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AN APPROACH TO THE STUDY OF MICROSACCADES DURING READING USING WAVELETS

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Abstract. Reading requires the integration of several central cognitive subsystems from attention and oculomotor control to word identification and language comprehension. When reading, the eyes alternate between long movements and relative stillness, that are called saccadic movements and fixations, respectively. The average fixation lasts for 150 to 250 ms and it is composed by three movements called microsaccades (or microsaccadic movements), tremor and drift. Drift and tremor are slow movements with small amplitude; microsaccades represent a ballistic component of fixational eye movements. Then, microsaccades are characterized as roughly linear movement epochs with durations up to 30ms and a frequency of one to two per second in fixations not related with reading. There are just a few works analyzing microsaccades while subjects are processing complex information and fewer when doing predictions about upcoming events. In all of them there is evidence that microsaccades are sensitive to changes of perceptual inputs as well as modulations of cognitive states. Changes in perceptual inputs are related to the type of sentences (low/high predictability, proverbs) and the characteristics of the words in the sentence (frequency, predictability, length, etc.). Let us recall the definition of maxjump: it is the word with the largest difference between the cloze predictability of two consecutive words. Then, in this work we present a first analysis of the energy of the wavelet coefficients of microsaccades during reading proverbs and low predictability sentences on words before maxjump, during maxjump and words after maxjump. The idea of this approach is to try to characterize its behavior along each one of those set of words in order to have another tool for evaluating microsaccades during reading sentences with different contextual predictability since this might provide information about specific effect of cue attention on complex task.

1 INTRODUCTION

Reading is an ordinary daily activity that integrates a number of central cognitive subsystems that go from attention and oculomotor control to word identification and language comprehension. During reading process, the eye movements alternate between long movements called saccades or saccadic movements and movements of relatively stillness called fixations. The average period of fixations lasts 150−250 ms and each fixation is really composed by three movements called microsaccades (or microsaccadic movements), tremor and drift. Tremor and drift are slow movements with small amplitude while microsaccades represent the ballistic component of fixational eye movements. That is, microsaccades are roughly characterized as linear movement epochs with duration up to 30ms and a frequency of one to two per second in fixations not related with reading (Martínez-Conde et al., 2009).

In the 1950s, studies reported that stationary objects faded perceptually in the absence of the fixational movements (Ditchburn and Ginsborg, 1952; Riggs and Ratliff, 1952; Yarbus, 1957) and in the following decades the role played by some of the fixational movements was identified (see, for example, (Ditchburn, 1980)), except for microsaccades that were supposed to "serve no useful purpose" (Kowler and Steinman, 1980). Over the last ten years, progress has been made in the study of the role of microsaccades for vision (Hafed and Clark, 2002; Martínez-Conde, 2006; Rolfs et al., 2006; Gowen et al., 2007; Otero-Millán et al., 2008; Rolfs et al., 2008; Hafed et al., 2009; Martínez-Conde et al., 2009; Chen et al., 2010; Martínez-Conde and Macknik, 2011; Otero-Millán et al., 2011a,b, 2012; McCamy et al., 2012). In (Martínez-Conde et al., 2013) the authors present a very interesting unified theory of microsaccades with emphasis on their functions. Recent works (see for example (Engbert and Kliegl, 2003; van Dam and van Ee, 2005; Shi et al., 2012; Di Stasi et al., 2013)) show diverse functions of microsaccadic movements while (Kapoula et al., 2014) shows that microsaccades corresponding to people with mild cognitive impairment have distinctive features.

In all those previous works, the main experiment performed to extract the microsaccades consist on presenting a visual stimulus on a PC to the participants and record the eye movements using an eyetracker. In order to perform the corresponding analysis, the microsaccades were identified following the article (Bettenbühl et al., 2010). However, to the best of our knowledge, the identification of microsaccades during sentence reading has not been done before.

Nevertheless, there are few works that analyze microsaccades while subjects are processing complex information and fewer when doing predictions about upcoming events. In all of them there is evidence that microsaccades are sensitive to changes of perceptual inputs as well as modulations of cognitive states (Piras et al., 2015). Changes in perceptual inputs are related to the type of sentences (low/high predictability, proverbs) and the characteristics of the words in the sentence (frequency, predictability, length, etc.). Analysis of sentences with different predictability could provide an excellent tool for understanding microsaccadic behavior in complex top-down processes. When reading proverbs, there is a typical word at which not only the next word but the entire sentence becomes available. To capture this sharp transition in predictability occurring when a subject matches the entire sentence he is actually reading to one held in his memory, it has been used the word with the maximum change in cloze predictability relative to the previous word in a given sentence. This word is called *maxjump word* (Fernández et al., 2014c) in the context of reading.

We think that it could be possible to use the energy of the wavelet coefficients related to microsaccades in the evaluation of cognitive traces during sentence reading. This would give us another tool for evaluating microsaccadic movements during reading sentences with different

contextual predictability that might provide information about specific effect of cue attention on complex task.

In that direction, the aim of this first work is to characterize the energy of the microsaccades along three set of words during reading low predictability sentences and proverbs: the words before the maxjump word, on the maxjump word and on the words after the maxjump word.

2 EXPERIMENT SETUP

In this section we describe the study we conducted to obtain the data used in this work.

2.1 Participants

We considered two different groups of healthy people with similar education: one group of young adults and other group of elderly people. The first group consisted of 40 adults with mean age 28 (SD=4.2 years) and mean education 18.2 (in years). The second one involved 40 adults with mean age 71 (SD=6.1 years), mean education 15.1 (in years). We only took into account data of 22 subjects from the first group and 24 from the second one.

2.2 Sentence corpus

To perform the experiment, we used a Spanish sentence corpus composed of 76 regular sentences that represent a large variety of grammatical structures, also called Low Predictability Sentences, and 64 Proverbs that are common in our Argentinian culture. The sentences ranged from 5 to 14 words in length; mean length being 7.3 (SD=1.9) words. The words ranged from 1 to 14 letters in length; the mean word length was 4.0 (SD=2) letters.

This sentence corpus has been used in previous works (see, for example, (Fernández et al., 2014a,b,c, 2015)).

Word Predictability. Word predictability was determined by performing an independent experiment with 18 researchers of the Departamento de Ingeniería Eléctrica y de Computadoras, Universidad Nacional del Sur. We used an incremental Cloze Task (Taylor, 1953) procedure in which participants had to guess the next word given only the prior words of the sentence. Participants guessed the first word of the unknown sentence and entered it *via* the keyboard. In return, the computer presented the first word of the original sentence on the screen. Responding to it, participants entered their guess for the second word and so on, until a period indicated the end of the sentence. Correct words stayed on the screen. The predictability of the words ranged from 0 to 1 with a mean of 0.38 (SD=0.36). Participants were between 31 and 62 years of age and did not participate in the reading experiment. The academic background of the group involved in the reading experiment and the Cloze Task group was similar. The average predictability measured from the incremental Cloze Task was transformed using the logit function defined by:

$$\mathrm{logit}(pred) = 0.5 \ln \left(\frac{pred}{1 - pred} \right), \tag{1}$$

being $pred$ the determined word predictability. The term in parentheses is called *the odds*. In order to be well defined, $pred = 0$ and $pred = 1$ in the Cloze Task procedure were replaced by $\mathrm{logit}\left(\frac{1}{2N_p}\right) = -1.77$ and $\mathrm{logit}\left(1 - \frac{1}{2N_p}\right) = 1.77$, respectively, being $N_p = 18$ the number of subjects that completed the reading. The mean of logit predictability was -0.9 (SD=0.9) for regular sentences and 0.8 (SD=1.23) for proverbs.

Maxjump word. It is the word with the largest difference between the cloze predictability

of two consecutive words and can be determined according to the following equation:

$$maxjumpword = \max\left[\text{logit}\left(pred_{N+1}\right) - \text{logit}\left(pred_N\right)\right], \tag{2}$$

being $pred_k$ the predictability of word k.

Then, $maxjumpword$ separates the sentence in three regions: before, during and after maxjump word. With this maxjump variable it is possible to test the contextual word predictability effect due to memory retrieval (Kliegl et al., 2006; Fernández et al., 2014c).

2.3 Register of eye movements

Each sentence was displayed in the centerline of a 20-inch LCD Monitor (1024×768 pixels resolution; font: regular New Courier, 18 point, vertical size of one character: 0.2 in height). The participants were seated in front of the monitor at a distance of 60 cm. Head movements were minimized using a chin rest. The participants eye movements were recorded with an EyeLink 1000 Desktop Mount (SR Research) eyetracker, with a sampling rate of 1000 Hz and an eye position resolution of 20-s arc. All recordings and calibration were binocular. The participants gaze was calibrated with a standard 13-point grid for both eyes. After validating the calibration, a fixation point appeared at the position where the first letter of the sentence was to be presented. As soon as both eyes were detected within a $1°$C radius relative to the fixation point, the sentence was presented. After reading it, participants had to move their eyes to a dot in the lower right corner of the screen to end the trial.

3 CONTINUOUS WAVELET TRANSFORM

The *continuous wavelet transform* (CWT) (see for example (Mallat, 1998)) is an efficient method for displaying and analyzing characteristics of nonstationary signals that are dependent on time and scale and then on frequency. Taking this into account, it is possible to say that it provides a very useful tool for detecting and identifying particular spectral features of the analyzed signal, transient information content and the nonstationary properties, among others. In the context of eye movements, it has been used to characterize and extract microsaccades (Bettenbühl et al., 2010).

The CWT is defined respect to a single function, called *mother wavelet* (or *analyzing wavelet*), that has particular properties which not any function fulfills. The must important property of a function for being a mother wavelet is the so called *admissibility condition* that it is required for the existence of the inverse of the CWT. The invertibility of the transform is necessary to assure that no information of the analyzed signal is lost in the CWT. In fact, the signal information can be restructured or rearranged but must be present in the CWT for the original signal to be reconstructed accurately. The admissibility condition implies that the Fourier Transform (FT) of the mother wavelet is zero at the zero frequency. That is, the mother wavelet has no DC bias and therefore must oscillate to cause it to act as a bandpass filter.

Starting with a mother wavelet ψ, it is possible to define the family $\{\psi_{a,b}(t)\}_{a,b\in\mathbb{R}}$ simply by scaling and translating the mother wavelet ψ:

$$\psi_{a,b} = \frac{1}{\sqrt{|a|}}\psi\left(\frac{t-b}{a}\right), \; a, b \in \mathbb{R}, \; a \neq 0. \tag{3}$$

The parameters a and b are called the *scaling* and *translating* parameters, respectively. Then, the parameter a gives information about its position in frequency while the parameter b gives the position of the wavelet in time. In fact, if $\widehat{\psi}(\omega)$ denotes the FT of the function ψ and μ_ω is

the media of the probability density function $\widehat{\psi}^2(\omega)|/||\widehat{\psi}||^2$, then scale and frequency are related by

$$\omega(a) = \frac{\mu_\omega}{a}. \tag{4}$$

Supposing that a function $\psi(t), t \in \mathbb{R}$ satisfies the admissibility condition, that is $\widehat{\psi}(0) = 0$, it is possible to define the CWT of a function $f \in L^2(\mathbb{R})$ in the following way

$$W_{f,\psi}(a,b) = \int_{-\infty}^{+\infty} f(t) \frac{1}{\sqrt{|a|}} \overline{\psi}\left(\frac{t-b}{a}\right) dt, \quad a, b \in \mathbb{R}. \tag{5}$$

Taking into account that ψ satisfies the admissibility condition, it is possible to reconstruct the signal $f(t)$ from its CWT by the following inversion formula

$$f(t) = \frac{2}{C_\psi} \int_0^{+\infty} \left[\int_{-\infty}^{+\infty} W_{f,\psi}(a,b) \psi_{a,b}(t) db \right] \frac{da}{a^2}, \tag{6}$$

that shows that no information is lost if we restrict the computation of the transform only to positive values of the scaling parameter a which is a usual requirement in practice. Also, the integration can be limited over to a selected range of scales, performing a band-pass filtering of the original signal. The constant C_ψ is called the *admissibility constant* and it is given by Daubechies (1992)

$$0 < C_\psi = \int_{-\infty}^{+\infty} \frac{|\widehat{\psi}(\omega)|^2}{|\omega|} d\omega < \infty. \tag{7}$$

In this work we have used the real Morlet wavelet that is a cosine function multiplied by a Gaussian window because it is closely related to human vision and hearing and has some interesting properties. One of them is that the conversion from scales to frequencies is simple, has optimal joint time-frequency concentration and represents the best compromise between time and frequency concentration (the reader is referred to (Aguiar-Conraria and Soares, 2011) for a detailed review of these properties). Its mathematical expression (Teolis, 1998; Daubechies, 1992) is given by

$$\psi(t) = \frac{1}{\sqrt{\pi f_b}} \cos(2\pi f_c t) \mathrm{e}^{-t^2/f_b}, \tag{8}$$

where f_b controls the wavelet bandwidth and f_c is the wavelet center frequency. In this paper we have set $f_c = 5$ and $f_b = 2$.

Finally, the (local) *wavelet power spectrum* or *scalogram* is defined as

$$(WPS)_{f,\psi}(a,b) = |W_{f,\psi}(a,b)|^2; \tag{9}$$

that is, it provides information about the energy of the wavelet coefficients.

4 LOCALIZATION OF MICROSACCADES

For each group of subjects, we considered all sentences, all fixations produced during each sentence reading and both eyes. Fixations on the first and the last word were removed and only fixations that lasts between 51 and 750 ms were considered. Two different methods for extracting microsaccades are (Engbert and Kliegl, 2003; Bettenbühl et al., 2010) but in both of them the set up of the experiment is different from ours. Nevertheless, we followed the ideas presented in (Bettenbühl et al., 2010) and considered the microsaccades detected using the maximum modulus lines obtained using the CWT.

Microsaccades can be modeled as smoothed singularities within a time series. These local singularities can be identified using, for example, the CWT (Arneodo et al., 1988; Mallat and Hwang, 1992) and the results are not sensitive to the choice of the mother wavelet.

In time-frequency representation, a singularity at time t_0 appears as a cone-like structure in the modulus of the wavelet transform. At lower frequencies, the wavelet is broader and the width of the cone scales with the width of the wavelet function at each voice or scale a. The wavelet focuses the whole variance at time points of singularities into the cone and its maximum at each voice corresponds to the position of the singularity in the time series. Therefore, the singularities can be detected using the modulus of the wavelet transform (Holschneider, 1988).

The *method of maximum modulus lines* (see, for example, (Marr and Hildreth, 1980; Witkin, 1983)) is a numerical method for detecting singularities in time series using the CWT. A maximum modulus line is a line on the time-scale plane on which the modulus of the wavelet transform has a local maximum with respect to small variation of the parameter b_0, that is

$$|W_{f,\psi}(a, b_0)| > |W_{f,\psi}(a, b_0 \pm \epsilon)|, \tag{10}$$

and connecting such points will give the maximum modulus lines. It can be shown that if a signal has a singularity at a given point, then there is a maximum modulus line that converges towards the location of the singularity at small scales (Mallat and Hwang, 1992). In smoothed singularities the maximum modulus line may end at a scale which is approximately the smoothing scale of the singularity. For this reason, the maximum modulus lines, which go from a fixed highest frequency/smallest scale to a smallest frequency/largest scale were considered and the estimated position of the singularity is simply the small-scale end of the corresponding maximum modulus line.

In Figure 1 there are the graphics of the horizontal position of the left and right eyes during a single fixation, together with their corresponding scalograms 9 and the maximum modulus lines. The maximum modulus line around 20 ms corresponds to a binocular microsaccadic movement.

5 DATA ANALYSIS

For analyzing the data, we considered the following signals defined for each eye

$$\begin{aligned} \tilde{h}_{eye}(t) &= (h(t) - \bar{h})/\sigma_h, \\ \tilde{v}_{eye}(t) &= (v(t) - \bar{v})/\sigma_v, \end{aligned} \tag{11}$$

where $h(t)$ is the horizontal position of one eye at the instant t, $v(t)$ is the vertical position of the same eye at the same instant, and $\bar{\cdot}$ and $\sigma_{\cdot}$ are the mean and standard deviation of the horizontal and vertical positions, respectively.

We performed the CWT using the Morlet wavelet given by (8) to both signals defined by (11). In order to identify the maximum modulus lines, we summed the square of the coefficients at every time point t over all the scales and obtained what we called the *instantaneous energy* of the signal (see Figure 1). The value of t where the local maximum of the instantaneous energy is simultaneously located for both eyes, corresponds to the time where lies the maximum modulus line associated with a binocular microssacade (see Figure 1). Finally, we kept all the values of the instantaneous energy corresponding to the binocular microsaccades and separated them in three groups depending if, at an instant t, the microssacade was located during a fixation on a word before de maxjump word (BMJ), during the maxjump word (DMJ), or during a word after the maxjump word (AMJ).

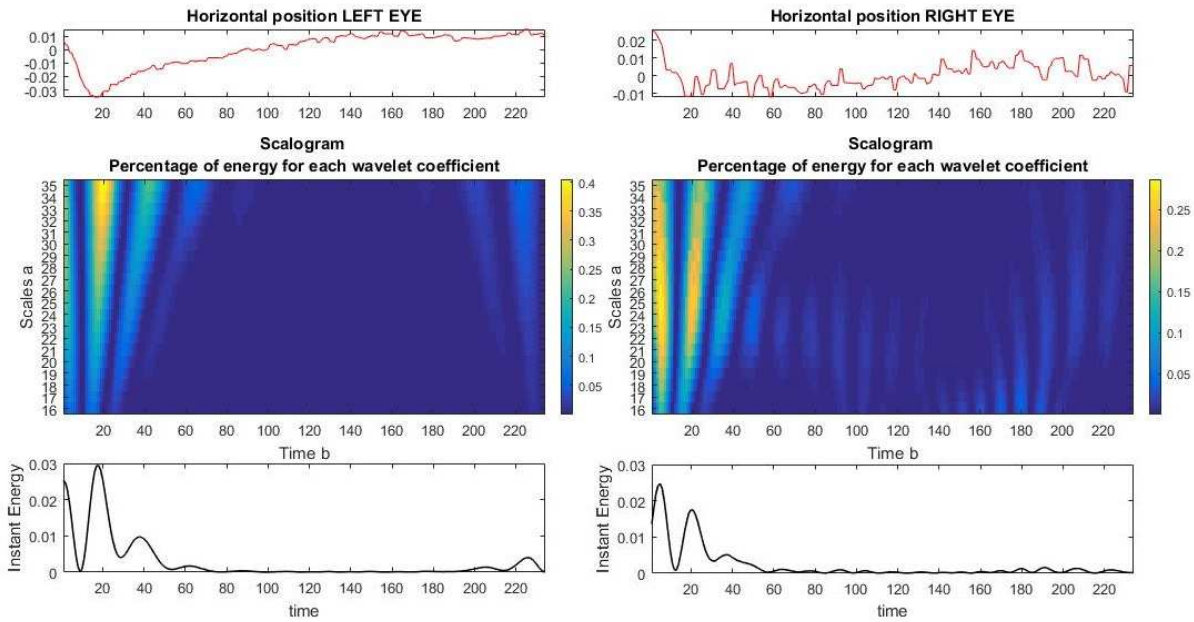

Figure 1: Above: Horizontal position of the left and right eyes during a fixation. Middle: The scalograms for each signal. Down: Instantaneous energy of each signal.

6 DISCUSSION AND RESULTS

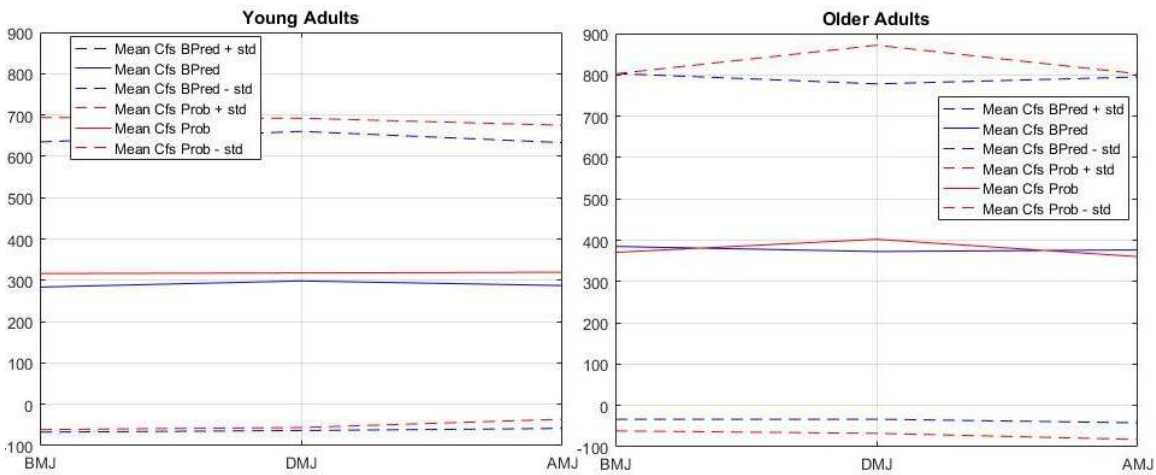

Figure 2: Distribution of coefficients in the groups BMJ, DMJ and AMJ. Full lines: mean of the coefficients. Dashed lines: mean plus(up)/minus(down) the standard deviation. Blue lines: low predictability sentences (BPred); red lines: proverbs (Prob). The graph on the left corresponds to young adults and the right one to older adults.

In order to check if the groups of coefficients were significantly different, we performed a one-way ANOVA analysis between the coefficients in the sets BMJ and DMJ, and another one-way ANOVA analysis between the coefficients in the sets DMJ and AMJ. In both cases the test showed significative differences.

In Figure 2 we simultaneously display the mean of the coefficients for the three sets BMJ, DMJ and DMJ corresponding to young and older adults (left and right figures, respectively) and

both low predictability sentences (BPred, blue filled line) and proverbs (Prob, red filled line).

In Figure 2 can be observed that the mean of the energy of the coefficients of microsaccades corresponding to young adults is similar for the three groups AMJ, DMJ, AMJ and for both groups of sentences while for older adults the value of the mean is maximum in the DMJ for proverbs while is almost constant for the low predictability sentences. Also, the media is slightly greater for older adults than for young ones. These results confirm that the microsaccadic movements change according to the characteristics of the input information during reading, and according to the age of the subjects.

7 CONCLUSIONS AND FUTURE WORK

In this work we have characterized the microsaccadic movements during reading using the energy of the wavelet coefficients. We have found that the coefficients lying on the maximum modulus lines showed differences between the groups of subjects (young and adults), the kind of sentences (proverbs and low-predictability), and the position of the word respect to the maxjump word.

We will refine the methodology for characterizing the energy of microsaccadic movements during reading with the idea of associate the change of energy with cognitive processes. Another line of work is to perform the analysis using the refined methodology to subjects with neurodegenerative diseases and compare the characteristics of the microsaccades with control subjects.

REFERENCES

Aguiar-Conraria L. and Soares M.J. The continuous wavelet transform: a primer. Documentos de trabalho - working paper series, Universidade do Minho, 2011. NIPE WP 16/2011.

Arneodo A., Grasseau G., and Holschneider M. Wavelet transform of multifractals. *Physical Review Letters*, 61(20):2281–2284, 1988.

Bettenbühl M., Paladini C., Mergenthaler K., Kliegl R., Engbert R., and Holschneider M. Microsaccade characterization using the continuous wavelet transform and principal component analysis. *Journal of Eye Movement Research*, 3(5):1–14, 2010.

Chen A. et al. The disturbance of gaze in progressive supranuclear palsy: implications for pathogenesis. *Front. Neurol.*, 1:147, 2010.

Daubechies I. *Ten Lectures on Wavelets*. Society for Industrial and Applied Mathematics-SIAM, Philadelphia, Pennsylvania, 1992.

Di Stasi L., McCamy M., Catena A., Macknik S., Cañas J., and Marínez-Conde S. Microsaccade and drift dynamics reflect mental fatigue. *Eur. J. Neurosci.*, 3(12248):2389–2398, 2013.

Ditchburn R. The function of small saccades. *Vision Research*, 20:271–271, 1980.

Ditchburn R. and Ginsborg B. Vision with a stabilized retinal image. *Nature*, 170:36–37, 1952.

Engbert R. and Kliegl R. Microsaccades uncover the orientation of covert attention. *Vision Research*, 43:1035–1045, 2003.

Fernández G., Castro L., Schumacher M., and Agamennoni O. Diagnosis of mild Alzheimer disease through the analysis of eye movements during reading. *Journal of Integrative Neuroscience*, 14(1):1–13, 2014a.

Fernández G., Laubrock J., Mandolesi P., Colombo O., and Agamennoni O. Registering eye movements during reading in Alzheimer disease: difficulties in predicting upcoming words. *Journal of Clinical and Experimental Neuropsychology*, 36(3):302–316, 2014b.

Fernández G., Schumacher M., Castro L., Orozco D., and Agamennoni O. Patients with mild

Alzheimer's disease produced shorter outgoing saccades when reading sentences. *Psychiatry Research*, 229(1-2):470–478, 2015.

Fernández G., Shalom D., Kliegl R., and Sigman M. Eye movements during reading proverbs and regular sentences: the incoming word predictability effect. *Language, Cognition and Neuroscience*, 29(3):260–273, 2014c.

Gowen E., Abadi R., Poliakoff E., Hansen P., and Miall R. Modulation of saccadic intrusions by exogenous and endogenous attention. *Brain Research*, 1141:154–167, 2007.

Hafed Z. and Clark J. Microsaccadic as an overt measure of covert attention shift. *Vision Research*, 42:2533–2545, 2002.

Hafed Z., Goffart L., and Krauzlis R. A neural mechanism of microsaccade generation in the primate superior colliculus. *Science*, 323:940–943, 2009.

Holschneider M. On the wavelet transform of fractal objects. *J. of Statistical Physics*, 50:963–993, 1988.

Kapoula Z., Yang Q., Otero-Millán J., Xiao S., Macknik S., Lang A., Verny M., and Martínez-Conde S. Distinctive features of microsaccades in Alzheimer's disease and mild cognitive impairment. *Age*, 36:535–543, 2014.

Kliegl R., Nuthaman R., and Engbert A. Tracking the mind during reading: the influence of past, present and future words on fixations duration. *Journal of Experimental Psychology*, 135(1):12–35, 2006.

Kowler E. and Steinman R. Small saccades serve no useful purpose: Reply to a letter by R. W. Ditchburn. *Vision Research*, 20:273–276, 1980.

Mallat S. *A Wavelet Tour of Signal Processing*. Academic Press, USA, 1998.

Mallat S. and Hwang W. Singularity detection and processing with wavelets. *IEEE Transactions on Information Theory*, 38(2):617–643, 1992.

Marr D. and Hildreth E. Theory of edge detection. In *Proceedings of the Royal Society of London*, volume 207 (1167) of *B, Biological Sciences*, pages 187–217. The Royal Society of London, Great Britain, 1980.

Martínez-Conde S. Fixational eye movements in normal and pathological vision. *Prog. Brain Research*, 154:151–176, 2006.

Martínez-Conde S. and Macknik S. Shifting focus. *Sci. Am. Mind.*, 22:48–55, 2011.

Martínez-Conde S., Macknik S., Troncoso X., and Hubel D. Microsaccades: a neurophysiological analysis. *Trends in Neuroscience*, 32:463–475, 2009.

Martínez-Conde S., Otero-Millán J., and Macknik S. The impact of microsaccades on vision: towards a unified theory of saccadic function. *Nature Reviews*, 14(2):83–96, 2013.

McCamy M. et al. Microsaccadic efficacy and contribution to foveal and peripheral vision. *Journal of Neuroscience*, 32:9194–9204, 2012.

Otero-Millán J., Macknik S., and Martínez-Conde S. Microsaccades and blinks trigger illusory rotation in the "rotating snakes" illusion. *Journal of Neuroscience*, 32:6043–6051, 2012.

Otero-Millán J., Macknik S., Serra A., Leigh R., and Martínez-Conde S. Triggering mechanisms in microsaccade and saccade generation: a novel proposal. *Ann. NY Acad. Sci.*, 1233:107–116, 2011a.

Otero-Millán J., Troncoso X., Macknik S., Serrano-Pedraza S., and Martínez-Conde S. Saccades and microsaccades during visual fixation, exploration, and search: foundations for a common saccadic generator. *Journal of Vision*, 8(14):21.1–18, 2008.

Otero-Millán J. et al. Distinctive features of saccadic intrusions and microsaccades in progressive supranuclear palsy. *Journal of Neuroscience*, 31:4379–4387, 2011b.

Piras A., Raffi M., Malagoli L., Lanzoni I., Persian M., and Squatrito S. Microsaccades and

prediction of a motor act outcome in a dynamic sport situation. *Investigative Ophthalmology & Visual Sciences*, 56(8):4520–4530, 2015.

Riggs L. and Ratliff F. The effects of counteracting the normal movements of the eye. *J. Opt. Soc. Am.*, 42:872–873, 1952.

Rolfs M., Laubrock J., and Kliegl R. Shortening and prolongation of saccade latencies following microsaccades. *Journal of Eye Movement Research*, 169:369–376, 2006.

Rolfs M., Laubrock J., and Kliegl R. Microsaccade-induced prolongation of saccadic latencies depends on microsaccadic amplitude. *Exp. Brain Research*, 1(3):1, 1–8, 2008.

Shi X., Xu L., Li Y., Wang T., Zhao K., and Sabel B. Fixational saccadic eye movements are altered in anisometropic amblyopia. *Restor. Neurol. Neurosci.*, 30(6):445–462, 2012.

Taylor L. Cloze procedure: a new tool for measuring readability. *Journalism Quarterly*, 30:415–433, 1953.

Teolis A. *Computational signal processing with Wavelets*. Birkäuser Boston Inc., Boston, MA, 1998.

van Dam L. and van Ee R. The role of (micro) saccades and blinks in perceptual bi-stability from slant rivalry. *Vision Res.*, 45(18):2417–2435, 2005.

Witkin A.P. Scale-space filtering. In *Proc. of the eighth international joint conference on artificial intelligence, IJCAI'83*, volume 2, pages 1019–1022. 1983.

Yarbus A. The perception of an image fixed with respect to the retina. *Biophysics*, 2:683–690, 1957.