EVALUATION OF VERTICAL AND HORIZONTAL SACCADDES USING THE DEVELOPMENTAL EYE MOVEMENT TEST COMPARED TO THE KING-DEVICK TEST

John D. Heick, PT, PhD, DPT, OCS, NCS, SCS¹

Curt Bay, PhD²

Tamara C. Valovich McLeod, PhD, ATC, FNATA³

ABSTRACT

Background: Oculomotor function is impaired when an individual has a concussion and as such, it is important to identify tests that are able to assess oculomotor impairment. The King-Devick (K-D) test assesses horizontal saccadic eye movement and attention. The Developmental Eye Movement (DEM) test is designed to identify oculomotor dysfunction in children. It measures both horizontal and vertical saccades. The K-D test shows promise as a concussion-screening tool and part of a multifactorial assessment. The DEM has not been tested as a concussion assessment tool, but the neuroanatomical control of horizontal and vertical saccades originates from different areas of the brain, so one might expect to see differences in performance on the K-D and DEM tests when administered to concussed patients. First, it is important to determine if performance on the DEM and K-D tests, particularly with respect to the measurement of vertical and horizontal saccades, is similar in a healthy population.

Hypothesis/Purpose: The primary purpose was to evaluate the relationship between horizontal and vertical saccade tests over repeated trials in normal, healthy subjects. A secondary purpose of this study was to determine the number of trials needed to reach a performance plateau for both the DEM and K-D tests.

Study Design: This study used a prospective cohort research design

Methods: Forty-two healthy non-concussed participants (22 males, 20 females; mean age, 24.2 ± 2.92 years) completed six repeated trials of both the DEM, and then six trials of the K-D test in a single testing session. Trials within each test were performed in random order and participants were offered short rest breaks as needed between test administrations.

Results: Results indicated strong correlations, $r = .67$, or greater, between measurements of horizontal and vertical saccades. Performance plateaued on the K-D at trial three and on the DEM at trial two for both horizontal and vertical saccades.

Conclusion: It appears that the DEM and K-D tests measure similar constructs in healthy individuals and that no additional information is provided by assessment of vertical saccades. Additional studies are required to investigate the usefulness of the DEM in concussed individuals.

Level of Evidence: 3: Laboratory study with repeated measures.

Key words: Concussion baseline testing, ocular motor dysfunction, saccades

¹ Northern Arizona University, Program in Physical Therapy, Flagstaff, AZ, USA

² Department of Interdisciplinary Health Sciences, A.T. Still University, Mesa, AZ, USA

³ Athletic Training Programs and School of Osteopathic Medicine in Arizona, A.T. Still University, Mesa, AZ, USA

The authors have no financial disclosures or conflict of interests to report. The authors have no commercial or proprietary interest in the Developmental Eye Movement test or the King-Devick test.

CORRESPONDING AUTHOR

John D. Heick, PT, PhD, DPT
Northern Arizona University
PO Box 15105, Flagstaff, Arizona 86011
Telephone: 928-523-8394
Fax: 928-523-9289
E-mail: John.Heick@nau.edu

INTRODUCTION

Sport-related concussions are considered a public health issue¹ because of the number of athletes who sustain concussions and the potential for cumulative effects following repeated injuries. Evaluation of the visual or oculomotor system has been incorporated into concussion assessment and continues to be investigated.²⁻⁴ Ocular motor dysfunction following a concussion may include disruptions to convergence, accommodation, and smooth pursuit with or without disruptions to saccades or saccadic fixation,⁴ so evaluating oculomotor function may be beneficial. Currently, the King-Devick (K-D) test shows promise as an assessment of horizontal saccades, within a multifactorial concussion assessment battery.²⁻⁷ The K-D test was created in 1976, as a modification of the Pierce Saccadic test,⁸ to assess the association of oculomotor dysfunction and learning disabilities.⁹ The K-D test was initially designed to mimic a child's ability to read.⁸ As individuals quickly scan numbers on test cards, they are replicating the horizontal ocular motion that occurs when reading with abrupt, rapid, discrete jumps from number to number.⁸ The pause that occurs as individuals interpret the number is known as a saccadic fixation and requires gaze stability.⁸

The Developmental Eye Movement (DEM) test was developed in 1990 and is similar to the K-D test, but in addition to assessing horizontal saccades it also incorporates two subtests of vertical saccades.^{10,11} Research on the DEM has been limited to its use as an oculomotor function test for children. Similar to the K-D test, when an individual scans numbers on the vertical and horizontal cards, the eyes make abrupt, discrete jumps from one number to the next. Unlike the K-D test, the DEM assesses horizontal and vertical saccades.^{8,10,12} In one study investigating children, Garzia et al¹² found excellent test-retest reliability for both the vertical ($r = 0.89$) and horizontal ($r = 0.89$) saccade times. However, these results were not replicated in a separate study¹⁰ that found third-grade children read the DEM vertical cards faster than the horizontal card. Lower reliability was also noted for both vertical (ICC = 0.60 (95% CI 0.32, 0.79) and horizontal saccade tests, ICC = 0.55 (95% CI 0.25, 0.76).¹⁰ Interestingly, the majority of studies dealing with saccadic eye movements focus on

horizontal saccades,¹³⁻¹⁷ but it is important to investigate both horizontal and vertical saccades because the neuroanatomical control of these eye motions originates from different areas of the brain.¹⁸⁻²¹ Specifically, horizontal saccades originating from the pons and vertical saccades involve the rostral mesencephalon.^{22,23} Different neuroanatomical regions of the brain may be affected by a concussion and result in differential changes in saccade reaction times. Further, the saccadic fixation that occurs while the individual interprets the number is slower for horizontal than vertical saccades.^{8,10,12} The DEM test may provide additional information to concussion assessment since it measures both horizontal and vertical saccades.

During preseason baseline concussion assessment, the recommended procedure requires performing the K-D test twice. The lowest of the two trials, or fastest, is then used to determine the athlete's baseline K-D composite score.^{2,3,24} This protocol, however, does not accommodate the potential practice effects associated with repeated administration of a novel test. When using performance tests, practice effects may be reduced by adding trials until a performance plateau occurs.²⁵ Achieving a performance plateau during baseline concussion testing is important because it provides a stable reference against which performance can be measured following concussion. In a recent study, Heick et al²⁵ showed that administering the K-D three times, and interpreting only trials 2 and 3 improved the reliability of the K-D test estimate of baseline performance.

The primary purpose of this study was to evaluate the relationship between horizontal and vertical saccade tests over repeated trials in normal, healthy subjects. A secondary purpose was to determine the number of trials needed to reach a performance plateau for both the DEM and K-D tests.

METHODS

The current study employed a prospective research design of a cohort to evaluate the relationship between the DEM and K-D tests across six repeated trials, and to determine the number of trials needed to reach a performance plateau in both tests for 42 healthy adolescents and adults. All experimental

procedures were approved by the A.T. Still University institutional review board.

Participants

Participants in the current study were between the ages of 14 and 35 years and possessed sufficient English skills to complete all tasks. Applicants with a diagnosis of a head injury in the past year and those with vision, vestibular, or balance disorders were excluded. Participants completed a personal/medical history form prior to testing which included questions about current reading levels, attention deficit disorder, learning disorders, and sports participation.

Participants were recruited through flyers distributed to public and private school systems in a metropolitan community. An initial telephone screening was used to ascertain eligibility and potential participants were provided information about the purpose of the study. All participants provided informed consent or the parent/guardian provided permission and the child assented.

Procedures

All testing was administered by the same investigator in a university research laboratory. Participants were permitted to use glasses or contacts, if desired. Standardized instructions were provided before performing the DEM and K-D tests. Participants completed the DEM, and then the K-D test. The six trials of both the DEM and the K-D tests were performed in random order during a single testing session and participants were offered short rest breaks as needed for no more than five minutes between test administrations. To determine the score for both tests, time began and ended when the first and last number was read on each testing card. This procedure was repeated for all test cards for six trials of both tests. To eliminate order effect, participants were randomly assigned the sequence of testing with either DEM or K-D test first.

Instrumentation

DEM Test

The DEM test is a rapid number-naming test that uses visual processing and cognitive demands for both vertical and horizontal saccades.¹⁰⁻¹² Standardized instructions were used. The DEM test includes one practice card and three test cards.¹¹ The sum

of the time to complete the three test cards constitutes the summary score for the entire test, known as the DEM score. The first two test cards are composed of 40, single-digit numbers arranged in two vertical columns with equally spaced small vertical saccades. The third test card has 16 horizontal rows each with five unevenly spaced digits requiring horizontal saccades in order to read from left to right.¹¹ The DEM test ratio is the horizontal score (test card three time corrected for any omission or addition errors) divided by the vertical score (time for test card 1 plus card 2). The DEM test ratio is designed to differentiate between an individual having poor saccadic function (assumed to give a better horizontal time and ratio) and poor ability to rapidly name numbers.¹⁰ There is evidence both for¹⁰ and against the use of the DEM test ratio, but the current evidence suggests that the DEM test cards may provide more important information than the DEM test ratio.¹¹ Therefore, in the current study the DEM test ratio was not used. The six trials of the DEM test in the current study were performed with participants in a seated position and at a self-selected distance for reading. The time for each trial and the average of the three scores from each trial were recorded and used for statistical comparisons. The time required to complete each trial was measured by a stopwatch to the nearest hundredth of a second.

K-D Test

The K-D test is a screening tool that assesses impairment of eye movements, attention, language, and areas of the brain that correlate with suboptimal brain function.^{2,3,26} The K-D test is based on measurement of the speed of rapid number naming^{2,3} and involves reading aloud a series of single-digit numbers from left to right on three test cards that progressively increase in difficulty.⁸ Standardized instructions were used, and the test includes one practice card and three test cards. The sum of the time to complete the three test cards constitutes the summary score for the test, known as the K-D composite score. Each of the three K-D test cards is composed of eight rows with each row having five 20/100 reduced Snellen equivalent numbers (at a recommended 40 cm reading distance).⁸ A demonstration card is used to familiarize the participant with the K-D test. Card 1 consists of randomly spaced numbers connected by horizontal lines. Cards 2 and

3 do not have horizontal lines, and the vertical separation between rows in card 3 is reduced to 3/8 inch compared to 1/4 inch for the first two cards.⁸ Thus, cards 2 and 3 are more difficult than the demonstration card or card 1. The K-D test was performed with participants in a seated position and at a self-selected distance for reading.^{2,3,5,27} The time required to complete the six trials, measured by a stopwatch to the nearest hundredth of a second, was recorded.

Statistical Analysis

Means (standard deviations) and counts (percentages) are provided to summarize descriptive and outcome data, as appropriate. Pearson correlation coefficients were used to estimate the magnitude of the relationship between the vertical and horizontal aspects of the DEM and the K-D test during each of six trials. Fisher r-to-z transformations were used to test for differences in Pearson correlation coefficients. Generalized linear mixed models with random effects for participants and a gamma log-link were used to analyze change in the DEM and K-D scores across trials. A priori Helmert contrasts (comparing the mean of each trial [except the last] to the mean of subsequent levels) were conducted to identify the trial beyond which scores did not improve, on average. Two-way, random effects intraclass correlation coefficients (ICCs) were calculated for the six trials of the DEM test, and the six trials of the K-D test. A sample size analysis performed using G*power showed that a minimum of 36 participants would be required to achieve a power of .80 for the Helmert contrasts with Bonferroni correction, $\alpha = .05$, 2-tailed, assuming a medium effect size (Cohen's d) = 0.50. Analyses were performed using SPSS, version 24 (IBM Corp., Armonk NY).

Table 1. Demographic Characteristics of the Healthy Young Adults ($n = 42$) included in the Current Study.

Demographic Characteristic	No. (%) or Mean (SD)*
Sex	
Male	22 (52.4)
Female	20 (47.6)
Age (years)	24.3 (2.92)
Glasses/contacts	15 (35.7)
Attention deficit disorder	5 (11.9)
Sports history	42 (100)
*Age is reported as mean (SD).	
Abbreviation: SD, standard deviation.	

RESULTS

The demographic characteristics of the 42 participants who completed testing (20 females, 22 males) are provided in Table 1.

Relationship between Developmental Eye Movement and King-Devick Scores

Correlations between the DEM horizontal and vertical and K-D scores, within trial, were all, $r = .67$, or greater, as noted in Table 2. The correlation coefficients (all $p < 0.001$) increased nominally from Trial 1 to Trial 5, and then decreased on Trial 6. None of the differences between correlations for the horizontal and vertical scores on the DEM Test, within trial, were significantly different, $p > 0.15$.

Developmental Eye Movement Score

A significant downward linear trend was also noted for the DEM composite score ($p = .021$), (Figure 2). Results of the Helmert contrasts for the DEM are provided in Table 5. Performance did not improve

Table 2. Pearson Correlation Coefficients for the King-Devick (K-D) Test and Horizontal and Vertical Developmental Eye Movement (DEM) Test Card Times Within Trial ($N = 42$)

Trial	Correlation between K-D Test and DEM Horizontal	Correlation between K-D Test and DEM Vertical
1	0.67	0.69
2	0.84	0.83
3	0.89	0.84
4	0.90	0.86
5	0.91	0.87
6	0.82	0.79

Table 3. King-Devick (K-D) Test and Horizontal and Vertical Developmental Eye Movement (DEM) Test Card Times to Complete the Six Trials (n=42). All data are reported in seconds.

Trial	K-D Composite Score Mean (95% CI)	DEM Horizontal Card Score Mean (95% CI)	DEM Vertical Card Score Mean (95% CI)
1	39.71 (37.20-42.21)	27.93 (25.92-29.92)	25.29 (23.97-26.61)
2	38.07 (35.82-40.32)	26.69 (24.91-28.48)	25.21 (23.93-26.50)
3	37.75 (35.35-40.15)	25.92 (24.13-27.72)	25.17 (23.76-26.59)
4	36.35 (34.11-38.59)	25.84 (24.13-27.55)	24.88 (23.55-26.21)
5	36.19 (34.00-38.38)	25.21 (23.58-26.83)	25.21 (23.75-26.67)
6	35.85 (33.75-37.96)	25.38 (23.48-27.28)	25.42 (23.96-26.89)

Abbreviation: CI, confidence interval.

Figure 1. Means and Standard Deviations of King-Devick (K-D) Test Composite Scores for the Six Trials of the Healthy Young Adults in the Current Study (N=42).

***Statistically significant, $p < .001$

after Trial 2. The reliability of the DEM composite score across the six trials was excellent, (ICC = 0.98; 95% CI, 0.97, 0.99).

King-Devick Composite Score

Table 3 provides the means and 95% confidence intervals (CIs) for the K-D composite score for each of the six trials. The K-D composite score decreased across the six trials, as shown in Figure 1 (test of linearity, $p < .001$). Results of the Helmert contrasts for the K-D are provided in Table 4. Performance did

not improve after Trial 3. The reliability of the K-D composite score across the six trials was excellent, (ICC = 0.98; 95% CI, 0.97, 0.99).

DISCUSSION

In the current study, the K-D and DEM tests appear to be measuring the same, underlying phenomenon, as there were no differences in the correlations between the K-D and DEM tests when the horizontal and vertical components of the DEM test were segregated. Both horizontal and vertical saccades are

Figure 2. Means and Standard Deviations of Developmental Eye Movement (DEM) Vertical Test Scores for the six Trials of the Healthy Young Adults in the Current Study ($N = 42$).

**Statistically significant, $p < .05$

Table 4. Results of Mean Comparison using Helmert Contrasts with Bonferroni Corrections for the King-Devick Test Across the Six Trials ($n = 42$).

Helmert Contrast	Contrast Estimate	Standard Error	p-Value (Bonferroni)
Trial 1 vs. later trials	2.87	0.60	<0.001*
Trial 2 vs. later trials	1.54	0.45	0.002*
Trial 3 vs. later trials	1.62	0.36	<0.001*
Trial 4 vs. later trials	0.32	0.31	0.52
Trial 5 vs. last trial	0.34	0.30	0.52

*Denotes statistically significant difference, $p < 0.05$

components of the Vestibular Ocular Motor Screening (VOMS) tool and recommended for inclusion in any ocular motor assessment of concussion.²⁸ Recently, Anzalone et al²⁹ showed athletes reported dizziness symptoms primarily during the vertical saccade component and the vertical vestibular ocular reflex component of the VOMS post-concussion. It was also suggested that identification of specific vestibular/ocular motor abnormalities may aid clinicians in management of concussion and allow a targeted vestibular/ocular motor approach to address specific deficits of the athlete.²⁹ The DEM and K-D

Table 5. Results of Mean Comparisons using Helmert Contrasts with Bonferroni corrections for the Horizontal and Vertical Developmental Eye Movement Test Cards Across the Six Trials ($n = 42$).

Helmert Contrast	Horizontal Contrast Estimate	Horizontal Standard Error	Horizontal p-Value (Bonferroni)	Vertical Contrast Estimate	Vertical Standard Error	Vertical p-Value (Bonferroni)
Trial 1 vs. later trials	2.27	0.54	<0.001*	2.27	0.54	<0.001*
Trial 2 vs. later trials	1.20	0.42	0.02*	1.20	0.42	0.02*
Trial 3 vs. later trials	0.53	0.53	0.97	0.53	0.53	0.97
Trial 4 vs. later trials	-0.23	0.63	>0.99	-0.23	0.63	>0.99
Trial 5 vs. last trial	-0.18	0.88	>0.99	-0.18	0.88	>0.99

*Denotes statistically significant differences, $p < 0.05$

Figure 3. Means and Standard Deviations of Developmental Eye Movement (DEM) Horizontal Test Scores for the Six Trials of the Healthy Young Adults in the Current Study (N = 42).

**Statistically significant, $p < .05$

tests provide a quantitative measure to identify these abnormalities and do not rely on the potentially subjective nature of other clinical assessment tests such as the VOMS.

The use of objective measures during assessment that does not rely on subjective responses is important because athletes' motivation to return to sport may skew their self-report. Objective physiologic measures such as oculomotor testing potentially provide a more accurate assessment of their neurologic status than subjective report. Baseline testing for athletes that includes an assessment of oculomotor function provides an objective measure that offers an objective comparison point for evaluation following concussion. A multifaceted assessment approach must include vision because vision uses half of the pathways within the brain and these anatomical structures are susceptible to injury from concussion.⁴ Visual-motor disruptions include difficulty with saccades, accommodation, smooth pursuit, and fixation⁴ with an estimated 65% to 90% of concussed patients showing oculomotor disruptions^{26,30} such as convergence insufficiency, slowed saccadic function, and smooth pursuit deficits.⁴ Thus, evaluating visual-motor dysfunction is an important aspect

of a multifaceted concussion assessment and may include the DEM or K-D test to provide an objective measure of oculomotor function.

Both saccadic tests were originally designed to assess the association of oculomotor dysfunction and learning disabilities in children.^{2,8,10,11} The DEM test has not been evaluated as a potential concussion assessment tool. However, the K-D test has been evaluated in patients with concussion,^{2,3,24,31-33} multiple sclerosis,^{34,35} and Parkinson's disease.³⁶ The administration of these two saccadic tests is similar in concept but different in format and interpretation.

The tests are also different in the way they assess the function of different neuroanatomical locations. The neuroanatomical correlates of function differ for the horizontal and vertical saccades.³⁷ The caudal pons is an important neuroanatomical region for initiating horizontal saccades; whereas the rostral mesencephalon is associated with vertical saccades.^{22,23} Burst neurons, responsible for the ballistic movement of a saccade³⁷ are present in different neuroanatomical regions for horizontal and vertical saccades. The burst neurons responsible for horizontal saccades are located within the paramedian

pontine reticular formation, and those for vertical saccades are in the rostral interstitial nucleus of the medial longitudinal fasciculus.³⁷⁻⁴⁰ The neural correlates associated with saccadic eye movements are well understood and involve areas of the frontal and parietal lobes, basal ganglia, thalamus, visual cortex, superior colliculus, cerebellum, and brainstem reticular formation.⁴¹ Each of these neuroanatomical structures contributes differently to saccadic performance, and altered performance may indicate the presence of a concussion because these structures are highly susceptible to neural injury.^{30,42}

Functional magnetic resonance imaging studies of patients with frontal lobe lesions have identified specific frontal regions that are involved in voluntary saccade control.^{21,43-45} Studies of patients with lesions to the posterior parietal cortex and supplementary motor area suggest their influence on the accuracy and timing of saccade reaction times.^{19,20,46} Therefore, changes in saccade reaction times should be reflected in slower times on the K-D or DEM test. Because the mechanism of injury and the neuroanatomical location of injury differ among individuals with concussion, we propose that a multifaceted assessment that includes horizontal and vertical saccades is logical, especially since the two saccadic tests involve different neuroanatomical regions of the brain. In the current study, there was a high correlation between the two saccadic tests but it is unknown if this would be the case in individuals who have sustained a concussion.

In terms of the secondary analysis, performance on the K-D did not improve after trial 3 and performance did not improve on the DEM after trial 2. This K-D result in performance is consistent with a previous study that investigated performance on repeated trials of the K-D test⁴⁷ but has not been investigated for the DEM test. Previous research has suggested⁴⁸ that practice effects can be reduced by performing additional trials until a performance plateau is reached. In the current study, the number of trials needed to reach a plateau were investigated because precision of baseline tests is important when used for comparison post-concussion.

Based on the findings, the DEM test may be more efficient because performance did not improve

after trial 2. This may translate, clinically, into less time required to baseline test a large team of athletes as the performance plateau was reached in two trials, rather than three trials for the K-D test. Another clinical advantage of determining a performance plateau in fewer trials is that it may provide a more precise baseline measurement. If an athlete is baseline-tested with the K-D and has a concussion, more than five seconds difference on the K-D composite relative to baseline has been shown to be a reliable indicator of concussion.^{2,3,24,31,32,49,50} The K-D test has shown excellent test-retest reliability.² Using mixed-martial arts fighters (mean age = 24) Galetta et al,² reported a test-retest ICC of 0.92. Oberlander et al,⁵¹ found an ICC of 0.81 in adolescents of both sexes (mean age = 15.4). The DEM test has not been tested in similarly-aged populations, but researchers have found excellent reliability in the horizontal (ICC=0.86) and vertical saccade (ICC=0.89) components when evaluated separately in 6-to-11 year olds.¹² Another important clinical consideration is the time required to administer each assessment to a patient. In comparison, the DEM and the K-D take less than two minutes making them efficient. The authors note that both of these tests are efficient but either the DEM or the K-D test must be a part of a multifaceted concussion assessment and it is yet to be determined the most efficient and most effective concussion assessment. In the current study, the composite scores for both tests were more reliable over six trials. Further investigation of the DEM test as a potential concussion assessment tool is needed to determine the usefulness of evaluation of vertical saccades following concussion. If the DEM test and K-D test are equally responsive in evaluating concussion, it seems more efficient to use the DEM test as part of a multifaceted concussion assessment because it evaluates both horizontal and vertical saccades.

The current study had several limitations. A convenience sample was used of graduate students, employees, and staff associated with a health sciences university as well as participants from local public and private school systems. When the study was initiated, there were two versions of the K-D test available: a spiral-bound version and a computer tablet version. Only the spiral-bound version of the K-D

test was investigated in the current study. At present, the computer tablet version is the only version available for purchase. Raynowska et al⁵⁰ found good agreement (ICC = 0.92; 95% CI 0.83- 0.96) between the two versions of the K-D test. These authors showed that lower scores on both the spiral bound and computer versions of the K-D test are associated with concussion.⁵⁰ Future studies should examine the test-retest reliability of the computer version of the K-D and the DEM test to evaluate the learning effect of both of these tests. Another limitation was that the test-retest interval was brief, averaging 30 minutes. This interval may have caused some mental fatigue given the volume of rapid number identification over several trials. Future studies should include a longer test-retest time. If a baseline test is done and an athlete does not sustain a concussion until three months later, the test-retest reliability is not known. Finally, all testing was performed in a controlled laboratory environment without noise and distraction, which may not translate well to a real-life clinical assessment environment.

CONCLUSIONS

The results of the current study indicate that performances on both the DEM and K-D are strongly correlated, suggesting that the two tests are measuring similar constructs. In addition, two trials of the DEM were sufficient to achieve a performance plateau. Additional studies should investigate the usefulness of the DEM in concussed individuals.

REFERENCES

1. Langlois JA, Rutland-Brown W, Wald MM. The epidemiology and impact of traumatic brain injury: a brief overview. *J Head Trauma Rehabil.* 2006;21(5):375-378.
2. Galetta KM, Barrett J, Allen M, et al. The King-Devick test as a determinant of head trauma and concussion in boxers and MMA fighters. *Neurology.* 2011;76(17):1456-1462.
3. Galetta KM, Brandes LE, Maki K, et al. The King-Devick test and sports-related concussion: study of a rapid visual screening tool in a collegiate cohort. *J Neurol Sci.* 2011;309(1-2):34-39.
4. Ventura RE, Balcer LJ, Galetta SL. The neuro-ophthalmology of head trauma. *Lancet Neurol.* 2014;13(10):1006-1016.
5. Vartiainen MV, Holm A, Peltonen K, Luoto TM, Iverson GL, Hokkanen L. King-Devick test normative reference values for professional male ice hockey players. *Scand J Med Sci Sports.* 2014.
6. Tjarks BJ, Dorman JC, Valentine VD, et al. Comparison and utility of King-Devick and ImPACT(R) composite scores in adolescent concussion patients. *J Neurol Sci.* 2013;334(1-2):148-153.
7. Patricios J, Fuller GW, Ellenbogen R, et al. What are the critical elements of sideline screening that can be used to establish the diagnosis of concussion? A systematic review. *Br J Sports Med.* 2017;51(11):888-894.
8. Lieberman S, Cohen AH, Rubin J. NYSOA K-D test. *J Am Optom Assoc.* 1983;54(7):631-637.
9. King D, Clark T, Gissane C. Use of a rapid visual screening tool for the assessment of concussion in amateur rugby league: a pilot study. *J Neurol Sci.* 2012;320(1-2):16-21.
10. Rouse MW, Nestor EM, Parot CJ, Deland PN. A reevaluation of the Developmental Eye Movement (DEM) test's repeatability. *Optom Vis Sci.* 2004;81(12):934-938.
11. Ayton LN, Abel LA, Fricke TR, McBrien NA. Developmental eye movement test: what is it really measuring? *Optom Vis Sci.* 2009;86(6):722-730.
12. Garzia RP, Richman JE, Nicholson SB, Gaines CS. A new visual-verbal saccade test: the development eye movement test (DEM). *J Am Optom Assoc.* 1990;61(2):124-135.
13. Seassau M, Bucci MP. Reading and visual search: a developmental study in normal children. *PLoS One.* 2013;8(7):e70261.
14. Fischer B, Gezeck S, Hartnegg K. The analysis of saccadic eye movements from gap and overlap paradigms. *Brain Res Brain Res Protoc.* 1997;2(1):47-52.
15. Fischer B, Biscaldi M, Gezeck S. On the development of voluntary and reflexive components in human saccade generation. *Brain Res.* 1997;754(1-2):285-297.
16. Gezeck S, Fischer B, Timmer J. Saccadic reaction times: a statistical analysis of multimodal distributions. *Vision Res.* 1997;37(15):2119-2131.
17. Parton A, Nachev P, Hodgson TL, et al. Role of the human supplementary eye field in the control of saccadic eye movements. *Neuropsychologia.* 2007;45(5):997-1008.
18. McDowell JE, Dyckman KA, Austin BP, Clementz BA. Neurophysiology and neuroanatomy of reflexive and volitional saccades: evidence from studies of humans. *Brain Cogn.* 2008;68(3):255-270.
19. Pierrot-Deseilligny C. Cortical control of saccades in man. *Acta Neurol Belg.* 1991;91(2):63-79.

-
20. Pierrot-Deseilligny C, Rivaud S, Gaymard B, Agid Y. Cortical control of reflexive visually-guided saccades. *Brain*. 1991;114 (Pt 3):1473-1485.
 21. Schraa-Tam CK, van Broekhoven P, van der Geest JN, Frens MA, Smits M, van der Lugt A. Cortical and cerebellar activation induced by reflexive and voluntary saccades. *Exp Brain Res*. 2009;192(2):175-187.
 22. Ghahari A, Enderle JD. A physiological neural controller of a muscle fiber oculomotor plant in horizontal monkey saccades. *ISRN Ophthalmol*. 2014;2014:406210.
 23. Gancarz G, Grossberg S. A neural model of the saccade generator in the reticular formation. *Neural Netw*. 1998;11(7-8):1159-1174.
 24. Leong DF, Balcer LJ, Galetta SL, Evans G, Gimre M, Watt D. The King-Devick test for sideline concussion screening in collegiate football. *J Optom*. 2015;8(2):131-139.
 25. Heick JD, Bay C, Dompier TP, Valovich McLeod TC. The Psychometric Properties of the King-Devick Test and the Influence of Age and Sex in Healthy Individuals Aged 14 to 24 Years. *Athletic Training and Sports Health Care*. 2016;8(5):222-229.
 26. Heitger MH, Jones RD, Macleod AD, Snell DL, Frampton CM, Anderson TJ. Impaired eye movements in post-concussion syndrome indicate suboptimal brain function beyond the influence of depression, malingering or intellectual ability. *Brain*. 2009;132(Pt 10):2850-2870.
 27. Braun PA, Kaminski, T.W., Swanik, C.B., Knight, C.A. . Oculomotor function in collegiate student athletes with a previous history of sport-related concussion. *Athl Train Sports Health Care*. 2013;6(5):282-288.
 28. Mucha A, Collins MW, Elbin RJ, et al. A Brief Vestibular/Ocular Motor Screening (VOMS) Assessment to Evaluate Concussions: Preliminary Findings. *Am J Sports Med*. 2014;42(10):2479-2486.
 29. Anzalone AJ, Blueitt D, Case T, et al. A Positive Vestibular/Ocular Motor Screening (VOMS) Is Associated With Increased Recovery Time After Sports-Related Concussion in Youth and Adolescent Athletes. *Am J Sports Med*. 2017;45(2):474-479.
 30. Heitger MH, Anderson TJ, Jones RD, Dalrymple-Alford JC, Frampton CM, Ardagh MW. Eye movement and visuomotor arm movement deficits following mild closed head injury. *Brain*. 2004;127(Pt 3):575-590.
 31. Rizzo JR, Hudson TE, Dai W, et al. Rapid number naming in chronic concussion: eye movements in the King-Devick test. *Ann Clin Transl Neurol*. 2016;3(10):801-811.
 32. Rizzo JR, Hudson TE, Dai W, et al. Objectifying eye movements during rapid number naming: Methodology for assessment of normative data for the King-Devick test. *J Neurol Sci*. 2016;362:232-239.
 33. Leong DF, Balcer LJ, Galetta SL, Liu Z, Master CL. The King-Devick test as a concussion screening tool administered by sports parents. *J Sports Med Phys Fitness*. 2014;54(1):70-77.
 34. Hainline C, Rizzo JR, Hudson TE, et al. Capturing saccades in multiple sclerosis with a digitized test of rapid number naming. *J Neurol*. 2017;264(5):989-998.
 35. Balcer LJ, Raynowska J, Nolan R, et al. Validity of low-contrast letter acuity as a visual performance outcome measure for multiple sclerosis. *Mult Scler*. 2017;23(5):734-747.
 36. Lin TP, Adler CH, Hentz JG, Balcer LJ, Galetta SL, Devick S. Slowing of number naming speed by King-Devick test in Parkinson's disease. *Parkinsonism Relat Disord*. 2014;20(2):226-229.
 37. Buttner-Ennever JA. Mapping the oculomotor system. *Prog Brain Res*. 2008;171:3-11.
 38. Enderle JD. Neural control of saccades. *Prog Brain Res*. 2002;140:21-49.
 39. Rufa A, Cerase A, De Santi L, et al. Impairment of vertical saccades from an acute pontine lesion in multiple sclerosis. *J Neuroophthalmol*. 2008;28(4):305-307.
 40. Takahashi M, Sugiuchi Y, Shinoda Y. Commissural mirror-symmetric excitation and reciprocal inhibition between the two superior colliculi and their roles in vertical and horizontal eye movements. *J Neurophysiol*. 2007;98(5):2664-2682.
 41. Van der Stigchel S, Meeter M, Theeuwes J. The spatial coding of the inhibition evoked by distractors. *Vision Res*. 2007;47(2):210-218.
 42. Heitger MH, Jones RD, Macleod AD, Snell DL, Frampton CM, Anderson TJ. Impaired eye movements in post-concussion syndrome indicate suboptimal brain function beyond the influence of depression, malingering or intellectual ability. *Brain*. 2009;132(Pt 10):2850-2870.
 43. Walker R, Techawachirakul P, Haggard P. Frontal eye field stimulation modulates the balance of salience between target and distractors. *Brain Res*. 2009;1270:54-63.
 44. van Broekhoven PC, Schraa-Tam CK, van der Lugt A, Smits M, Frens MA, van der Geest JN. Cerebellar contributions to the processing of saccadic errors. *Cerebellum*. 2009;8(3):403-415.
 45. Simo LS, Krisky CM, Sweeney JA. Functional neuroanatomy of anticipatory behavior: dissociation between sensory-driven and memory-driven systems. *Cereb Cortex*. 2005;15(12):1982-1991.
-

-
46. Hopp JJ, Fuchs AF. Investigating the site of human saccadic adaptation with express and targeting saccades. *Exp Brain Res*. 2002;144(4):538-548.
 47. Heick JD, Bay C, Dompier TP, Valovich McLeod TC. Relationships among Common Vision and Vestibular Tests in Healthy Recreational Athletes. *Int J Sports Phys Ther*. 2017;12(4):581-591.
 48. Weir JP. Quantifying test-retest reliability using the intraclass correlation coefficient and the SEM. *J Strength Cond Res*. 2005;19(1):231-240.
 49. Hasanaj L, Thawani SP, Webb N, et al. Rapid Number Naming and Quantitative Eye Movements May Reflect Contact Sport Exposure in a Collegiate Ice Hockey Cohort. *J Neuroophthalmol*. 2017.
 50. Raynowska J HL, Zhang I, Serrano L, Birkemeier J, Nolan R, Webb N, Silverio A, Rucker J, Galetta SL, Balcer LJ. . Agreement of the Spiral-Bound and Computerized Tablet Versions of the King-Devick Test of Rapid Number Naming for Sports Related Concussion. *Ann Sports Med Res*. 2015;2(9):1051-1057.
 51. Oberlander TJ, Olson BL, Weidauer L. Test-Retest Reliability of the King-Devick Test in an Adolescent Population. *J Athl Train*. 2017;52(5):439-445.
 52. Brett BL, Smyk N, Solomon G, Baughman BC, Schatz P. Long-term Stability and Reliability of Baseline Cognitive Assessments in High School Athletes Using ImPACT at 1-, 2-, and 3-year Test-Retest Intervals. *Arch Clin Neuropsychol*. 2016.
 53. Moran RN, Covassin T, Elbin RJ, Gould D, Nogle S. Reliability and Normative Reference Values for the Vestibular/Ocular Motor Screening (VOMS) Tool in Youth Athletes. *Am J Sports Med*. 2018:363546518756979.
 54. Kontos AP, Sufrinko A, Elbin RJ, Puskar A, Collins MW. Reliability and Associated Risk Factors for Performance on the Vestibular/Ocular Motor Screening (VOMS) Tool in Healthy Collegiate Athletes. *Am J Sports Med*. 2016;44(6):1400-1406.