Eye Fixation Operational Definition: Effect on Fixation Duration when Using I-DT

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Abstract

Many eye movement metrics such as the eye fixation duration metric depend, directly or indirectly, on eye fixations. However, eye fixations require an operational definition in order to be correctly classified by the eye movement event detection algorithms. This paper examines the effect of 24 different operational definitions of fixation on the results generated by Identification based on Dispersion Threshold (I-DT), the most popular eye movement event detection algorithm; and hence, the fixation duration metric. The 24 operational definitions are a combination of four different values (0.5º, 1.0º, 1.3º, and 2.0º) of the dispersion threshold and six different value (80ms, 100ms, 150ms, 200ms, 300ms, and 400ms) of the duration threshold of the I-DT algorithm. The preliminary results show that there is no statistically significant difference between the various operational definitions of fixation on the fixation duration metric.

Keywords:
Eye Tracking, Eye Movement Classification Algorithms, Eye Movement Event Detection Algorithms, I-DT, Eye Fixation, Eye Fixation Operational Defintion, Fixation Duration

1. Introduction

Eye tracking technology has been around since 1879 [10] and it went through different phases where it shifted from being intrusive and inconvenient to becoming unobtrusive and barely noticeable. Poole & Ball [35] generally define eye tracking as “a technique whereby an individual’s eye movements are measured, so that the researcher knows both where a person is looking at any given time and the sequence in which the person’s eyes are shifting from one location to another.” Eye fixation occurs when a person directs their visual gaze towards a particular location [two-dimensional coordinate points (horizontal and vertical)] on a display. However, an agreed-upon operational definition of fixation is still lacking ([33], [15], [23]). This operational definition of fixation is the essence of the eye movement event detection algorithms where it is being used to discriminate between two main events in the raw eye tracking data: fixations and saccades. The lack of such a de facto standard for the operational definition of fixation and the fact that such a definition greatly impacts the higher-level analysis, makes the measures resulting from the eye movement event detection algorithms very difficult to compare ([11], [23]).

This paper represents a preliminary study conducted to investigate the extent to which variants of the operational definition of fixation can impact the fixation duration metric, a widely used metric in many fields such as scene perception [8], educational research [24], and human behavioral research [12].

The authors in [5] & [17] mentioned a number of studies that utilized the eye fixation duration as a metric in their work. Different variants of the operational definition of fixation will be used on the best and most used eye movement event detection algorithm: Identification based on Dispersion Threshold (I-DT). I-DT is proposed by [23] which was adopted from [29].

Figure 1 shows the pseudo-code of the algorithm adopted from [23]. The algorithm starts by initializing a window based on the first raw fixation point. The window is expanded by adding more raw fixation points until the distance (i.e. the dispersion) between the farthest two points in the window is greater than the (maximum) dispersion threshold. When the newly added raw fixation points causes the dispersion of the window to go beyond the dispersion threshold, a fixation point will be created and centered based on average of all the points in the window. The process will repeat till no more raw fixation points exit.

Fig. 1. The pseudo-code of the I-DT algorithm proposed by [23]

```
INPUT: dispersion threshold, duration threshold

WHILE there are still points
   initialize window over first points to cover the duration threshold

   IF dispersion of window points <= threshold
      add additional points to the window until dispersion > threshold
         note a fixation at the centroid of the window points
      remove window points from points
   ELSE
      remove first point from points
   END IF
END WHILE

RETURN fixations
```

The fixation duration metric can be used to reveal various aspects of the task under study. Eye fixation duration refers to the amount of time a person fixates their eyes on a particular object in an area of interest [34]. Several authors believe that fixation duration determines the extent to which the person's cognitive processing is easy or difficult [37] & [33]. Specifically, the authors in [17] reported a number of plausible interpretation for the longer fixation duration when debugging a computer program such as the difficulty to understand, complexity, importance, and notability. In addition, the authors in [31] stated that "longer fixations are a sign of increased difficulty in extracting and processing information due to higher information density, ambiguity, or complexity." Similarly, the author in [36] claimed that long eye fixation duration indicates that a person is struggling and/or confused when cognitively processing an element on a display. For example, in a reading task, a longer fixation duration could mean that the text under study is conceptually difficult [21]. Similarly, in a visual search task, a longer fixation duration means, in general, that the objects presenting on the scene are not consistent [5] & [7].

Given such interpretations for the fixation duration and the fact that this metric is built on top of the fixations being generated by the eye movement event detection algorithms from the raw eye tracking data, the operational definition of fixation could play a significant role in these interpretations. This means if different operational definitions of fixation lead to significantly different fixation durations, the interpretations of such fixation durations will be different. This will lead to different conclusions and invalid results especially if the difference between the interpretation of success and failure is subtle [8] & [29].

The remaining of this paper proceeds as follows: Section 2 presents the details of the method used to investigate the research question. Section 3 details the process used to analyze the collected data from cleaning to perpetration to event detection and metric calculation. Section 4 shows the results obtained after analyzing the data and Section 5 discusses the implication of the obtained results and outlines some of the future directions.

2.Method

2.1 Participant

A 35-year old male graduate student from the University of Oklahoma took part in this study. The participant had a normal uncorrected vision.

2.2 Apparatus & software system

Tobii Pro TX300 screen-based eye tracker [25], ancestor of Tobii Pro Spectrum [27], has been used to track and collect the raw gaze data of the participant at a sampling rate of 120 Hz. Each tuple of the collected raw gaze data consists of seven main parts: timestamp, eye position, relative eye position, 3D gaze point, 2D gaze point, validity code, and pupil diameter. The timestamp holds one place in the tuple while each eye holds 13 places: three for eye position, three for relative eye position, three for 3D gaze point, two for 2D gaze point, one for pupil diameter, and one for validity code. Therefore, each packet received from the eye tracker contains a total of 27 pieces of information (see Figure 2). More information about the meaning of each part of the raw eye tracking data packet can be retrieved from Tobii Analytics SDK Developer's Guide [26].

Fig. 2. The structure of the data provided by Tobii Pro TX300 via the Tobii Analytics SDK.

Time Stamp	Left Eye													Right Eye													
	3D Eye Position			Relative 3 D Eye Position			2D Gaze Point		3D Gaze Point			Pupil Diameter	Validity Code	3D Eye Position			Relative 3 D Eye Position			2D Gaze Point		3D Gaze Point			Pupil Diameter	Validity Code
	X	Y	Z	X	Y	Z	X	Y	X	Y	Z			X	Y	Z	X	Y	Z	X	Y	X	Y	Z		

The stimulus was displayed on the monitor that comes attached to eye tracker. The monitor is 23" TFT with a resolution of 1920 x 1080 pixel and an aspect ratio of 16:9.

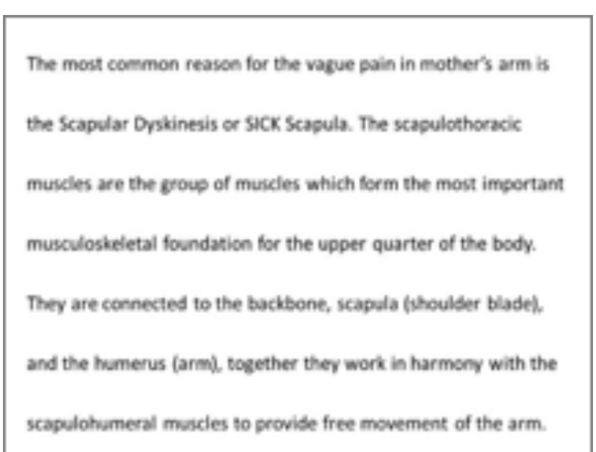
The raw eye tracking data packets recorded by the eye tracker has been read using a custom MATLAB script that utilizes Tobii Analytics SDK [27]

The software has been implemented to collect and store the raw eye tracking data into a CSV file for each session of the experiment.

2.3 Stimulus

A medical text, 69 words, excerpted and modified from [1] was used as a stimulus (Figure 3). The used text was purposely chosen as it contained several long medical terms. We assumed that those medical terms would have a low level of recognition and hence the participant would fixate longer on them [11], [20] & [21].

Fig. 3. The stimuli used in the experiment. An excerpt of a medical text with a few long medical terms. The lines of the excerpt have been spaced apart to allow for a more accurate discrimination of eye fixations.



The stimuli text, 7 lines, was prepared in a way that the lines were spaced apart to allow for more accurate discrimination of fixations. An accurate discrimination of fixations is needed to account for any precision issues of the eye tracker and allow for associating the fixations with the words that appear in the stimuli more confidently. A single space was used to separate the words in each line because the center of the word, more precisely the position before the center of the word, is considered the optimal viewing position [16] according to [18]. Given this case, a single space between the words of each line would be sufficient to accurately discriminate fixations that belong to different words.

A sans-serif font, Calibri, was used for the stimuli text. According to [14], a word displayed in a sans-serif font type is recognized faster that the same word displayed in a serif font type. In our experiment, the use of sans-serif font type would be expected to reduce the fixation duration the participant spends on the non-medical terms (i.e., frequently used words).

2.4 Procedure

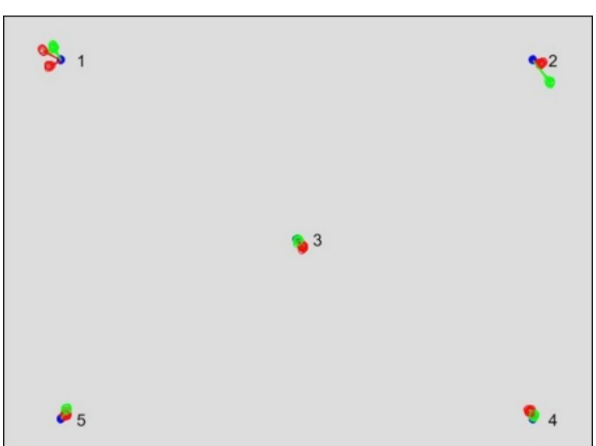
Upon the arrival of the participant to the experiment's site, a formal consent form was signed and short description about the experiment was given. To begin the experiment (reading task), the participant was seated at an average viewing distance of 68.8 cm (min=68.6 cm, max=71.7 cm) from the monitor. Then, a simple calibration of eye movements was performed. The MATLAB script available with Tobii

Analytics SDK [27] was adopted to do the calibration process that required the participant to fixate on five points in succession. If the calibration process was deemed satisfactory, which was determined based on the calibration visualization (see Figure 4), the reading task would be initiated by the experimenter. Otherwise, the calibration process would be repeated.

No eye tracking data were captured during the calibration process.

After the calibration process, the participant was asked to read the provided text carefully. The participants had been instructed to press the Escape button once he was done reading. The participant's raw eye tracking data were collected after the disappearance of the 5-second timer shown on the whole screen and blurring the stimuli (i.e., the medical text). Once the participant completed the given task and pressed the Escape button, the recording of the raw eye tracking data

Fig. 4. Visualization of the result of calibration process for the participant. The blue dots represent the calibration points where the participant needs to look at while doing the calibration. The green circles represent the left eye offset from calibration point while the red circles represent the right eye offset.



stopped accordingly. The raw eye tracking produced by the eye tracker device was saved into a CSV file at the end of the session to be processed afterward.

After finishing the reading task, the participant was asked to fill a brief survey about his English skills. The survey was intended to be used later when running the experiment with a larger sample and to account for any discrepancies that may arise from the differences in English proficiency levels of the participants and hopefully helps in explaining them.

3. Data Analysis

3.1 Data cleaning

Each packet of the collected raw eye tracking data contained a validity code for each eye. The validity code associated with the captured data about a particular eye represented how confident the eye tracker was assigning this particular data to that particular eye. A validity code of zero for both eyes represents the highest confidence level in detecting both eyes while a validity code of four for both eyes means that eye tracker was not able to detect any eye. Any mix of validity codes for the two eyes is either invalid or means that the eye tracker is not confident to which eye the captured data belong. For the complete list of different combinations of validity code, see [26].

Any raw eye tracking data packet with a validity code other than zero for any eye will not be included in the computation process. This is because the average of both eyes will be used when applying the eye movement event detection algorithm. In addition, any eye tracking data packet outside the stimuli boundary box will be excluded as well.

3.2 Data preparation

For the I-DT algorithm to work, the raw eye tracking data need to be provided. The four main components that need to be provided are: the x- and y-coordinates of the gaze on the monitor, the distance of the participant's eye from the monitor, and a reference point in time of when that raw gaze data had been collected. The gaze x- and y-coordinates are the average of the x- and y-coordinates of the 2D gaze point part of the left and right eyes reported in the raw eye tracking data package collected by the eye tracker. Similarly, the distance of the participant's eye from the monitor is the average z-coordinate of the left and right eyes reported in the 3D eye position part (refer to Apparatus & Software System section above for more information). The z-coordinate in the 3D eye position part is reported in cm while the x- and y-coordinates in the 2D gaze point part is reported in what is the Tobii call it 'Active Display Coordinate System (ADCS)'. In this system, the point (0,0) denotes the upper left corner and the point (1,1) denotes the lower right corner of the active display area which is the monitor in our case. All the x- and y-coordinates are converted from the ADCS to the monitor pixel-based coordinates.

A timestamp starting from zero is calculated for each raw eye tracking data packet based on the timestamp provided by the eye tracker. The processed version of the raw eye tracking data that are feed into the I-DT algorithm consists of four columns: timestamp, the gaze x- and y-coordinates on the monitor, and the gaze z-coordinate from the monitor (see Figure 5).

Fig. 5. Structure of data prepared from the raw gaze data provided by the Tobii Pro TX300 via Tobii Analytics SDK. The 'Time Stamp' column represents the zero-based time of when the corresponding raw gaze data packet had been collected. The 'X' and 'Y' columns represents the x- and y-coordinates of the gaze on the monitor. The 'Z' column represents how far (the z-coordinate) the eye was from the monitor.

Time Stamp	X	Y	Z

3.3 Event detection

The operational definition of fixation consists of two thresholds: duration and dispersion. The duration refers to the minimum time and the dispersion refers to the maximum area. Hence, the eyes must stay stationary within a particular area for a minimum time in order for a group of raw eye tracking data to be detected as a fixation by the I-DT algorithm. After detecting a fixation, the I-DT algorithm will continue to include all the following raw eye tracking data until the dispersion threshold is violated. When the violation happens, the duration of the fixation and the average x and y relative positions of all the raw eye gaze data packets that were part of the fixation will be recorded. The process will continue until all the raw eye tracking data are processed. Figure 1 shows the pseudo-code of the I-DT algorithm.

Table 1 presents the common values reported in the literature for the dispersion and duration thresholds as an operational definition for the fixation. This paper will investigate the effect of several combination of values for dispersion and duration thresholds, namely, 0.5º, 1.0º, 1.3º, and 2.0º for the dispersion threshold and 80ms, 100ms, 150ms, 200ms, 300ms, and 400ms for the duration threshold. Hence, a total of 24 sets of dispersion and duration thresholds combinations will be tested.

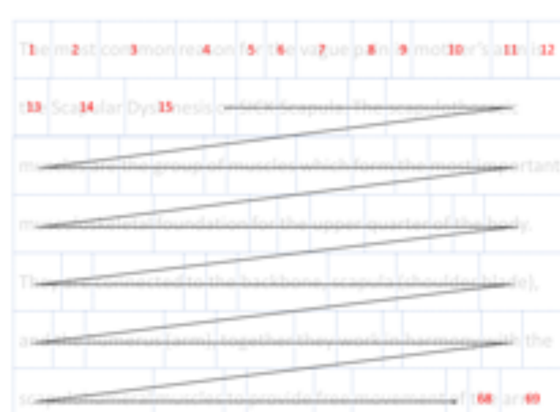
Table 1. Common values for the dispersion (in degrees) and duration (in milliseconds) thresholds reported in the literature as an operational definition for the fixation.

Source	(Maximum) Dispersion Threshold	(Minimum) Duration Threshold
(Buurman, Roersema, & Gerrissen, 1981)	1.3º	100ms
(Salthouse, Ellis, Diener, & Somberg, 1981)	2.0º	200ms
(Moffitt, 1980)	2.0º	200ms
(Widdel & Kaster, 1981)	2.0º	200ms
(Salvucci & Goldberg, 2000)	0.5º-1.0º	100-200ms
(Jacob & Karn, 2003)	2.0º	100-200ms
(Blascheck et al., 2017)	-	200-300ms
(Nyström & Holmqvist, 2010)	0.5º	80-150ms
(Blignaut, 2009)	0.5º-1.0º	100-400ms

3.4 Fixation duration metric calculation

The array of fixations obtained from the I-DT algorithm for each set of the dispersion and duration thresholds were used to calculate the fixation duration spent on each word in the stimulus. The coordinates of bounding box for each word in the stimulus (Figure 6) as well as the obtained fixations were provided into a custom MATLAB script to calculate the fixation durations as well as depict the fixations on top of the stimulus for each set of the combination of the dispersion and duration thresholds.

Fig. 6. The stimulus with a bounding box around each word. The bounding box is for illustration only. The coordinate of each bounding box, the x- and y-coordinates of the upper left and lower right corners, is what is provided to the MATLAB script.



4. Results

The participant took 42.6 seconds to finish the reading task and a total of 5019 raw eye tracking data had been collected by the eye tracker. Cleaning the raw eye tracking data resulted in excluding 52 (1.04%) packets of the data because the validity code reported by the eye tracker device is not zero for at least one of the eyes. All the raw eye tracking data were inside the stimuli bounding box and hence no data other than those that have invalid code were excluded from the analysis. Table 2 presents a fragment of the cleaned raw eye tracking data that are ready to be passed to the event detection algorithm. Figure 7 shows a visualization of the same data depicted over the stimulus.

Table 2. The raw eye tracking data after cleaning. The 'TS' column represents the zero-based time stamp for each raw eye tracking data packet. The 'X' and 'Y' columns represent the x- and y-coordinates of the gaze on the monitor in pixels. The 'Z' column represents how far the participants' eyes were from the monitor, the z-coordinate, in cm.

TS	X	Y	Z
0	964	623	686
25	968	691	686
33	967	691	686
42	968	692	686
50	971	689	686
…	…	…	…
20864	527	515	689
20872	533	522	689
20880	526	523	689
20889	528	509	689
20897	526	499	689
…	…	…	…
42519	1430	848	689
42527	1435	843	689
42536	1441	841	689
42544	1437	849	689
42552	1412	849	689

Fig. 7. The cleaned raw eye tracking data depicted over the stimuli. The small blue circles represent raw eye tracking data while the red lines represent the order in which the raw eye tracking data had been collected.

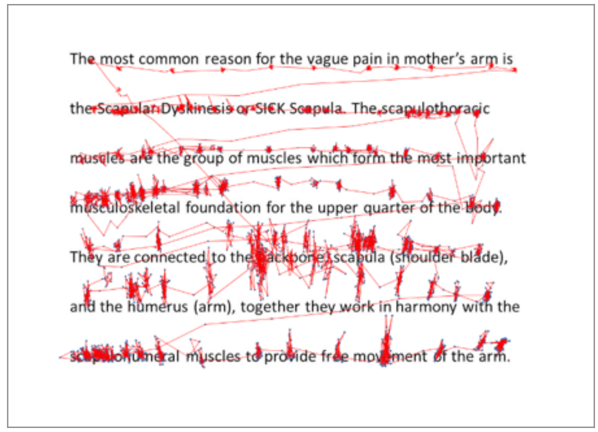


Figure 8 shows the eye fixations obtained from the I-DT algorithm from the raw eye tracking data for each of the 24 different combinations of the dispersion and duration thresholds. The eye fixations are depicted over the stimulus. The circles sizes are proportional to the fixation duration.

5. Discussion & Future Work

The reader may question the validity of the study given that only one participant was recruited. However, the main purpose of this study at this stage is not to deploy inferential statistic, i.e., to check whether there is a statistically significant differences between the different operation definitions of fixation. The goal at this stage is to check, given everything else (the participant, the task, etc.) the same, how the I-DT behave under different operational definitions of the fixation.

By looking at the patterns of the fixations in Figure 8 and the exact fixation durations in Table 3 under the different operational definitions for the fixation, we can clearly notice that the dispersion threshold is the most determinant factor of the fixation duration metric. Regardless of the duration threshold, the I-DT algorithm seems to result in almost exact fixation durations when fixing the dispersion threshold. For example, regardless of the duration threshold, 'Dyskinesis' (word #15 in line #2) was determined to be fixated on for a period of 2,217ms when the dispersion threshold was set to 0.5º; 4,374ms in the case of 1.0º dispersion threshold; 5,424ms in the case of 1.3º dispersion threshold; and zero ms in the case of 2.0º dispersion threshold. The rationale behind such behavior of the I-DT algorithm is the nature of the dispersion threshold. The dispersion threshold works as a perimeter within with the I-DT algorithm works. Hence, when the perimeter stays the same, the number of raw eye movements in close proximity that falls withing this parameter will most probably stay the same.

The other eye tracking metrics that can be taken into consideration are overall number of fixations on the whole stimulus; number of fixations on each part of the stimulus; fixation pattern, i.e., the order in which the participant scan the stimulus; time to first fixation, i.e., how long the participant spend till fixating on any part of the stimulus; number of fixated on parts of the stimulus; and others. Although some of these metrics such as the fixation pattern and the number of fixated on words can be answered here, we chose otherwise in order to keep the paper short.

Beside investigate the effect of the different settings of the two thresholds of the I-DT algorithm on other eye tracking metrics, it is worth in the future to investigate the effect of these setting when using different stimuli and/or tasks. In particular, how will the I-DT behave when administering a task that include pictures instead of text? When administering a search task instead of a reading task? Will the I-DT algorithm behave differently when using different values for its two thresholds?

Fig. 8. Fixations obtained from the I-DT algorithm for different combinations of the dispersion and duration thresholds depicted over the stimulus. The change of color from blue to yellow represents the time order of fixations where the dark blue represents the very beginning and the light yellow represent the very end. The size of the circles is proportional to the fixation duration.

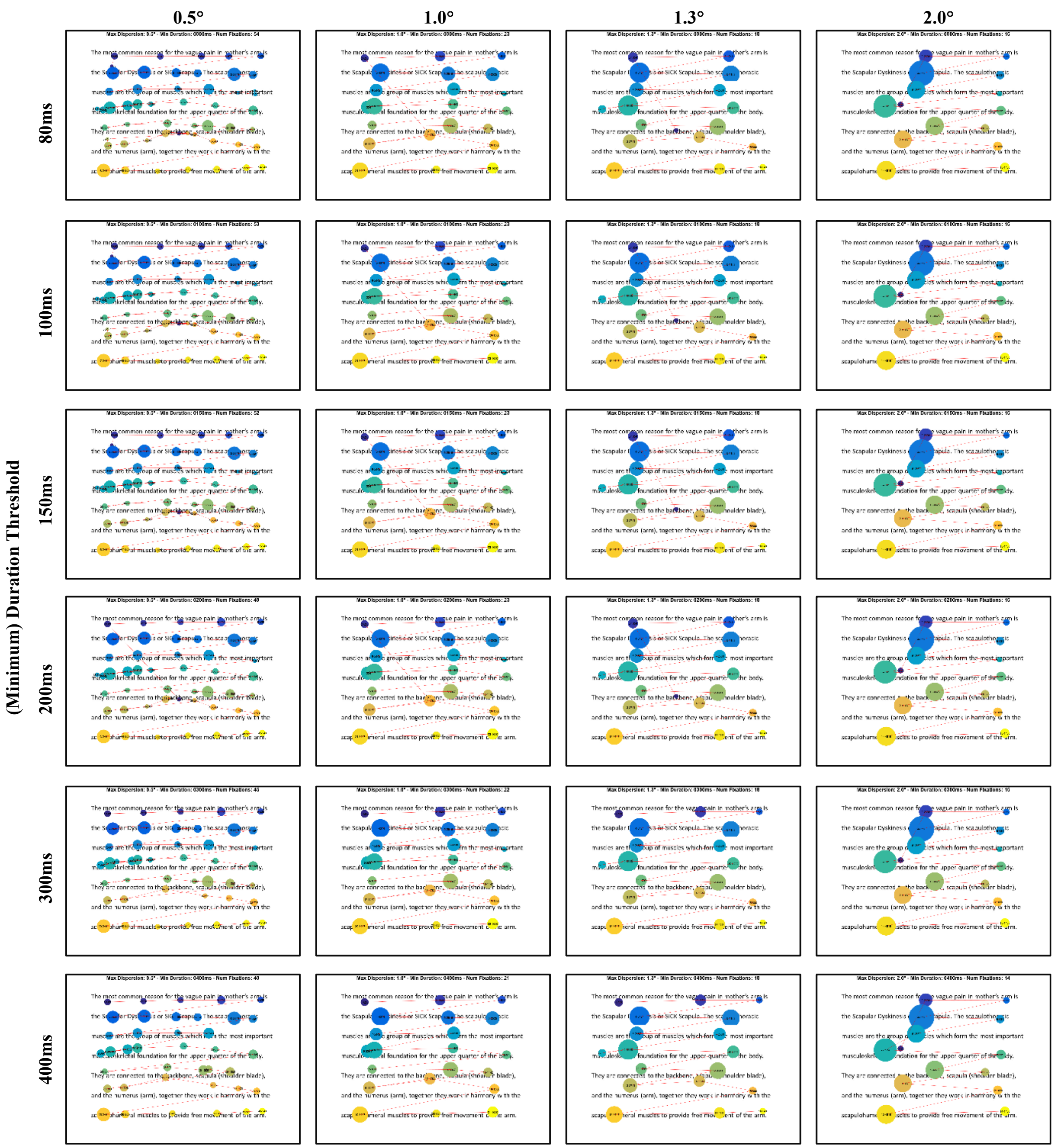


Table 3:The fixation duration (in millisecond) spent on each word in the stimulus reported by the I-DT algorithm for different combinations of values of the dispersion and duration thresholds. The empty cells if the table represent fixation duration of zero milliseconds, i.e., the I-DT algorithm does not report any eye fixation on that particular part of the stimulus when using the corresponding thresholds for dispersion and duration parameters.

Line	Word		0.5°						1.0°						1.3°						2.0°					
No	ID	Word	80	100	150	200	300	400	80	100	150	200	300	400	80	100	150	200	300	400	80	100	150	200	300	400
1	1	The																								
	2	most	642	642	642	583	583	583	825	825	825	825	825	825												
	3	common				516	516	516							1358	1358	1358	1358	925	925						
	4	reason	542	542	542																					
	5	for																								
	6	the				492	492	492													2392	2392	2392	2392	2392	2392
	7	vague	608	608	608				1433	1433	1433	1433	1433	1433					1633	1633						
	8	pain																								
	9	in				925	925	925																		
	10	mother's	575	575	575										1742	1742	1742	1742								
	11	arm	525	525	525	533	533	533	833	833	833	833	833	833					550	550	558	558	558	558	558	558
	12	is																								
2	13	the																								
	14	Scapular	2199	2199	2199	2041	2041	2041																		
	15	Dyskinesis	2217	2217	2217	2217	2217	2217	4374	4374	4374	4374	4374	4374	5424	5424	5424	5424	5424	5424						
	16	or																								
	17	SICK	1133	1133	1133	1133	1133	1133													8598	8598	8598	8598	8598	8598
	18	Scapula.	834	834	834	834	834	834	2616	2616	2616	2616	2616	2616												
	19	The																								
	20	scapulothoracic	3232	3232	3232	3232	3232	3232	2525	2525	2525	2525	2525	2525	4108	4108	4108	4108	4108	4108	933	933	933	933	933	933
3	21	muscles	867	867	867	867	867	867																		
	22	are																								
	23	the							2142	2142	2142	2142	2142	2142												
	24	group	1242	1242	1242	1242	1242	1242							2667	2667	2667	2667	2667	2667						
	25	of																								
	26	muscles	1208	1208	1208	1208	1208	1208													4350	4350	4350	4350	4350	4350
	27	which																								
	28	form	1500	1500	1500	1500	1500	1500	2208	2208	2208	2208	2208	2208												
	29	the													2066	2066	2066	2066	2066	2066						
	30	most	183	183	183																					
	31	important	333	233	233	241	325		366	366	366	366	366								383	383	383	383	383	
4	32	musculoskeletal	4167	4167	4167	4167	4157	4141	5874	5874	5874	5874	5874	5874	6216	6216	6216	6216	6216	6216	7091	7091	7091	7091	7091	7124
	33	foundation	1659	1659	1659	1659	1658	1275													425	425	425	425	425	425
	34	for																								
	35	the																								
	36	upper							1400	1400	1400	1400	1400	1400												
	37	quarter	533	533	533	533	533	533																		
	38	of													2050	2050	2050	2050	2050	2050						
	39	the																								
	40	body.	1150	1150	1150	1150	1150	1150	975	975	975	975	975	975							1192	1192	1192	1192	1192	1192
5	41	They	500	500	500	500	500	500																		
	42	are	350	350																						
	43	connected	333	333	333	333	333		1066	1066	1066	1066	1066	1066	1700	1700	1700	1700	1700	1700						
	44	to																			4166	4166	4166	4166	4166	4166
	45	the																								
	46	backbone,	2190	2190	2190	1999	1625	1541	2033	2033	2033	2033	1783	1783	258	258	258	258			4425	4425	4425	4425	4425	4425
	47	scapula	683	683	683	692	392	2150	3067	3067	3067	3067	3067	3067	5333	5333	5333	5333	5333	5333						
	48	(shoulder	1775	1775	1775	1775	1775	1050	1142	1142	1142	1142	1142	1142							875	875	875	875	875	875
	49	blade),	1050	1050	1050	1050	1050																			
6	50	and																								
	51	the	141	141	350	350	350	900																		
	52	humerus	791	791	900	900	900	808	1975	1975	1975	1975	1975	1975	2741	2741	2741	2741	2741	2741						
	53	(arm),	775	775	808	808																				
	54	together																								
	55	they																								
	56	work					716	517																		
	57	in																								
	58	harmony	275	275	275	275	325	475	1308	1308	1308	1308	1308	1308												
	59	with	500	500	500	500	517	591							800	800	800	800	800	800	1099	1099	1099	1099	1099	1099
	60	the																								

7	61	scapulohumeral	1066	1066	1066	1066	3216	3299	3467	3467	3467	3467	3467	3467	3717	3717	3717	3717	3717	3717	4816	4816	4816	4816	4816	4816
	62	muscles	2441	2441	2441	2441	858																			
	63	to																								
	64	provide	858	858	858	858	375	475	833	833	833	833	833	833												
	65	free																								
	66	movement	375	375	375	375	458	642							1691	1691	1691	1691	1691	1691						
	67	of																								
	68	the	458	458	458	458	642	583	1650	1650	1650	1650	1650	1650												
	69	arm.	642	642	642	642	583	541							541	541	541	541	541	541	1133	1133	1133	1133	1133	1133
		Total	**40552**	**40452**	**40453**	**40095**	**39761**	**38494**	**42112**	**42112**	**42112**	**42112**	**41862**	**41496**	**42412**	**42412**	**42412**	**42412**	**42162**	**42162**	**42436**	**42436**	**42436**	**42436**	**42436**	**42086**

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