Published in final edited form as:

J Neurol Sci. 2016 March 15; 362: 232–239. doi:10.1016/j.jns.2016.01.045.

Objectifying eye movements during rapid number naming: Methodology for assessment of normative data for the King– Devick test

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Abstract

Objective—Concussion is a major public health problem and considerable efforts are focused on sideline-based diagnostic testing to guide return-to-play decision-making and clinical care. The King–Devick (K–D) test, a sensitive sideline performance measure for concussion detection, reveals slowed reading times in acutely concussed subjects, as compared to healthy controls; however, the normal behavior of eye movements during the task and deficits underlying the slowing have not been defined.

Methods—Twelve healthy control subjects underwent quantitative eye tracking during digitized K–D testing.

Results—The total K–D reading time was 51.24 (± 9.7) seconds. A total of 145 saccades (± 15) per subject were generated, with average peak velocity 299.5°/s and average amplitude 8.2°. The average inter-saccadic interval was 248.4 ms. Task-specific horizontal and oblique saccades per subject numbered, respectively, 102 (± 10) and 17 (± 4). Subjects with the fewest saccades tended to blink more, resulting in a larger amount of missing data; whereas, subjects with the most saccades tended to make extra saccades during line transitions.

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Disclosures

None of the authors have any financial disclosures. This data has not been previously published. All work is original.

Conclusions—Establishment of normal and objective ocular motor behavior during the K–D test is a critical first step towards defining the range of deficits underlying abnormal testing in concussion. Further, it sets the groundwork for exploration of K–D correlations with cognitive dysfunction and saccadic paradigms that may reflect specific neuroanatomic deficits in the concussed brain.

Keywords

Brain concussion; Eye movements; Eye movement measurements; Saccades

1. Introduction

Concussion results from a biomechanically-induced alteration of brain physiology that produces clinical symptoms such as headaches, dizziness, blurred vision, and imbalance; clinical neurological and neuro-ophthalmologic examinations and standard neuroimaging are often unrevealing. However, there may be measurable neurologic impairments in cognition, reaction time, balance, or behavior on detailed diagnostic testing. Eye movement abnormalities have also been observed in mild traumatic brain injury [1,2] but they have not been widely and systematically studied in concussion.

Concussion in sports is a major societal concern, with 1.6 to 3.8 million sports-related concussions occurring annually in the United States [3] and many more unreported [4]. In males, the highest-risk sports include boxing, football, rugby, ice hockey, and wrestling. In females, soccer, field hockey and basketball are relatively high risk sports [5]. Repeat concussion rates vary from 5.6% to 36% [6] and are most often seen in the first 10 days following the initial episode [7]. Potential long-term effects of repeated concussions may include chronic neurocognitive and neuropathologic changes consistent with chronic traumatic encephalopathy (CTE) [8]. Given these possible sequelae, considerable efforts are focused on the development of sideline-based diagnostic testing to guide return-to-play decision-making and clinical care for concussion.

A rapid number-naming task called the King–Devick (K–D) test has been well validated as a sensitive sideline performance measure for concussion detection [9–13]. This test functions as a pseudo-reading task, which broadly captures aspects of afferent visual function, attention, language, visual fixation, and saccadic eye movements (fast eye movements utilized to point the fovea to targets of visual interest). Saccade generation involves weighing aspects of the stimulus, the goal of the eye movement, motor planning and organization, and motivation. Saccades must be both accurate (due to small foveal size) and fast (up to 600°/s and less than 100 ms in duration) to efficiently acquire image information in real time. Given that speed and accuracy typically trade off in human movement control, these criteria are particularly demanding. It is therefore not surprising that saccades would be prone to malfunction from neurological trauma more readily than other eye movement types.

Disruption of cortical structures (Fig. 1) integral to target selection, attention, motivation, and saccade programming may result in alterations of saccades. Of particular pertinence are frontal regions that mediate saccades [such as frontal eye fields (FEF), dorsolateral

prefrontal cortex (DLPFC), and cingulate eye field] (Fig. 1) as these regions are very prone to injury from head trauma [14–16]. The DLPFC plays a major role in producing anticipatory saccades when visual target location and timing can be predicted, inhibiting unwanted saccades that would disrupt vision, and in spatial working memory during saccades to a remembered target location after the target has disappeared (memory-guided saccades). Dysfunction of the DLPC has been speculated in concussion, given correlations between slowed K–D reading times and general cognitive function as assessed by the Standard Assessment of Concussion (SAC) test [11]. Dysfunction of the cingulate cortex could also play a potential role in saccadic abnormalities during K–D test performance in traumatic brain injury, as the cingulate cortex has been shown by functional imaging to play a role in reading of ‘pseudo-text’ (consonant letter strings) [17] similar to reading a series of numbers on K–D test cards.

The standard King–Devick (K–D) test is a simply-administered test consisting of three hand-held cards with 40 numbers arranged in 8 rows of five (Fig. 2A–C) [18]. Direct detection of the number of saccades generated, much less pathology within them, is not possible with the hand-held test. At present, the only objective metrics assessed with the hand-held test are testing time and error rate. Studies of the K–D test in athletes [9–13] have shown that testing completion times are significantly prolonged (worse) following concussion, but not after exercise or exertion alone [9]. Slowing of saccades, which would implicate brainstem dysfunction, is speculated as a possible explanation for prolonged K–D testing times following concussive events. However, this has not yet been proven using quantitative eye movement recordings and other ocular motor deficit possibilities exist, including increased duration of fixations, saccadic latencies, overall numbers of saccades due to backtracking or inaccurate saccades, or excessive saccadic intrusions superimposed upon otherwise normal eye movements — all of which may implicate brain dysfunction. The possibility also exists that ocular motor behavior on the K–D test is normal after concussion and slowed reading times may be due solely to cognitive or attentional deficits. To determine why concussion leads to slowed KD reading times, normal ocular motor behavior during this visual task must first be clearly characterized. The objective of the current study is to develop procedural methodology for analysis of eye movement behavior during rapid number naming tasks in a non-concussed cohort as the first step towards development of a large normative database.

2. Methods

Twelve healthy adult volunteers (age range 24–49, mean 32, 8 female) completed one trial of a novel digitized version of the K–D test under objective, video-based, infrared oculography (Eyelink 1000+, SR Research, Ontario Canada). K–D card images were imported into the eye tracking software with maintenance of stimulus matching (e.g. numbers presented, spacing between numbers). Historical information was obtained and exclusion criteria determined via subject-provided answers to direct questioning by the investigator. Healthy adults between the ages of 18 and 70 were deemed eligible for inclusion. Exclusion criteria included a history of concussion or traumatic brain injury and a history of neurological or ophthalmological disease (other than refractive error). None of the subjects had a history of concussion, neurological impairment, learning disability, or visual

dysfunction. None of the subjects were taking central nervous system-active medications. None of the subjects were athletes actively involved in team sports. This study was approved by the NYU Institutional Review Board. All participants provided written consent to participate in the study via signed formal consent forms approved by the NYU Institutional Review Board. The system recorded binocularly with a sampling frequency of 500 Hz and a spatial accuracy of approximately 0.5° .

Participants sat in a high-backed chair and were asked to remain as still as possible in front of a computer screen (screen dimensions: width 53 cm $\times$ height 30 cm, distance between screen and participant: 75 cm). Following a 13-point spatial calibration procedure, subjects were instructed to read a series of numbers on a demonstration test card virtually displayed on the computer screen. Eye positions were recorded for both eyes simultaneously, utilizing a non-stereotactic, remote, head-tracked recording paradigm to allow for verbalization of number reading during testing, as a stereotactic set-up is not advisable during a task requiring jaw movement such as reading aloud.

Following presentation of the initial demonstration card, screens depicting the three test cards that comprise the K–D test (Fig. 2A–C) were presented serially on the computer monitor. The total test time in seconds required to complete all three test cards was recorded, as was the time to complete each individual test card. The total number of errors, both commissions and omissions, was recorded via direct observation during completion of the rapid number naming task. Binocular eye movement kinematics were recorded continuously for each test card.

Eye movement data were analyzed off-line using custom programs written in Matlab that matched standard published methods of saccade analysis [19–22]. Data obtained between card presentations were manually excluded. Several saccade analyses were completed, as delineated below. For all analyses, data within 100 ms of a blink were automatically eliminated. Analyses of velocity, acceleration, amplitude and duration characteristics were undertaken. Data were initially analyzed independently for each eye and no statistically significant differences were identified. Final data was, thus, averaged for the right and left eyes for saccade characteristics. Main sequence analyses were performed to assess amplitude/peak velocity and amplitude/duration relationships.

The first analysis included all saccades made during the task. The second included all saccades with a horizontal component of at least 2° (named task-specific saccades). Two degrees is the smallest saccade needed for number reading progression in the K–D test at a specified testing distance. The third analysis was focused on two subsets of task-specific saccades with a horizontal component larger than 2° to capture the saccades most appropriate to the task that would be in keeping with normal reading flow and of the amplitude expected for movement between the numbers on each card. The first task-specific subset included horizontal task-specific saccades made during reading of each horizontal line of numbers on each K–D card. The second task-specific subset included oblique task-specific saccades made from right to left and simultaneously downward with a horizontal amplitude of at least 10° and a vertical amplitude of at least 0.5° . These oblique task-specific saccades represented those moving the eye from the end of one line on the test card to the

beginning of the next line. For each task-specific saccade, accuracy of identification was manually verified based on the serial progression of eye movement position steps across and between lines on the test card, from left to right, and from top to bottom.

Lastly, a surrogate of saccadic latency, the inter-saccadic interval (ISI) as a metric of time separating saccades was calculated [23]. True saccadic latency, defined as a reaction time following presentation of a visual stimulus, could not be assessed secondary to the nature of the task, as all visual targets were simultaneously displayed on each test card.

3. Results

The total K–D reading time for the subjects on average was 51.24 (± 9.7) s. The per-card averages for subjects were 17.47 (± 3.77) s for card one, 17.44 (± 4.28) seconds for card two, and 16.33 (± 2.77) for card three. The number of errors committed in the rapid number naming task was available for 8 participants. Errors were not documented in the initial 4 participants. Of documented errors, two participants made 2 errors, three participants made 1 error, and 3 participants made no errors. No omissions were made. Fig. 2(D–F) shows a graphical overview of saccades made between numbers and fixations made between saccades.

The total number of saccades per subject was 145 (± 15). Average characteristics for all saccades made during the task were as follows: duration 37.6 (± 17.4) ms, amplitude 8.2 (± 7.7)°, peak velocity 299.5 (± 153.2)°/s, and peak acceleration 22,403.0 ($\pm 11,154.9$)°/s (Table 1). The average inter-saccadic interval for all saccades was 235.5 (± 119.1) ms. The total number of task-specific saccades per subject with a horizontal component larger than 2° was 119 (± 10). Of these, 102 were task-specific horizontal saccades and 17 were task-specific oblique saccades. Of all task-specific saccades, 8.8% (with a range of 3.3–15.8%) occurred in an incorrect direction for proper reading flow (e.g. leftward or upward).

Data for task-specific horizontal and oblique saccades were averaged across the twelve subjects for determination of saccade characteristics. The total number of task-specific saccades for all subjects was 2863:2492 pure horizontal saccades representing left to right number reading and 371 oblique saccades representing gaze shifts from the end of a number line to the beginning of the next line. Data are summarized in Table 2. Average characteristics for task-specific horizontal saccades were as follows: duration 36.9 (± 9.8) ms, amplitude 7.2 (± 4.4)°, peak velocity 310.5 (± 96.3)°/s, and peak acceleration 23,580 (± 8528.0)°/s. Average characteristics for task-specific oblique saccades were as follows: duration 75.2 (± 16.5) ms, amplitude 26.4 (± 2.9)°, peak velocity 570.8 (± 76.9)°/s, and peak acceleration 35,349.7 ($\pm 13,222.3$)°/s. The average inter-saccadic interval for all task-specific saccades was 237.4 (± 106.6) ms.

Main sequence plots of peak velocity versus amplitude and duration versus amplitude are shown in Fig. 3 for all horizontal saccades and in Fig. 4 for task-specific horizontal and oblique saccades. Most horizontal saccades were less than 12° in amplitude, and corresponded closely to the exponential relation, $V_p = V_{\max} (1 - e^{-A/C})$. Horizontal saccades demonstrated consistency with main sequence plots in the literature [24]. Parameter C, a

measure of the rate of approach to the maximum value, was calculated via a quasi-newton method to minimize the mean absolute deviation.

4. Discussion

We present procedural methodology for analysis of ocular motor behavior during performance of a digitized version of the K–D test in a non-concussed cohort. This will provide the first step towards development of a large normative database, to be followed by determination of how this technique may be practically applied in concussion. Eye movement recordings will be critical in defining specific deficits underlying slowed K–D reading times in concussion and will lay the groundwork for exploration of potential correlations with dysfunction of cognitive processing and other abnormalities of eye movements. Careful, objective analysis of eye movements, in general, and specifically in a test that has been shown to be sensitive in multiple cohorts for identifying athletes with concussion, offers significant potential for insight into the neuroanatomic underpinnings of brain injury.

In this study, we collected objective eye movement data during the K–D test of rapid number naming in normal subjects. The average time to read all three test cards on the digitized version of the test in this study was 51.2 s, with a range of 41.5–60.9. This is longer than the average total test time to read the hand-held version of the K–D test of 38.4 s, with a range of 24.3–56.1 s, for a control pre-season population of athletes [13]. Similarly, time to read each of cards one, two, and three was longer on the digitized K–D test than on the respective cards on the hand-held version [13]. This was initially hypothesized to be due to a longer testing distance (75 cm) for the digitized version than for the hand-held version (35–38 cm) and wider distance spread between numbers on the digitized version; however there was minimal difference between the visual angles of the two versions (width $\times$ height in degrees: 29.9×22.6 for the digitized version, 31.6×23.5 for the hand-held version). It is possible that participant differences or psychophysical differences between reading on a screen versus on hand-held materials played a role.

Approximately 120 saccades between the specific number targets on the cards would be deployed for reading completion during the test if each number were captured with a single and accurate saccade, if each number was looked at directly, and if a single and accurate saccade were made between each line of numbers. One would not anticipate, however, that this would be the method strictly followed to read the cards, even in normal subjects. Indeed, we found that, in general, more saccades were generated during the task than this approximate minimum value. On average, subjects generated 145 saccades total during the test and 119 task-specific saccades with a horizontal component of at least 2° , with 102 of these as horizontal task-specific saccades during line reading and 17 as task-specific oblique saccades during line transitions. The larger total number of saccades included all saccades with a horizontal component less than 2° , as no lower size limit filter was placed on this analysis. Of these saccades, approximately 40% were microsaccades (less than 1°) and the remaining saccades between 1 and 2° represented a combination of corrective saccades and orienting saccades during line transitions.

The number of task-specific saccades generated was very close to 120 in some subjects and examination of position tracings in such subjects revealed individual saccades between numbers and during line transitions without excess saccades (Fig. 5A). In subjects with less than 120 task-specific saccades, the initial suspected cause was that the subject read some numbers without looking directly at them; however examination of position tracings in such subjects revealed excess blinking with loss of data during line reading (Fig. 5B). In those subjects who had greater than 120 task-specific saccades, excess saccades were captured in the 8.8% of task-specific saccades defined as saccades in the wrong-direction for reading. Back-tracking during horizontal reading of a line to verify proper eye placement on the line was anticipated to be the cause of this. However, examination of the position tracings of such subjects revealed that the excess saccades tended to occur during transitions between lines, possibly for re-orientation to proper visual target selection (Fig. 5C). Thus, even healthy controls do not read perfectly and capturing and defining the range of normal behaviors will be critical to detection of abnormal ocular motor behaviors in concussed subjects.

With regard to the inter-saccadic interval, a common surrogate measure of saccadic latency during reading tasks, definition of normal behavior will allow for determination of any component of excessive saccadic latency or increased fixation duration in concussed subjects. The ISI may also offer the most insight into eye movement strategies employed by athletes who intentionally ‘sandbag’ their baseline testing in order to create a prolonged baseline score to avoid detection of slowing if concussion occurs; thereby, allowing a chance to stay in the game. Such intentional slowing of reading time will likely be due to voluntarily prolonged fixations, given lack of ability to voluntarily control saccadic velocity.

Future opportunities are vast with K–D testing and include, most importantly, development of a large normative control database, followed by objective eye movement recordings during K–D performance in a cohort of acutely concussed subjects. Though current technology limits the portability of eye tracking, ideally and eventually technological advances will allow this tool to be incorporated on the sidelines of sporting games. Additional future directions include assessments of behavior across the 3 K–D test cards with particular attention to alterations in ocular motor behavior on the visually crowded third card and assessment of intra-subject test–retest reliability. Additional opportunities also include exploration of potential correlations of K–D ocular motor parameters with other saccade paradigms, cognitive and balance testing in concussion, and functional MRI studies during K–D performance. The main limitation of the current study is the lack of spatial metrics such as precision and accuracy during K–D test performance. This stems from implementation of images of the actual K–D test cards into the experimental program and re-creation of the task to allow for capture of spatial parameters is a logical next step.

5. Conclusion

Establishment of normative, objective ocular motor behavior during the K–D test, a sensitive sideline performance measure for concussion detection, is a critical first step towards later defining the range of deficits underlying abnormal testing in concussion. Further, quantification of eye movement abnormalities in mild traumatic brain injury has the

potential to provide outcome measures essential to clinical trials and therapeutic targets for tailored rehabilitation regimens.

Acknowledgments

Sources of funding

NYU School of Medicine.

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Fig. 1.

Simplified schematic of the major cortical centers for control of eye movements and visual processing, with projections illustrating pathways for saccade generation. Saccades are initiated by signals generated in the frontal, parietal, and supplementary eye fields (FEF, PEF, SEF) that are sent serially to the superior colliculus (SC) and the brainstem gaze centers (BGC). The FEF also sends signals directly to the BGC. There is an additional pathway that projects from the cortical eye fields through the basal ganglia. A major projection of this pathway is to the substantia nigra pars reticularis (SNPR), which inhibits the SC and prevents saccade initiation. The saccade pathways are a multi-distributed network, however the FEF plays a primary role in initiation of voluntary saccades and suppression of unwanted saccades. The PEF is important for shifts of attention and initiation of reflexive saccades. The SEF plays an important role in coordinating saccades with body movement and in sequencing successive saccades. The dorsolateral prefrontal cortex (DLPC) is important in working memory for saccades to remembered target locations after target disappearance. Abbreviations: FEF, frontal eye field; PEF, parietal eye field; SEF, supplementary eye field; SC, superior colliculus; BGC, brainstem gaze centers; SNPR, substantia nigra pars reticularis; DLPC, dorsolateral prefrontal cortex; CN, caudate nucleus.

Fig. 2.

A–C: Three test cards of the King–Devick (K–D) test. To perform the K–D test, participants are asked to read the numbers from left to right and top to bottom as quickly as possible without making any errors. Time required to complete each card is recorded in seconds and the K–D time score is based on the cumulative time taken to read all three test cards. The number of errors made in reading the test cards is also recorded; misspeaks on numbers are recorded as errors if the subject does not immediately correct the mistake before continuing on to the next number. D–F: An example of task-specific eye movements utilized during the K–D test. Blue lines represent saccades between numbers and red circles represent fixations.

Fig. 3.

Main sequence plots for all horizontal saccades during the K–D test. A. Plot of peak velocity versus amplitude showing that as saccadic amplitude increases, the peak velocity increases in an asymptotic distribution. Red hatched lines indicate 5th and 95th percentiles for curve fit. B. Plot of duration versus amplitude, demonstrating a linear relation between increasing saccade amplitude and duration.

Fig. 4.

Main sequence plots for task-specific pure horizontal saccades and for task-specific oblique saccades between number lines. A. Plot of peak velocity versus amplitude for horizontal saccades showing that as saccadic amplitude increases, the peak velocity increases in an asymptotic distribution. Red hatched lines indicate 5th and 95th percentiles for curve fit. B. Plot of duration versus amplitude for horizontal saccades, demonstrating a linear relation between increasing saccade amplitude and duration. C. Plot of peak velocity versus amplitude for oblique saccades showing that as saccadic amplitude increases, the peak velocity increases in an asymptotic distribution. Red hatched lines indicate 5th and 95th percentiles for curve fit. D. Plot of duration versus amplitude for oblique saccades, demonstrating a linear relation between increasing saccade amplitude and duration.

Fig. 5.

Horizontal position (top traces in blue) and velocity (bottom traces in red) tracings of horizontal saccades on a single K–D test card in 3 healthy control subjects. A. Subject with 125 task-specific horizontal saccades during the K–D task, showing few excess saccades and no loss of data from blinks during reading of K–D card 1. B. Subject with 111 task-specific saccades, showing loss of data due to blinks (arrows) during reading of K–D card 1. C. Subject with 130 task-specific saccades, showing that excess saccades tended to occur during transitions between lines (arrows) during reading of K–D card 2. In C, the y-scale corresponds to amplitude and the velocity scale is not displayed. By convention, the upward direction on tracings corresponds to rightward eye movements and the downward direction corresponds to leftward eye movements.

Table 1

All saccades analysis averages during the K–D rapid number naming test.***

	Number of saccades	Average duration (ms)	Average amplitude (°)	Average peak velocity (°/s)	Average peak acceleration (°/s)	Inter-saccadic interval (ms)
All saccades	3236	37.6 ± 17.4	8.2 ± 7.7	299.5 ± 153.2	22,403.0 ± 11,154.9	235.5 ± 119.1

All data represent mean +/- standard deviation.

Table 2

Task-specific saccade analysis averages during the K–D rapid number naming test.^a

Type of saccade	Number of saccades	Average duration (ms)	Average amplitude (°)	Average peak velocity (°/s)	Average peak acceleration (°/s)	Inter-saccadic interval (ms)
Saccades >= 2°						
Horizontal ^b	2492	36.9 ± 9.8	7.2 ± 4.4	310.5 ± 96.3	23,580 ± 8528.0	264.7 ± 129.1
Oblique ^c	371	75.2 ± 16.5	26.4 ± 2.9	570.8 ± 76.9	35,349.7 ± 13,222.3	220.3 ± 87.8

^a All data represent mean +/- standard deviation.
^b Pure horizontal saccades, capturing left to right number reading on a line.
^c Oblique left and downward saccades, representing transitions between lines.