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The Effect of Linguistic Background on Rapid Number Naming: Implications for Native Versus Non-Native English speakers on Sideline-Focused Concussion Assessments

John-Ross Rizzo[1,2], **Todd E. Hudson**[1,2], **Prin X. Amorapanth**[1], **Weiwei Dai**[2,3], **Joel Birkemeier**[1], **Rosa Pasculli**[1], **Kyle Conti**[1], **Charles Feinberg**[1], **Jan Verstraete**[1], **Katie Dempsey**[2], **Ivan Selesnick**[3], **Laura J. Balcer**[2,4,5], **Steven L. Galetta**[2,5], and **Janet C. Rucker**[2,5]

[1]Department of Physical Medicine & Rehabilitation, NYU School of Medicine, New York, NY

[2]Department of Neurology, NYU School of Medicine, New York, NY

[3]Department of Electrical & Computer Engineering, NYU Tandon School of Engineering, New York, NY

[4]Department of Population Health, NYU School of Medicine, New York, NY

[5]Department of Ophthalmology, NYU School of Medicine, New York, NY

Abstract

Objective: To determine if native English speakers perform differently compared to non-native English speakers on a sideline-focused rapid number naming task. A secondary aim was to characterize objective differences in eye movement behavior between these cohorts.

Background: The King-Devick (KD) test is a rapid number-naming task in which numbers are read from left-to-right. This performance measure adds a component of vision-based assessment to sideline concussion testing. Reading strategies differ by language (e.g. left-to-right vs. right-to-left). Concussion may also impact language and attention. Both factors may affect test performance.

Methods: Twenty-seven healthy non-native English speakers and a healthy native English speaking control cohort performed a computerized KD test under high-resolution video-oculography. Non-native English speakers also performed a Bilingual Dominance Scale (BDS) questionnaire to weight linguistic preferences (i.e., reliance on non-English language(s)).

Results: Inter-saccadic intervals were significantly longer in non-native English speakers (346.3 78.3 ms vs. 286.1 ±49.7 ms, p=0.001), as were KD test times (54.4 ±15.1 sec vs. 43.8 ±8.6 sec, p=0.002). Higher BDS scores, reflecting higher native language dominance, were associated with longer inter-saccadic intervals in non-native English speakers.

Corresponding Author:John-Ross Rizzo, MD, MSCI, Assistant Professor, Departments of Rehabilitation Medicine and Neurology, NYU School of Medicine, 240 East 38th Street, New York, NY 10016, Phone: 212-263-7828.

Declaration of interest
The authors report no declarations of interest.

Conclusion: These findings have direct implications for the assessment of athlete performance on vision-based and other verbal sideline concussion tests; these results are particularly important given the international scope of sport. Pre-season baseline scores are therefore essential to evaluation in the event of concussion, and performance of sideline tests in the athlete's native language should be considered to optimize both baseline and post-injury test accuracy.

Keywords

bilingualism; concussion; King-Devick test; rapid number naming; saccades

INTRODUCTION:

The King-Devick (KD) test [1] is a rapid number-naming task that has been demonstrated through individual studies and meta-analyses to be a sensitive and specific performance measure for identifying athletes with concussion [2–7]. The test is a pseudo-reading task that consists of one demonstration card and three test cards of numbers with variable spatial formats that are read aloud as rapidly as possible from left to right and top to bottom in serial order. The test is administered in either spiral bound book or electronic tablet formats. The total test time and error rate are then determined. Following baseline administration, total test times are prolonged after having sustained a concussion. The test captures aspects of afferent and efferent vision, including saccades (fast eye movements) between numbers, the necessary interleaved time between fixations (the inter-saccadic intervals), as well as aspects of cognitive function. The widely-distributed nature of the physiological processes captured by the KD test helps to explain its value in the detection of neurological disorders. Quantitative eye tracking during KD testing in patients with a history of concussion has revealed inter-saccadic interval prolongation as the most likely factor associated with prolonged KD test times [8].

As the KD and other vision-based tests become more widely used among youth, collegiate and professional athletes, factors other than immediate post-impact neurologic dysfunction on KD test performance are becoming important considerations for proper test interpretation [9]. The effect of bilingualism may be one such factor, especially if a baseline assessment is not available and normative data is referenced only to native English speakers. Reading strategies with regard to when, where, and in which direction to look vary by language [10]. These strategy differences result in behavioral differences at the level of eye movement control during reading [10]. Furthermore, eye movement strategies also differ amongst visual tasks such as reading, visual scene viewing, and visual search [11]. However, little work has been done to assess the effects of language or linguistic background on eye movement strategies during rapid number naming – precisely the task with the most immediate relevance to accurate concussion detection with the KD test.

The primary aim of this investigation was to determine the relation of native- vs. non-native (fluent) English-speaking language status to KD performance and eye movement recording measurements in healthy volunteers. English was used as the language for rapid number naming. The visual-verbal task requirements of the KD test involve conversion of graphemic, or symbolic, depictions of numbers to their phonologic, or vocalized, representations [12,13]. Further complexity may arise for non-native language speakers if the subject's native language does not use Arabic numerals or if speakers have unique non-reading eye behavior approaches for task completion. These features may prolong test times. The hypothesis was that KD test times would be prolonged in non-native English-language speakers and that eye movement strategies for KD test completion would vary among native languages spoken.

METHODS:

Participants

Adult volunteers without histories of neurological impairment or visual dysfunction (other than corrected refractive error) were invited to participate in the study in two groups. One group self-reported English as their native language and the second group self-reported other languages as their native language first spoken in early life. All participants were required to be able to speak and understand written English for purposes of number naming, understanding testing instructions, and providing informed consent. Each participant completed a computerized version of the KD test under objective, video-based oculography (EyeLink 1000+). All research protocols were approved by the NYU Institutional Review Board. Written informed consent was obtained from each participant.

Materials and Performance Measures

Digitized King-Devick (KD) Testing—A computerized version of the KD test was administered. The KD test consists of four cards with a series of numbers arranged in sequential rows (Fig. 1). The first card is a demonstration card, consisting of five rows of five numbers with horizontal and oblique arrowed lines guiding the subject to correctly read the card (right to left from top to bottom/book style reading), which the participant uses as practice. The three subsequent cards are the test cards; each consists of eight rows with five numbers per row or line. Each test card varies in either visual 'guides' to direct gaze or in spatial configuration. The first test card has horizontal lines between the numbers in the row to guide horizontal saccade accuracy. The second test card rows do not contain horizontal lines between the numbers, but retain a similar spatial configuration with identical inter-row spacing. The third test card also lacks lines between numbers, but vertically compresses the space between rows of numbers by approximately 50%, narrowing the inter-row distance. The KD test administered in this paradigm was digitized and computer-generated via custom Matlab scripts. The test card dimensions were adjusted based on viewing distance to match the visual angles of the standard test cards held at a normal viewing distance.

Bilingual Dominance Scale—For participants who were non-native English speakers or whose first language was not English, a 12-question Bilingual Dominance Scale (BDS) questionnaire was orally administered in English and graded to determine the degree of subjects' language dominance. The BDS consists of closed-ended questions centered on comfort and proficiency level with both English and the primary language, defined as the first language spoken by the participant early in life. The questionnaire is graded with a scoring system developed based on correlations between question content and relevance to overall language dominance. Using methods reported in a study by Dunn and Fox Tree [14], an aggregate BDS score is generated. Study participants were unaware of the BDS grading system. The weighted accumulation of points on the BDS demonstrates whether the speaker is dominant in either English or their non-English native language and to what extent. A positive score indicates English-language dominance and a negative score, native language dominance.

Eye Movement Recordings—Binocular eye movement recordings were obtained with an infrared oculography camera (Eyelink 1000+, SR Research, Mississauga, Ontario, Canada) in remote mode utilizing a forehead-rest for maximum head stability while simultaneously allowing for mouth movements required for number naming (Fig. 2). The system has a sampling rate of 500 Hz and 0.25 to 0.5 degree of accuracy. Each participant underwent a 13-point spatial calibration procedure, followed by one KD rapid number naming test trial. The total test time in seconds needed to read all the numbers in English on the three test cards (excluding time between cards) was recorded, as was the time to complete each individual test card. The total number of errors was also recorded. Eye movements were recorded continuously during each test card administration.

Eye movement data were analyzed off-line using custom Matlab software. Data for eye movements that occurred between card presentations (i.e., not associated with the rapid number naming task) were automatically identified for exclusion and manually confirmed. Data recorded within 100 ms of each eye blink were automatically eliminated. Saccades were identified via an adaptive threshold mechanism and velocities and accelerations were computed from position traces using a low-pass differentiator. Saccades were analyzed in two groups: all saccades and task-specific saccades; task-specific saccades were defined as saccades of greater than 2 degrees of horizontal amplitude (smallest saccade needed for number reading progression in K-D at chosen testing distance)[15].

Data Analyses

For continuous variables, such as KD test time and intersaccadic intervals (ISI), between-group comparisons of means for native English vs. non-native English speakers were performed using two-sample t-tests. Pearson linear correlations were calculated to assess the relation between KD test times and saccade metrics such as numbers of saccades and ISI durations. Linear regression models were also incorporated to examine associations of continuous variables such as KD test time and ISI, accounting simultaneously for age. Continuous variables fit assumptions for normality throughout the dataset.

RESULTS:

Study Cohort

Forty-two native English speakers (age range 19–52 years, mean 32 ± 9 years, 28 women) and 27 non-native English speakers (age range 24–58 years, mean 34 ± 9 years, 16 women) (Table 1) were included. Non-native English speaking participants varied with regard to level of English speaking proficiency, as measured by the Bilingual Dominance Scale questionnaire, and were grouped into the following categories: heavily dominant in native language (11 subjects), slightly dominant in native language (4 subjects), non-dominance in language proficiency (7 subjects), and heavily dominant in English language (5 subjects). The 27 non-native English speakers had a variety of different languages as their native language; languages included Spanish (n=5), Chinese (n=4), Farsi, (n=2), German (n=2), and one each for Albanian, Garifuna, Gujarati, Hebrew, Hindi, Italian, Japanese, Korean, Portuguese, Romanian, Russian, Tagalog, Turkish, and Urdu (Table 1).

KD Test Measures

Average KD total completion times ranged from 43.8 ± 8.6 seconds (native English speakers) to 54.4 ± 15.1 seconds (non-native English speakers), with longer times in the non-native group (p=0.002, two-sample t-test) (Table 2). Per-card averages are shown in Table 2. Number naming errors included 1 error each in 2 non-native participants and 3 native participants, 2 errors in 1 native participant, 5 errors in 1 non-native participant, 8 errors in 1 non-native participant, and 30 errors in 1 non-native English speaking participant. This subject with 30 errors skipped entire lines of numbers on the KD cards, decreasing overall performance.

Eye Movement Analysis

Kinematic Measures + Main Sequence Relationships—Kinematics, including peak velocity and peak acceleration/deceleration, were similar between cohorts and within expected ranges (all p>0.05, Table 2). Overall mean saccadic duration was also similar between groups. Saccade main sequence relationships between saccade amplitude, peak velocity, and duration (Table 2) were similar in native and non-native English speakers, as demonstrated by the overlap in main sequence plots and fitted curves (Fig. 3). No statistically significant differences were found in fits to main sequence data (all p>0.05). Overall, main sequence relationships were preserved in each cohort.

Inter-saccadic interval (ISI)—Significant differences in ISI were found between the two cohorts (native English speaking: 286.1 ± 49.7 ms, non-native English speaking: 346.3 ± 78.3, p=0.001, t-test). Distributions of ISI values are shown in Fig. 4. We present histograms of ISI values to highlight the overall pattern of ISI values produced by these two groups, and raster plots to highlight individual differences in the distribution of ISI values. ISI values were greater among participants with longer KD test times (Fig. 5, Top) in the native English speaking group (r = 0.79, p<0.01), but not in the non-native English speaking group (r = 0.31). ISI values were, however, significantly correlated with negative BDS scores (BDS score −30 to 0) in the non-native group (r = −0.69, p = 0.001; Fig. 5, Bottom), demonstrating a link between greater dominance in a non-English first language and prolonged ISI values.

Number of saccades—The number of task-specific saccades varied by individual and was greater among participants with longer KD test times (Fig. 5, Middle) in the native English-speaking group (r = 0.60, p < 0.01). These inter-individual differences in the number of task-specific saccades were greater in the non-native English speaking group (p = 0.02, t-test) for the shortest task-specific saccades (those less than 6 degrees of amplitude). However, the number of saccades produced by non-native English speaking subjects (in all task-specific, and the shortest task-specific range) was not significantly associated with longer (worse) KD completion times (p =0.08 to 0.50).

BDS Scores—Non-native English speaking subjects had a median BDS score of −6 (Fig. 6), with an inter-quartile range of 18.5. For non-native English speaking participants with negative BDS scores (e.g. dominant in their native tongue), there was a significant correlation with median ISI ($r = -0.69$, $p = 0.001$), but not with the number of saccades ($r = 0.07$, $p = 0.39$). In addition, greater ISI values were produced by non-native English speaking participants. Accounting simultaneously for number of saccades, ISI continued to be a significant predictor of BDS score ($p = 0.01$, linear regression).

Spatial measures—Of the spatial measures examined in this study, only average saccade amplitudes showed a significant difference between native and non-native English speaking participants ($p = 0.02$). There were no differences between non-native and native English-speaking participants on any other spatial metrics, including x- or y-position relative to the closest visible numbers, and 2D distance of the eye and the closest visible number during fixation ($p = 0.18$ to 0.61).

DISCUSSION:

This study demonstrates differences in performance and eye movement strategies between non-native and native English speakers during a rapid number naming task. The most salient of these differences include: prolongation of total KD test times, longer ISI durations, and an increased variability in the number of task-specific saccades used for task completion in non-native English speakers. Furthermore, correlations are demonstrated between linguistic dominance and ISI duration in those non-native English speakers with dominance in their native language (negative BDS scores), between ISI durations and total KD test time in native English speakers, and between the number of task-specific saccades and total KD test time in native English speakers. Each of these findings will be discussed, in turn, with attention to potential implications for baseline testing and sideline assessment for mild traumatic brain injury with the KD test.

Saccade Kinematics

Classical measures of saccade function, including velocity, duration, acceleration, and deceleration showed no differences between non-native and native English speaking subjects. Saccade main sequence relationships between peak velocity, amplitude, and duration were similar between the groups. This result is not surprising, since vision is suppressed during saccadic eye movements [16] to prevent visual blur. Furthermore, new information about the visual targets on the KD test is acquired only between saccadic eye movements in the inter-saccadic fixation intervals. Saccade speed is largely controlled at the level of the brainstem by saccade burst neurons and language-based differences between the two groups would be expected to be mediated at a higher-order cortical level.

Intersection of ISI Duration & Cognitive Linguistics

ISI durations were significantly prolonged for the non-native English speaking cohort, as compared to the native English speakers. Further, ISI duration correlated with degree of dominance in the native tongue among those non-native English speakers who were more dominant in their native tongue (negative BDS scores). The ISI is a measure of the time between saccades that represents a complicated set of processes, including saccade planning, latency/reaction time, fixation, and cognitive underpinnings, including number recognition and identification, and language retrieval. The hypothesis for this study was that ISI and the relative contribution of its components would be different for linguistically diverse individuals (non-native English speakers). For example, if one is highly practiced in reading numbers aloud in English (e.g., an American elementary school math teacher), the major components of the ISI might be the time necessary to plan the next eye movement and saccade latency. On the other hand, in participants for whom speaking numbers in English is less automatic, the time necessary to match the symbol to a stored memory and recall the English name of each number symbol (i.e., conversion of orthographic to phonologic information) might be significantly lengthened. The major ISI components, while still including saccade planning and latency, would also be lengthened by additional cognitive processing [17–19].

Language is integral to cognitive function and vice versa. Both are pivotal to reading and to the visual-verbal and pseudo-reading nature of the KD test. In bilingual individuals, native and non-native languages may compete or conflict and precipitate processing delays and inefficiencies in the orthographic to phonologic conversion of numbers needed for task completion [20]. This may be even more dramatic if the native tongue is not dependent on Arabic numerals. For example, if one is a non-English native speaker who is relatively fluent in the English language that he or she learned later in life, he or she may still 'default' to an indigenous numerical system that is not relevant to the Arabic numerals required by the KD task. These issues may be even more dramatic in the setting of concussion, when the executive control required to control competition between language activation and additional centers may be impaired, leading to conflicts [21].

In addition to the issues related to orthographic/phonologic conversion, another mechanism by which language may prolong ISI during the KD test is related to the lateralization of neural systems underlying number, magnitude, and language processing. This lateralization may influence both afferent and efferent aspects of KD performance. On the afferent side, directional preferences have been demonstrated for the processing of time, numbers, movement, and action, with reaction time and accuracy advantages for stimuli with left-to-right orientations for English speaking subjects [22–25]. On the efferent side, faster eye movement initiation occurs with categorization of numbers oriented in a mental "number line," with smaller numbers on the left and larger numbers on the right. This is called the spatial-numerical association of code, or SNARC, effect [26,27]. Thus, in considering the KD, speakers of languages that read from right-to-left may have a relative impairment when processing stimuli from left-to-right as a result of developmental lateralization preferences for right-to-left stimuli. Taken together, these effects are an interesting instantiation of the Sapir-Whorf hypothesis that language may constrain cognitive processes [28,29].

Of particular interest with regard to this study, eye movement investigations have been utilized to study the cognitive effects of bilingualism [10,30]. Certainly, second language exposure can modify reading behaviour; including allocation of visual attention and global measures of reading difficulty [31].

KD Test Times relative to ISI, as a component metric

The ISI was strongly correlated with KD test times in this study for native English speakers. This has been shown in healthy and individuals with chronic concussion in a separate study [8]. However, in this study, ISI did not correlate well with total KD test times for the entire cohort of non-native English-speakers but did correlate well in those non-native English speakers that were dominant in their native language (BDS score −30 to 0). In other words, non-native English speakers not dominant in English had prolonged ISI times that correlated with prolonged KD times. It is likely that the lack of whole group correlation is a by-product of the variable linguistic dominance in the non-native English language group, thus confounding the expected correlation observed in prior studies. Non-native English speaking subjects had quantified dominance scores that varied highly, as assessed by their BDS scores (11: heavily dominant in native; 4 slightly dominant in native; 7 neutral; and 5 heavily dominant in English), and this likely precipitated a reciprocal variability in the ISI differences as compared to the native English speakers (i.e., non-native speakers had a significant amount of variability across the ISI metric when considered across the cohort; small differences between ISI scores when more dominant in English, and larger differences between ISI scores when more dominant in their native language; these differences appear to a have affected the correlations to the total KD test times).

Saccade Frequency and Spatial Analysis

The number of task-specific saccades varied by individual and was correlated with KD completion times in the native English speaking group, and uncorrelated in the non-native English speaking subjects. However, inter-individual differences in the number of task-specific saccades were greater in the non-native English speaking group for the smallest task-specific saccades. This greater inter-individual variability and loss of correlation in the non-native English speaking group is also likely a by-product of the wide-ranging linguistic dominance scores in the original language (BDS variability). Within the non-native group, disparate ocular motor strategies were deployed during task completion between subgroups, yielding fewer saccades in those more dominant in English but still considered non-native English speakers (positive BDS scores) and more saccades in those more dominant in their native language (negative BDS scores).

It was anticipated that different spatial strategies would be identified between the non-native and native groups, given the higher cognitive burden imposed in the non-native English speakers. Such differences exist in other common dual-task scenarios such as gait kinematics and cognitive burden [32,33], where modifications in performance on one task may occur at expense of another [34]. However, such differences were not observed in the spatial eye movement behaviour during the KD test in non-native English speakers compared to native English speakers. Despite these initial findings, this direction of research is rife with opportunity and warrants further exploration.

Limitations and Future Directions

The wide-ranging linguistic contributions to and variable degrees of native language dominance in the non-native English speaking cohort in this study are potential study limitations. Larger sample sizes dedicated to specific languages and greater dominance ‘spread’ to allow for data stratification and subgroup analyses would be ideal for future studies beyond this pilot investigation.

CONCLUSIONS

In summary, total testing times on the KD test were prolonged in healthy non-native English speakers due to prolonged inter-saccadic intervals; this language effect was more pronounced the more dominant an individual was in their native tongue. Caution should be taken in comparing the KD test times of non-native English speakers to a native English speaking-based control database as a substitute for comparisons to individual baselines. Concussion screening best practice is to establish individual pre-season baseline scores to allow for intra-subject comparisons after head impact.

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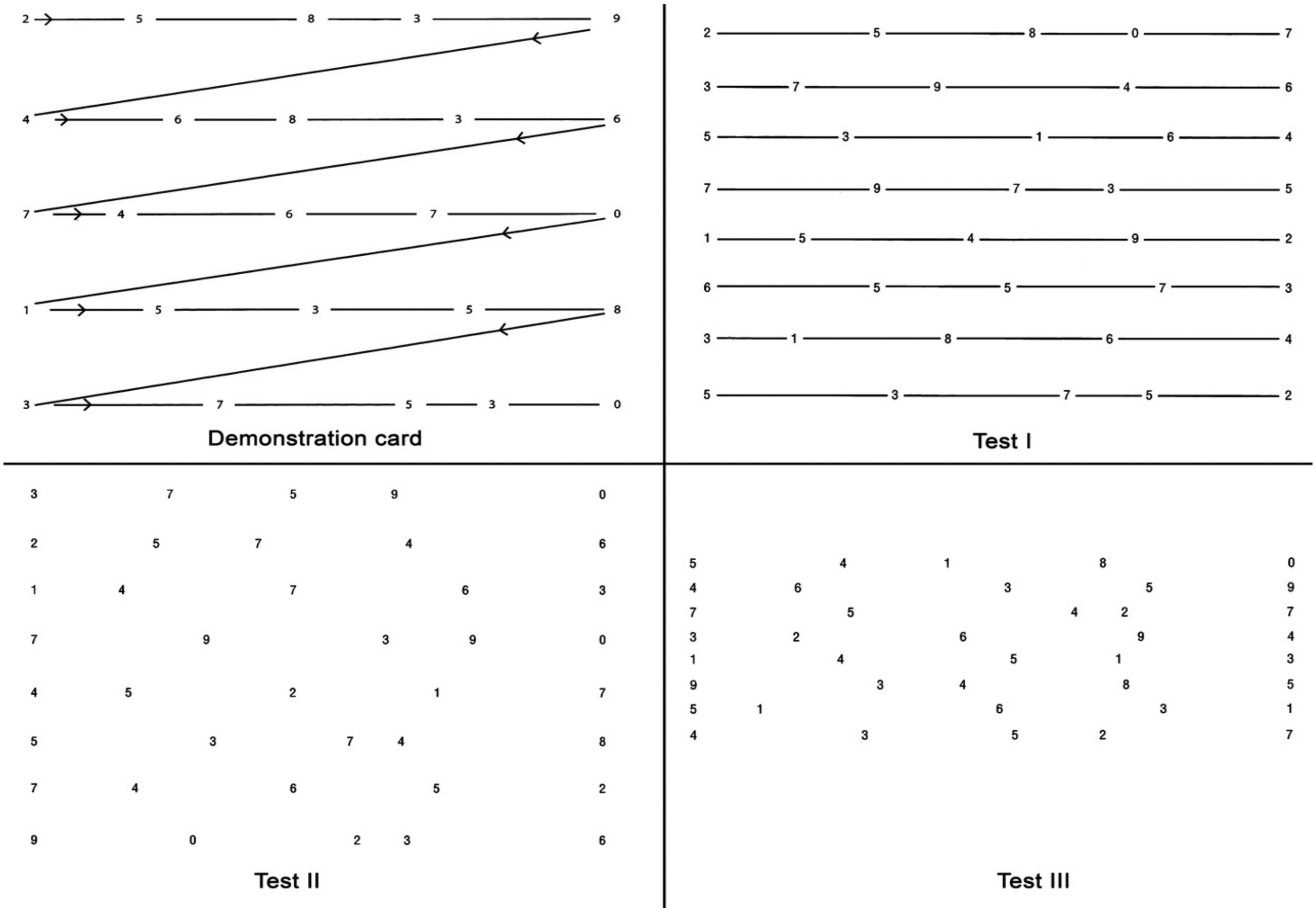

Fig. 1.
King Devick test cards. Demonstration card and test cards 1, 2, and 3 (as implemented in digital paradigm and on sideline testing).

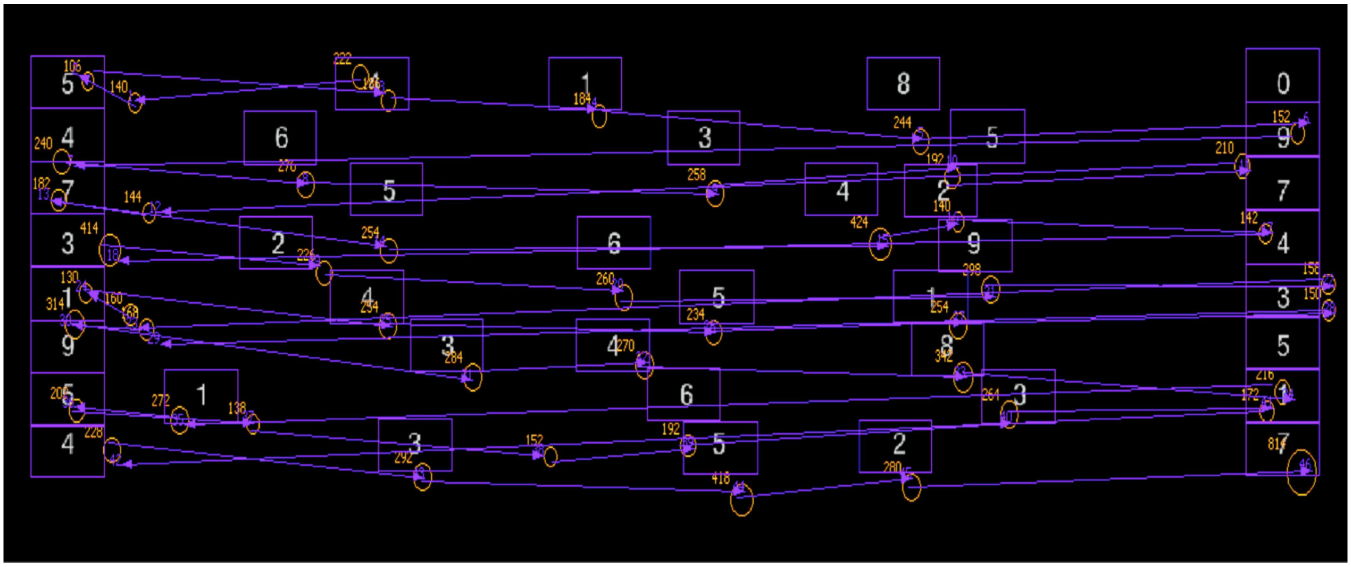

Fig. 2.

Demonstration of eye tracking position tracings of saccades and fixations overlaid on KD test card 3 for a representative native English speaking subject. Purple lines represent ‘task-specific’ horizontal and and oblique saccades and yellow circles represent fixations.

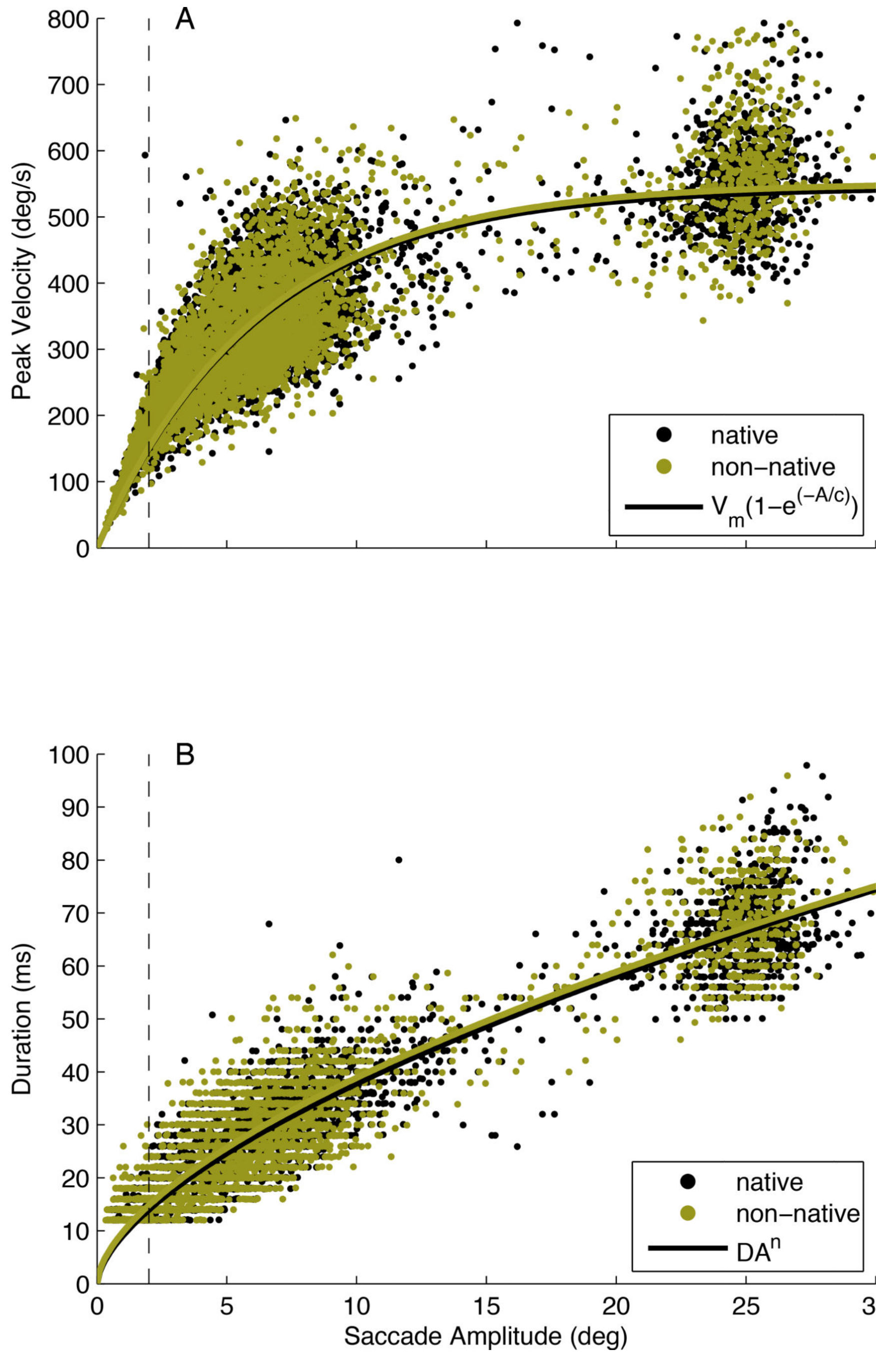

Fig. 3.

Main sequence plots of non-native and native English speakers for all saccades during the KD test. Dotted line demarcates task-specific saccades (2 degrees or greater) **Top.** Plot of peak velocity versus amplitude showing that as saccade amplitude increases, the peak velocity increases in an asymptotic distribution. Parameters: Non-native Vm = 551.6 deg/sec, c = 6.2; Native Vm = 545.4 deg/sec, c = 6.2. **Bottom.** Plot of duration versus amplitude. Parameters: Non-native D = 9.8 ms, n = 0.6; Native D = 9.1 ms, n = 0.6. No differences are seen in these relationships between non-native and native English speaking subjects in either plot.

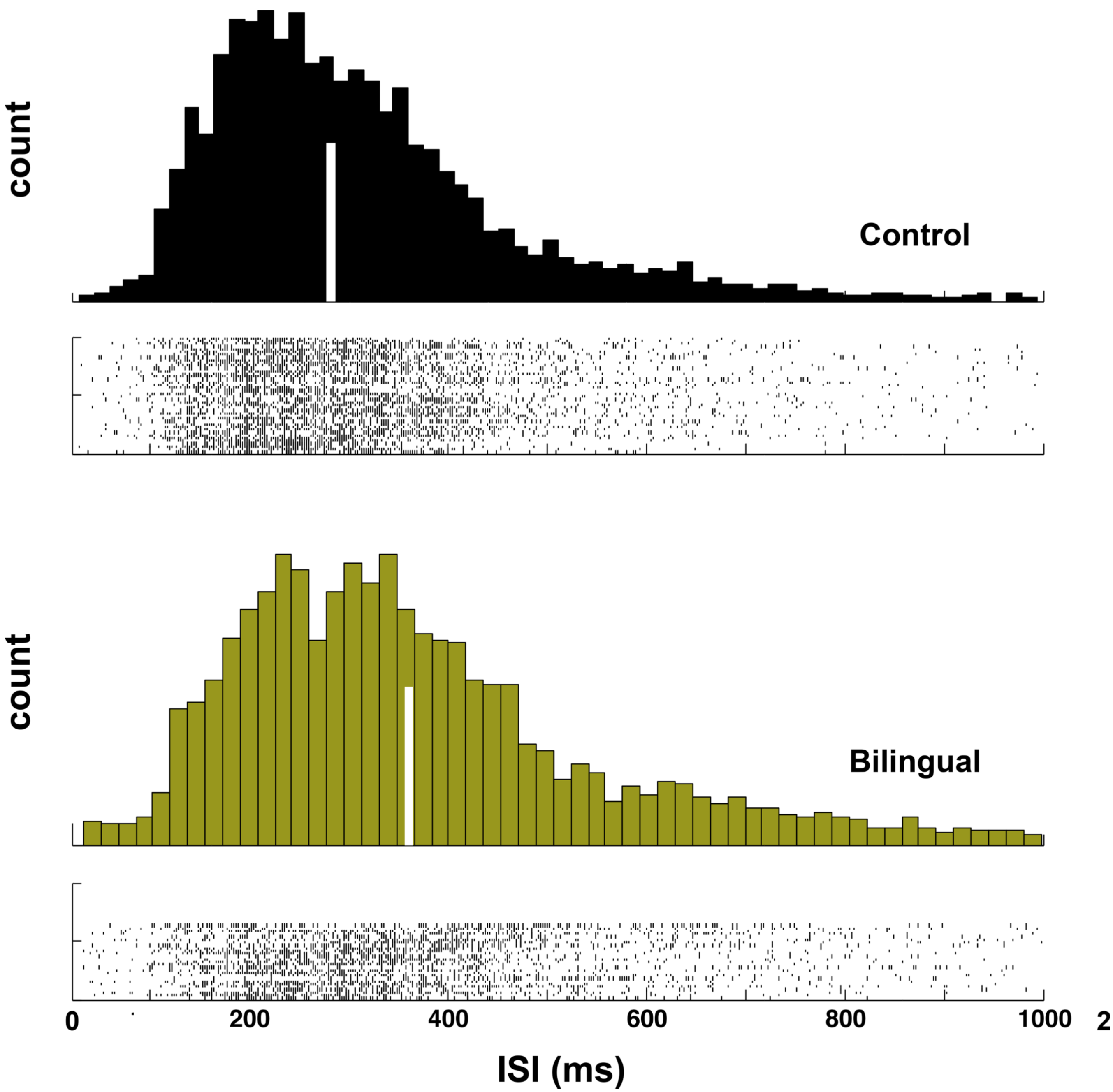

Fig. 4.

Distributions of inter-saccadic intervals in non-native (labeled Bilingual) and native (labeled Control) English-speakers. Histograms of inter-saccadic interval (ISI) values are plotted over subject-by-subject raster plots of the same data. Histograms highlight the overall distribution of ISI values, while rasters highlight any individual differences in the pattern of ISI values relative to the group.

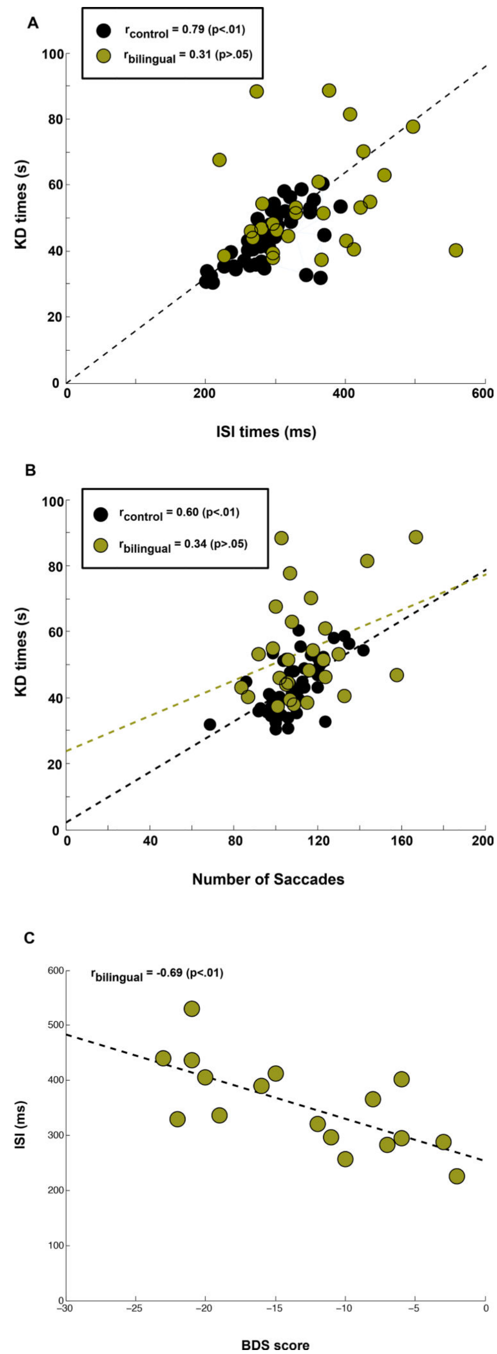

Fig. 5.

Correlation plots. **Top.** Correlations between median ISI values and KD test times. **Middle.** Correlations between the number of saccades below 20 degrees produced by each subject and that subject's KD test time. **Bottom.** Correlation between ISI times and BDS scores for subjects producing negative BDS scores (displaying dominance in a language other than English). In all panels, dashed lines are the best-fitted line through the origin that minimizes total squared error of the fit.

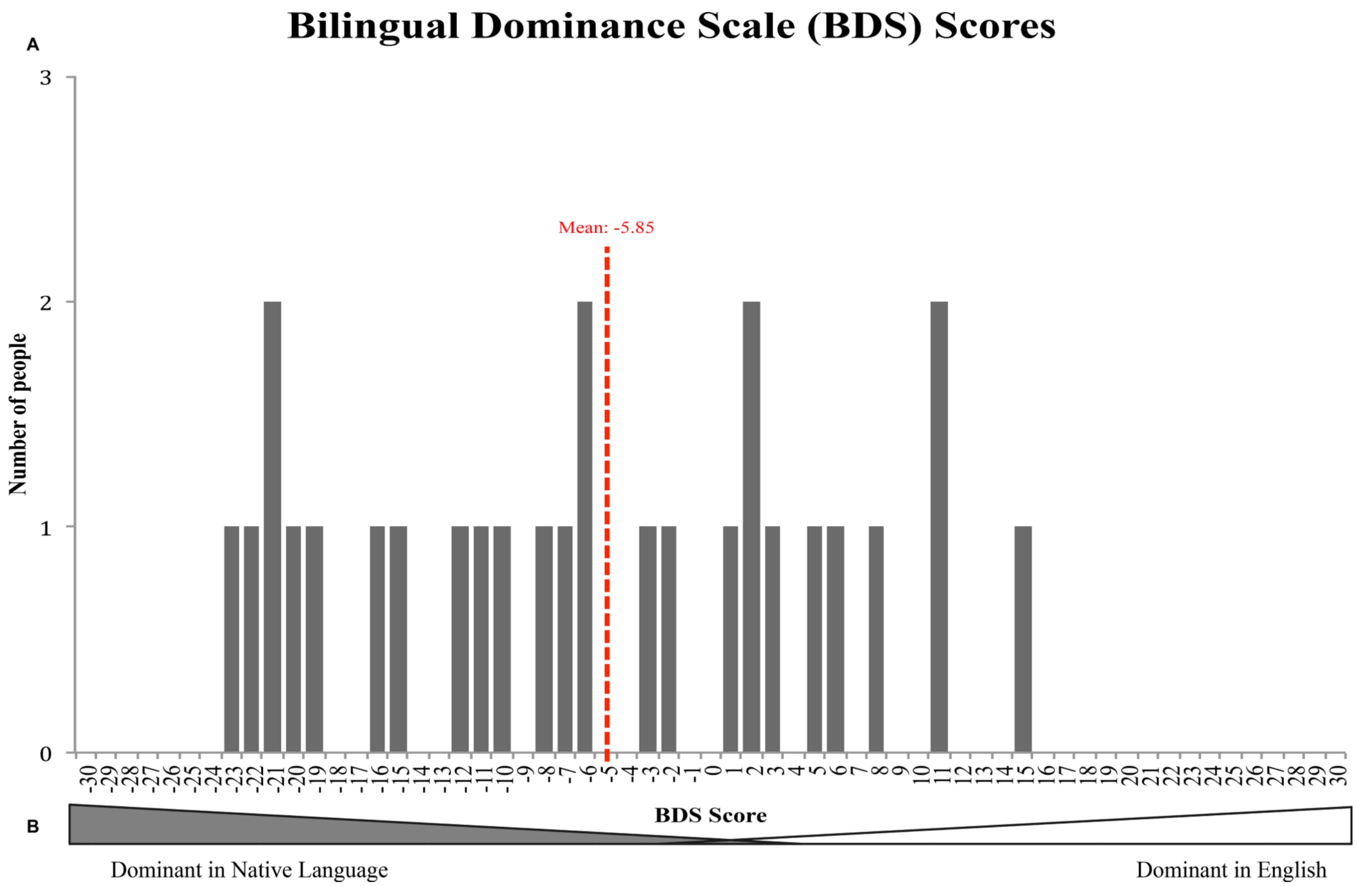

Fig. 6.

Bilingual Dominance Scale (BDS) Scores. (A) Histogram of the non-native (Bilinguals) English-speakers (B) Schematic demonstrating the dominance in either the non-native speakers' native language or their non-native language, in this case English, as assessed by numerical magnitude and sign.

TABLE 1:

Non-Native English Speaker Demographics

Gender	Age (y)	First Language	Years Speaking English	BDS score*	KD error
Female	34	Spanish	9	−11	0
Male	28	Russian	17	2	0
Female	27	Albanian	14	11	0
Female	27	German	16	−12	0
Male	31	Italian	25	−15	0
Female	39	Romanian	25	−7	0
Female	26	Turkish	17	−6	0
Male	25	Chinese	12	−21	0
Male	30	Farsi	20	−8	0
Female	45	Hebrew	36	−2	0
Female	34	Hindi	31	8	0
Female	30	Japanese	26	6	30
Male	32	German	21	−3	0
Female	37	Spanish	34	1	0
Male	45	Spanish	39	15	0
Female	25	Chinese	12	−19	0
Male	25	Gujarati	17	−10	0
Female	38	Korean	35	11	0
Male	35	Farsi	19	−22	0
Female	34	Chinese	21	−20	0
Male	48	Garifuna	35	−16	8
Female	58	Tagalog	46	−6	5
Female	31	Portuguese	31	3	0
Female	24	Chinese	13	−21	0
Male	26	Urdu	20	2	0
Male	33	Spanish	25	−23	1
Female	52	Spanish	13	5	1

* BDS = Bilingual Dominance Scale score. A positive number indicates dominance in the English language. A negative number indicates dominance in the native language.

TABLE 2:

Eye Movement Data

Variables	Native English (n = 42)	Non-Native English (n=27)
Numbers of all saccades	138 ± 18	149 ± 28
Numbers of KD saccades	124 ± 15	128 ± 18
Wrong Directional Saccade Percentage (%)	10.1% ± 5.3%	12.3% ± 8.5%
Temporal		
Total KD Time (s)	43.8 ± 8.6	54.4 ± 15.1
Card 1 time (s)	14.3 ± 2.9	16.9 ± 3.9
Card 2 time (s)	14.4 ± 2.7	18.2 ± 6.0
Card 3 time (s)	15.1 ± 3.3	19.3 ± 6.3
Duration (ms)	32.0 ± 4.0	31.8 ± 4.8
Peak velocity (deg/s)	341.6 ± 49.7	337.8 ± 54.5
Peak acceleration (deg/ss)	38754.0 ± 6881.6	37885.9 ± 8098.9
Peak deceleration (deg/ss)	32828.7 ± 5659.5	32463.3 ± 7599.1
ISI - 2 (ms)	286.1 ± 49.7	346.3 ± 78.3
Spatial		
Amplitude (deg)	8.5 ± 0.9	8.0 ± 0.9
Distance (deg)	1.0 ± 0.3	1.1 ± 0.3
X Disparity (deg)	0.1 ± 0.3	0.1 ± 0.4
Y Disparity (deg)	0.1 ± 0.2	0.1 ± 0.2

Values are mean +/− standard deviation unless otherwise indicated.

Total KD time is the time used to finish three test cards in King-Devick Test.

All other measures were calculated for task-specific saccades.