closed circle to an open Landolt-C ring (Fig 1a). It then continued to move at a constant speed for 255 ms. Observers were instructed to track the Landolt-C ring with their eyes as soon as it appeared, and to report the location of the gap by pressing one of four buttons on the computer keyboard corresponding to the four possible gap locations (4-alternative forced choice procedure; 25% chance of guessing correctly). To assess DVA, we manipulated the size of the Landolt-C's gap in each trial in a procedure that was adaptive to each individual's performance ("staircase" procedure). In the first trial, the gap width was set to 7 pixels to make the gap easily visible to each observer. In subsequent trials, the gap width was reduced if observers gave a correct response three times in a row, and increased if observers made a mistake (1-up-3-down adaptive procedure; [25]). Gap width was modulated in 2-pixel increments until the first reversal point (going from "correct" to "incorrect" or vice versa), and in 1-pixel increments until the first reversal point (going from "correct" to "incorrect" or vice versa), and in 1-pixel increments until the first reversal point (going from "correct" to "incorrect" or vice versa), and in 1-pixel increments until the first reversal point (going from "correct" to "incorrect" or vice versa), and in 1-pixel increments until the first reversal point (going from "correct" to "incorrect" or vice versa). pixel increments thereafter. Separate staircases were run for the two speed conditions with conditions randomly interleaved in blocks of 80 trials maximum of 30 minutes. Perceptual thresholds were then determined for each staircase as the mean gap width at all reversal points, excluding the first reversal. Following computerized assessment of dynamic-object DVA, we next used a standard clinical test to measure static-object DVA. Observers were seated in a chair with the experimenter standing behind them and viewed a visual-acuity pocket eye chart (Rosenbaum pocket vision screener; Prestige Medical Inc., Northridge, CA) positioned in front of them at a distance of 35 cm. Participants were instructed to read aloud the numbers on the acuity chart from top (large font; 20/800 vision) to bottom (small font, 20/20 vision) during head rotation. This is a well-established procedure frequently used in clinical settings. To reduce variability we introduced additional experimenter control over the task by having the experimenter actively rotate the observer's head gently to the beat of a metronome (120 beats per minute; Fig 1c). Static visual acuity (ETDRS chart) and static-object DVA (Rosenbaum chart) were recorded as Snellen acuity and converted to degrees of visual angle following conversion tables [26]. Normal vision, i.e., 20/20 Snellen acuity, corresponds to a LogMAR score of 0, equivalent to 1 MAR or 0.0167 degrees. To calculate the acuity of observers who resolved all but one or two of the symbols on their last attempted line of the ETDRS or Rosenbaum visual acuity charts, each letter missed was weighted as a fraction of the numbers or letters on that line. For example, the ETDRS chart has five letters per line. If the observer resolved all letters on the line corresponding to 20/20 Snellen acuity (0.0167 degrees), then that observer would be evaluated as being able to resolve a visual angle of 0.0175 degrees ([(0.0208-0.0167)/5] + 0.0167). During computer-based testing, position of the right eye was recorded with a desktop-mounted video-based eye tracker (Fig 1b; Eyelink 1000 Desktop Mount; SR Research Ltd., Ottawa, ON, Canada) and sampled at 1000 Hz, i.e., yielding one sample of eye position data per millisecond. Eye movements were analyzed off-line using custom-made routines in Matlab [19]. Eye position, velocity, and acceleration profiles were filtered (smoothed) and saccades were detected when three consecutive samples exceeded a fixed velocity criterion of 75 deg/s. Saccade on- and offsets were detected when three consecutive samples exceeded a fixed velocity criterion of 75 deg/s. Saccade on- and offsets were detected when three consecutive samples exceeded a fixed velocity criterion of 75 deg/s. the acceleration occurring before and after the samples exceeding the velocity criterion, respectively. Visual inspection was used to verify saccade detection in the closest acceleration minimum and maximum, respectively, manual correct for small detection errors. We then segmented the remaining eye movement traces into fixation and smooth pursuit based on the eye trajectory's angular dispersion, using directional statistics to determine whether the eye movement parameters as indicators of observers' eye movement quality: (a) Smooth pursuit latency, the temporal differences between DVA target onset and onset of the smooth pursuit onset in which tracking was initiated between 100 ms after stimulus onset (to exclude trials with anticipatory pursuit) to stimulus offset. (b) Smooth pursuit eye position error, the absolute difference between the horizontal position of the eye and the stimulus, computed for the time period between DVA target onset and offset, during the non-saccadic portion of the trace. (c) We also calculated the minimum position error occurring in this time interval as indicator of the closest distance to the target achieved by the eye. (d) Smooth pursuit gain, the saccade or smooth pursuit onset. (e) Cumulative saccade amplitude, the sum of the amplitude of all saccades that occurred between target onset and offset. (f) Direction of the first saccade, specifically, the proportion of the stimulus stepped away from the fixation position and then moved back towards it for the first 120 ms before passing it (the pre-ramp period), subjects could employ two distinct strategies: they could either initiate tracking in the direction of stimulus motion, using the pre-ramp period), subjects could employ two distinct strategies: they could either initiate tracking in the direction of stimulus motion, using the pre-ramp period to offset the cost of eye movement latency and initiate a saccade in the opposite direction of stimulus motion in an attempt to intercept the stimulus before it reached the fixation position. We excluded trials from further analysis when data were lost due to blinks during stimulus presentation or lost signal from the eye tracker (82 trials total; approx. 3.5% across all subjects and conditions). Observers for whom we were unable to obtain clear cornea reflection due to reflections off their eye glasses or contact lenses were not included in the eye movement analysis (subjects #8 and #57), yielding usable eye movement data sets from 21 observers. Main effects of baseball playing experience, we added seniority as a between-subjects factor; n = 11 were junior (freshmen, yr 1) and n = 12 were senior players (yrs 2-4). To investigate the link between eye movement quality and DVA, we used correlational analyses, reporting bivariate correlation coefficients and results of two-sided significance testing at a level of α = 0.05. For all tests we report effect sizes, either r, η2, or Cohen's d. All statistical analyses were conducted in IBM SPSS Statistics Version 24 (Armonk, NY, USA). The main purpose of this study was to link individual eye movement kinematics to DVA performance. We will report results in three steps: first, we will describe perceptual DVA and relate dynamic-object DVA to static visual acuity and clinical-type static-object DVA. These results are shown separately for junior and senior players, because effects of expertise have been reported throughout the literature. Second, we will describe oculomotor performance in our computerized dynamic-object DVA paradigm. Third, we will identify eye movement characteristics that are related to dynamic-object DVA. Seniority was not a significant factor driving eye movement kinematics, and these results were thus averaged across all players. Fig 2a shows proportion of correct trials as a function of gap size for two speeds in the computer-based DVA task. We found significantly better performance for slower than for faster speeds with average thresholds at 1.95 and 2.31 pixels, respectively, corresponding to .040 and .047 degrees of visual angle (main effect of speed, F(1,21) = 8.80, p = .007, $\eta = .30$). Senior players—team members with >1 year collegiate experience—had lower thresholds (.037 for slow and .044 for fast) than junior players (.043 and .050, respectively; compare solid and dashed lines in Fig 2a). However, thresholds were not significantly different (no main effect of between-subjects factor seniority, F(1,21) = 2.43, p = .13, η2 = .14). For both speeds and both groups, performance rose quickly going from near chance at 1 pixel gap size to >80% correct at 2 pixels. Performance saturated to near perfect at 4 pixels for the slow speed and 5 pixels for the fast speed, indicating low rates of attentional lapse. Download: PowerPoint slide larger image Fig 2. Perceptual acuity results. A. Proportion correct in dynamic visual acuity task as a function of gap size for n = 23 observers; n = 11 were junior players (open symbols) and n = 12 were senior players (filled symbols). Speed is denoted by color, seniority by line type; error bars are standard errors of the mean. B. Relation between static visual acuity (binocular ETDRS) and dynamic-object DVA in degrees of visual angle. participants completed standard visual acuity at slow target speed (r = .40, p = .05; Fig 2b), but not at fast speed (r = .20, p = .36). This finding indicates that visual acuity might contribute to slow-target DVA, but might not limit perceptual performance in response to fast targets. We assessed DVA in two ways—during head fixation vs. clinical examination of DVA with static objects during head rotation (Fig 2c), indicating that both tests assess different types of eye movements they require. Similar to dynamic-objects DVA, in accordance with the different types of eye movements they require. Similar to dynamic-objects DVA, seniority also had no effect on static-object DVA (independent-samples t-test, t(21) < 1, n.s.). To address the question what determines DVA performance across speeds, we next assessed smooth pursuit responses to DVA targets. Fig 3 shows representative eye position and velocity traces in response to faster stimulus motion and reveals different eye movement patterns. In some trials, observers were able to lock their eyes onto the target promptly after it reached the fovea, or even before and to then track it smoothly (Fig 3a). However, the eye did not reach target by making a large saccade (Fig 3b). In other trials, after a brief period of smooth pursuit, observers, we found that players tried to intercept the target early by making a saccade in the opposite direction of stimulus motion (reverse saccade) before changing the direction of eye movement (Fig 3e and 3f). This pattern occurred frequently even though the step-ramp stimulus design was employed to facilitate smooth pursuit initiation in the direction of the target. The use of reverse saccades was suboptimal and often resulted in less effective tracking, i.e., no pursuit or delayed pur obtained from representative observer #16. Dotted red line denotes target trajectory: peripheral fixation at 5 deg from screen center, target step, target ramp onset. Horizontal eye position in black, vertical eye position in blue. Smooth components marked in green, saccades marked in magenta. A,B. Trial with smooth pursuit (green) following target onset. C,D. Trial with a large, early catch-up saccade (magenta) following target motion. with perceptual results, smooth pursuit eye movements were faster, smoother, and more accurate when tracking slow as compared to fast target motion. However, pursuit onset, minimum position error, and reverse saccades were unaffected by speed (Table 1). We found no main effect of seniority on any of the pursuit measures (all p > .17), but junior players made reverse saccades in almost twice as many trials (42%, SD = 23.3) as compared to senior players (23%, SD = 16.6). When analyzed separately by speed, this difference was significant for fast speed (t(19) = 2.05, p = .05, d = .89). To identify which aspects of eye movement kinematics were related to perceptual performance, we correlated eye movement metrics—latency, velocity gain, absolute and minimum position errors, cumulative saccade amplitude, and proportion of trials with a reverse saccade—with perceptual thresholds on an individual observer basis. At slow target speed, there was no relation between any of the eye movement metrics and perceptual performance (Fig 4). However, at fast target speed, where eye movements are likely a limiting factor to performance—humans cannot usually track targets moving at 70 deg/s smoothly—we found a strong relation between all metrics and DVA, except latency (Fig 4a). Better perceptual performance, i.e., a lower DVA threshold, was associated with a smaller minimum eye position error (Fig 4c). Thus, observers who were better able to center their gaze on the target at any time during the trial were better able to resolve fine spatial detail. Reverse saccades, likely made to intercept the target before it reached fixation (see Fig 3e and 3f), showed the strongest relation with perceptual performance (Fig 4e): a higher proportion of trials with reverse saccades was associated with higher DVA thresholds. Similarly, subjects who covered more overall distance with saccades performed more poorly in the perceptual task (Fig 4d). This relationship might be mediated by reverse saccades, associated with poor DVA, and causing an increase in cumulative saccade amplitude. In support of this interpretation, the proportion of reverse saccades was highly correlated with cumulative saccade amplitude (r = .67, p < .001). The partial correlated with cumulative saccade amplitude and DVA was non-significant when controlling for proportion of reverse saccades (r = -.07, p = .79). In conjunction with the finding that senior players made fewer reverse saccades than junior players this result indicates that athletic experience might be linked to the use of more effective oculomotor control decisions. In this particular task, with the chosen target speeds, an effective oculomotor strategy is characterized by an efficient and accurate use of saccades in the direction of the pursuit target. Download: PowerPoint slide larger image original image Fig 4. Correlations between perceptual DVA thresholds and eye movement data. Each data point is one observer in a given category; speed is denoted by color. Lines denote best linear fits. A. Eye velocity gain. C. Minimum position error (deg). D. Cumulative saccade amplitude (deg). E. Proportion of trials with reverse saccade. better perceptual performance was related to a lower eye velocity gain at fast target speed (Fig 4b), confirmed by a significant positive correlation between gain and DVA threshold (r = .52, p = .02), i.e., high gain is associated with a high DVA threshold and thus with poor performance in this task. This finding indicates that observers who attempted to match the speed of their eye movement to that of the target by using smooth eye movements alone performed more poorly. In line with this result, we found a highly significant positive correlation between gain and minimum position error. Indeed, the relation between gain and DVA is no longer significant when controlling for minimum position error (r = .24, p = .32). Overall, the correlations between perceptual performance and eye movement metrics indicate a stronger relation between perceptual performance and eye movement metrics indicate a stronger relation between DVA and saccade parameters—reverse saccades, cumulative saccade amplitude and minimum position error, which can be achieved by making a saccade—than with parameters reflecting high-quality smooth tracking. This study shows that dynamic visual acuity is related to two distinct eye movement metrics: minimum position error corresponds to how well gaze is aligned with a moving object of interest, such as a baseball. The occurrence of reverse saccades likely reflects a failure to produce or learn optimal saccade control. We also found that static visual acuity was only related to dynamic-object DVA at slow speed, indicating that DVA performance at fast speed is not constrained by visual acuity alone. Static-object DVA and dynamic-object DVA were unrelated and can thus be considered tasks that measure different aspects of DVA. Previous studies investigating DVA consistently report large effects of expertise. Our study did not reveal such differences between junior and senior baseball players. The cohort of varsity athletes tested here might have been more homogenous than cohorts of athletes and non-athletes, or experienced and naïve athletes that have been compared in previous studies [1-9]. Our study identifies specific eye movement metrics as potential predictors of DVA. Previous studies have not quantitatively differentiated the role of different types of eye movements, particularly smooth pursuit and saccades, in their contribution to DVA. This is surprising, given the importance of these types of eye movements in ball tracking in the real world [27,28] or in a virtual-reality sports setting [29]. Uchida et al. compared DVA when observers were allowed to track the target with their eyes vs. when they were asked to fixate [7]. Baseball athletes performed better than non-athletes in the free eye movement condition but not during fixation, indicating that superior DVA in athletes to eye movements with shorter latency, higher peak velocity, and lower minimum position error [8]. However, the stimulus velocities in this study were beyond the limits of human smooth pursuit. Their paradigm did not involve a step-ramp procedure to smoothly initiate pursuit, and participants likely used saccades to reduce the initially accumulating position error, thereby matching eye velocity to stimulus velocities and employed a step-ramp procedure to initiate pursuit. Interestingly, high smooth pursuit velocity gain in our study was associated with poorer perceptual performance at fast target speed, indicating that observers who attempted to match the speed of their eye movement to that of the target, using smooth pursuit gain and low minimum position error, which was supported by a positive correlation between the two metrics at high target velocity to h In general, high velocity gain is necessary to match target speed and to reduce motion blur [17,18]. High-quality pursuit is also beneficial for tasks in which observers with targets moving at high speeds along a predictable trajectory. Observers had to discriminate the location of a small target feature, requiring the matching the eyes to that of the eyes to the eye catch-up saccade, there is a brief moment of low position error and low retinal slip, during which the target could be perceived at high acuity. Because this occurs during the trajectory of a saccade, it is not reflected in our measure of smooth pursuit gain. This saccadic strategy likely also underlies the findings reported by Uchida et al. [8], although their stimulus velocities made smooth pursuit impossible, while in our paradigm pursuit was often achieved but possibly not effective. Overall, it seems that the use of high-gain smooth pursuit is less critical to DVA (see Fig 4b) than minimizing position error (Fig 4c), especially if this is achieved with an optimal saccade strategy (Fig 4d and 4e). Frequent and high-amplitude saccades are equally detrimental to DVA performance (Fig 4d) as the attempt to match target before it reached the fixation point was associated with poor perceptual performance, indicating a suboptimal strategy. With a slower target this maneuver might lead to a more immediate reduction in position and trajectory of the target, or to plan and execute the saccade and subsequent reversal of eye movement direction. Players achieved higher DVA by not attempting to correct for the initial position error, in accordance with task performance [31]. This finding could reflect superior ability to use and adapt internal models of the target state and the control of the eye. Such forward models are used to predict the sensory consequences of movements [32]. Past research has shown that ball sport athletes demonstrate a faster rate of saccadic adaptation to experimentally imposed position errors [33]; a process purported to result from updating of internal forward models [34]. We observed that more experienced players performed the suboptimal strategy of using reverse saccades significantly less frequently at the higher target speed. In general, oculomotor predictors of DVA likely depend on the parameters of the task. We used a task with stimuli presented briefly and moving at speeds near the limits of smooth pursuit to mimic real-world task requirements in baseball. DVA can be tested either by asking an observer to identify static objects during head rotation, or to judge dynamic objects while the observer's head is fixed. These two types of DVA-tests require different types of oculomotor control mechanisms: the VOR compensates for fast head rotation, whereas smooth pursuit eye movements serve to keep small moving targets close to the fovea when the head is relatively stable. Thus, not surprisingly, these tests examine different aspects of DVA, which are uncorrelated in our study. In principle, both types of eye movements are needed to successfully stabilize the image of a baseball on the retina, especially in outfielders who have to track the ball with their eyes while their body is in motion. Even though hitters naturally rotate their upper torso and head when they hit the ball, little head rotation is needed during trajectory estimation. The VOR is suppressed during head rotations in professional batters [27]. Rather, tracking a pitched baseball requires a combination of smooth pursuit, saccades, and vergence eye movements to focus on the ball moving through different depth planes as well as anticipatory saccades [28]. In recent years, visual and perceptual components have become a core component in athlete performance assessment [35–38]. Our study reveals the importance of smooth pursuit eye movements for the ability to resolve spatial detail in moving objects and identifies patterns that might enhance perceptual performance. Eye movement tasks could be useful additions to perceptual training programs for baseball [39] and might potentially provide useful tools in assessing and recruiting athletes, ZIP) The authors thank UBC baseball director Terry McKaig and head coach Chris Pritchett for help with recruitment and members of the Spering lab for comments on the manuscript. Conceptualization: DJP JF MS. Formal analysis: DJP JF MS. Formal analysis: DJP JF PAW-H MS. Funding acquisition: MS. Investigation: DJP PAW-H JF. Methodology: DJP JF MS. Software: DJP. Writing - original draft: DJP MS. Writing - review & editing: DJP PAW-H JF MS. 1. Hughes PK, Bhundell NL, Waken JM. Visual and psychomotor performance of elite, intermediate and novice table tennis competitors. Clin Exp Optom. 1993;76: 51-60. 2. Ishigaki H, Miyao M. Differences in dynamic visual acuity between athletes and nonathletes. Percept Mot Skills 1993;77: 835-839. pmid:8284163 3. Millslagle DG. 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