Effect of stimulus type and motion on smooth pursuit in adults and children

Valldeflors Vinuela-Navarro[1*]; Jonathan T. Erichsen[1*]; Cathy Williams[2†]; J. Margaret Woodhouse[1*]

[*]PhD
[†]PhD, FRCOphth

[1]School of Optometry and Vision Sciences
Cardiff University
Maindy Road
Cardiff
CF24 4HQ
UK

[2]School of Social and Community Medicine
University of Bristol
Oakfield House
Oakfield Grove
Clifton
Bristol
BS8 2BN
UK

Correspondence to:
Valldeflors Vinuela-Navarro
School of Optometry and Vision Sciences
Cardiff University
Maindy Road
Cardiff
CF24 4HQ
UK
Phone: +44 (0)29 2087 0551
Fax: +44 (0)29 2087 4859
Email: VinuelaNavarroV@cardiff.ac.uk

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Abstract

Purpose: This study presents a 2° customized animated stimulus developed to evaluate smooth pursuit in children and investigates the effect of its predetermined characteristics (stimulus type and size) in an adult population. Then, the animated stimulus is used to evaluate the impact of different pursuit motion paradigms in children.

Methods: To study the effect of animating a stimulus, eye movement recordings were obtained from 20 young adults while the customised animated stimulus and a standard dot stimulus were presented moving horizontally at a constant velocity. In order to study the effect of using a larger stimulus size, eye movement recordings were obtained from 10 young adults while presenting a standard dot stimulus of different size (1° and 2°) moving horizontally at a constant velocity. Finally, eye movement recordings were obtained from 12 children while the 2° customized animated stimulus was presented following three different smooth pursuit motion paradigms. Performance parameters, including gains and number of saccades, were calculated for each stimulus condition.

Results: The animated stimulus produced in young adults significantly higher velocity gain (mean: 0.93; 95% CI: 0.90-0.96; p=0.014), position gain (0.93; 0.85-1; p=0.025), proportion of smooth pursuit (0.94; 0.91-0.96, p=0.002) and fewer saccades (5.30; 3.64-6.96, p=0.008) than a standard dot (velocity gain: 0.87; 0.82-0.92; position gain: 0.82; 0.72-0.92; proportion smooth pursuit: 0.872; 0.83-0.90; number of saccades: 7.75; 5.30-10.46). In contrast, changing the size of a standard dot stimulus from 1° to 2° did not have an effect on smooth pursuit in young adults (p>0.05). Finally, smooth pursuit performance did not significantly differ in children for the different motion paradigms when using the animated stimulus (p>0.05).

Conclusions: Attention-grabbing and more dynamic stimuli, such the developed animated stimulus might potentially be useful for eye movement research. Finally, with such stimuli, children perform equally well irrespective of the motion paradigm used.

Keywords: smooth pursuit, animated stimulus, children, pursuit performance, child-friendly

Exploration of the space around us ideally requires not only normal visual acuity but also the absence of any ocular pathology, including normal eye movements. In order to stabilise the retinal image, there are different types of eye movements that suit different types of objects, motions and conditions.[1] For instance, smooth pursuit involves conjugate eye movements responsible for smooth, accurate tracking of a slow moving object in order to maintain its image on the foveas,[1] whereas saccades are the eye movements responsible for shifts of gaze that bring the image of a peripherally placed object of interest into the foveal region.[1]

Saccades and smooth pursuit eye movements have been traditionally studied using dots and light spots in both adults[2-4] and children.[3, 5-8] In contrast, different stimuli, such as cartoon characters[9] or faces,[10] have been designed to study eye movements in infants. The wider variety of stimuli used for eye movement research in infants are intended to maintain infant's attention, the main reason being that there might be a relationship between attention and eye movements, such that higher attention engagement might improve eye movement performance.[11, 12] Interestingly, such approaches aimed at increasing/maintaining attention in infants have not been adopted as a standard for eye movement research, even though recent evidence has shown that the stimulus type and its features also have an impact on eye movement performance in non-infant populations.[13] For example, Irving et al. (2011) reported significantly higher saccadic peak velocities, shorter saccadic latencies, and more accurate saccades when using cartoon pictures as stimuli than when using standard dots. The difference in performance between the stimuli was evident and statistically significant in young children but decreased up to the age of 8-9 years, while in adults the differences were negligible.[13] Similar results were found by the same authors for smooth pursuit eye movements. For instance, in children the use of animal pictures as smooth pursuit targets resulted in significantly higher gains compared to standard dots.[13] Although higher gains using cartoons were also observed in adults, the difference in performance between stimuli was not significant.[13] These results support the idea that eye movements can be assessed more successfully using more interesting and meaningful targets and heighten the need for more appropriate stimuli to investigate oculomotor control, especially in young populations.

Moreover, there is currently no standardised stimulus motion to study smooth pursuit eye movements, resulting in three main motion paradigms having been used in pursuit studies: the ramp, the step-ramp, and the sinusoidal. The ramp is probably the simplest approach, using a target that starts moving suddenly at a constant velocity for a certain period of time.[14] At the onset of the target movement, the smooth pursuit performance is poor and often begins with an initial saccade, but then there is a notable increase in eye velocity that leads to an improvement in the smooth pursuit response.[14] To avoid or minimize the effect of this initial saccade, some authors have modified the stimulus motion and developed what is known as the step-ramp paradigm. In this approach, the fixation target suddenly moves (step) prior to the constant velocity (ramp) movement of the target,[14] in order to ‘alert’ the subject to the onset of motion. Eye movements can also be studied in response to a stimulus for which velocity continuously changes in a sinusoidal manner. While multiple studies evaluating the effect of age on smooth pursuit in adults have used stimuli moving at constant velocity,[15-17] studies in children and infants have used not only different constant velocity motions[8, 18] but also sinusoidal motion paradigms.[6, 7, 19] Moreover, the literature suggests that there is an issue with the choice of smooth pursuit motion paradigm in infant and child populations, which does not persist in adult populations. For instance, an early study suggested that the step-ramp should be used in young infants to increase their attention.[20] The rationale discussed by the author was that the saccade prior to the movement of the target may be more effective in increasing infants' awareness and attention than other stimulus motions. In contrast, sinusoidal motions have been described as a better option for school age children.[6, 20] Interestingly, we are not aware of any published study assessing smooth pursuit differences in young populations between these motion paradigms.

This study aimed to evaluate any possible advantage of using an animated stimulus developed for eye movement studies in children and investigate the effect of the predetermined characteristics of such stimulus (type and size) in young adults. Finally, this animated stimulus was used in a study of pursuit in a small group of children to investigate the effect of motion paradigm on smooth pursuit performance in young populations.

Materials and Methods

Participants

Twenty young adults (mean age 24 ± *SD* 1.42; range: 21 to 27) predominantly males (13/20) were recruited for experiment 1, and ten young adults (mean age of 21.50 ± *SD* 2.12; range: 20 to 25) with no difference in gender distribution (5/10) were recruited for experiment 2. Twelve child participants (mean age 6.33 ± *SD* 3.31; range 3 to 14), predominantly males (7/12) were recruited for experiment 3. The adult subjects were students and staff at the School of Optometry and Vision Sciences at Cardiff University, and the child subjects were recruited through local advertising.

All three experiments received ethical approval from the Cardiff University School of Optometry and Vision Sciences Research and Audit Ethics Committee, and procedures were in accordance with the guidelines of the Declaration of Helsinki. Written consent forms were obtained from the young adult participants and consent forms were received from both the children and their parents or legal guardians. All participants were screened to confirm visual acuity of at least logMAR 0.1 and the absence of strabismus. The tests comprised near and distance visual acuity with current prescription, if any, and eye alignment by cover test. The visual acuity criteria were set to include participants with low uncorrected refractive errors, mainly myopia.

Visual stimulus and setup

The newly developed animated stimulus comprised an animal cartoon image that moved horizontally, while continuously changing shape and colour as it morphed into different animals (Figure 1 and Video 1, Supplemental Digital Content 1, Video that shows the eye movement recording of a 4 year old child using our customised setup and animated stimulus). The perception of a more complex image such as a face, can be influenced by the size of that image,[21] such that larger angular size may improve recognition and performance, especially in young populations. In addition, eye movements such as saccades are not dependent on stimulus size up to sizes of 3-5º.[22, 23] For these reasons, the size chosen for the customised animated stimulus was 2º, in order to maximise attention and to ensure that the size of the stimuli was the minimum necessary to allow the discrimination of the animal cartoon features. The animal’s eyes and a small dot situated in the centre of the cartoon were maintained constant in order to provide a fixation point throughout the test.

The unchanging visual stimulus, referred to as a *“standard dot”* was a black filled circle containing a small white dot in the centre, which provided a fixation point. This standard visual stimulus was consistent with that used in previous studies.[5, 6, 8, 13, 24] Both visual stimuli were displayed on a computer monitor on a white background.

Procedure and eye movement recordings

Eye Tracker

Simultaneous eye movement recordings were performed using the Tobii TX300 (Tobii Technology, Stockholm, Sweden) eye tracker. The system comprises an eye tracker unit and a removable 23” widescreen monitor with 1920x1080 pixel resolution and an integrated webcam. This remote eye tracker uses the different Purkinje reflections of the eye to establish the horizontal and vertical position of both eyes at a sample rate of 300Hz, and with a maximum gaze angle of ±35º. The system gaze accuracy given by the manufacturer is ±0.5º for monocular and ±0.4º for binocular conditions.[25]

The participants’ eye movements were recorded using Tobii Studio™ (Tobii Technology, Stockholm, Sweden) while displaying the stimuli on the monitor situated immediately above the eye tracker unit. Participants’ performance and behaviour were recorded and also monitored live via the widescreen monitor integrated webcam.

Calibration

The position and height of the participant’s chair and/or the eye tracker desk were adjusted to ensure that the subject’s eyes were positioned 65cm away from the eye tracker and in front of the geometrical centre of the screen monitor. Prior to eye movement recording, the eye tracker was successfully calibrated for each participant at 5 target positions on the monitor using the standard Tobii five point calibration. All stimuli presented later were contained within the calibrated area.

Experiment 1: Effect of stimulus type on smooth pursuit performance in young adults

The customised animated stimulus (Figure 1 and Video 1, Supplemental Digital Content 1) moved horizontally following a 6º/sec ramp paradigm. The stimulus appeared for one second at 10º to the left of the participant’s straight ahead position.

After this initial fixation period, the stimulus moved horizontally (left to right) following a constant velocity motion (6º/sec) that lasted 3.33 seconds. The stimulus stopped when it was at 10º to the right of the participant's straight ahead position (Figure 2). Fixation periods were presented for two seconds between each ramp (left to right or right to left) before the stimulus moved again to the left or to the right. A total of four smooth pursuit ramps were presented, so that the stimulus moved left to right and right to left twice. The stimulus presentation lasted for 22.33 seconds. Then, the stimulus was changed to a standard dot subtending 1º and measures were repeated following the same motion paradigm and velocity. The authors chose to present the animated stimulus first so that the participants did not have previous experience with the smooth pursuit task, and therefore any learning effects were avoided when presenting this stimulus.

Experiment 2: Effect of stimulus size on smooth pursuit performance in young adults

In order to evaluate the effect of using a larger stimulus size on smooth pursuit performance, a standard dot stimulus was presented in two different sizes: subtending 1º and 2º of visual angle. The presentation order of the two stimuli was alternated between participants. The stimuli followed the same motion and velocity as experiment 1.

Experiment 3: Effect of stimulus motion paradigm on smooth pursuit performance in children

In this last experiment, the 2º customised animated stimulus was presented to study eye movements in a small group of children.

Because children are more likely to move during the eye movement recording than adults, a customised child-friendly head stabiliser was developed. This consisted of an articulated arm with a forehead rest attached to the end (Figure 3). The forehead rest featured an adjustable plastic toy crown. The head stabiliser allowed participants to make slight head movements laterally and maintained their head at the optimal distance of 65cm from the monitor and eye tracker throughout the test. This customised head stabiliser naturally encouraged child participants to keep a steady position as large movements resulted in the crown falling off their head (Video 1, Supplemental Digital Content 1). This customised head stabiliser was aimed at maintaining the participants' distance from the eye tracker, and therefore maintaining the relative velocity of the smooth pursuit stimulus constant throughout the experiments and across subjects.

The same calibration and recording procedures were followed, but two additional motion paradigms were also presented using the animated stimulus. After the standard five point calibration was performed, the stimulus was presented following three different motion paradigms in the same order: a 6°/sec ramp, a 6°/sec step-ramp and a sinusoidal motion paradigm (peak velocity 6°/sec). The ramp motion paradigm, presented was identical to that used in experiments 1 and 2. In the step-ramp paradigm, the stimulus initially appeared at its starting position for one second, and then the stimulus was displaced 1° horizontally where it remained for another second before returning to the previous position to start the constant velocity ramp at 6°/sec. The target displacement (step) was repeated before the next ramp started. This smooth pursuit task lasted 23.33 seconds. For the sinusoidal motion, the fixation periods between ramps were deleted and the velocity of the stimulus changed continuously following a sinusoidal waveform. The duration for that task was 14.33 seconds. The complete experiment lasted 60 seconds.

Table 1 summarizes the number of participants taking part and the stimulus type, size, and motion presented in each of the three experiments carried out.

Data analysis

Eye position traces were analysed offline using custom software written in MATLAB (The Mathworks, Inc., Natick, MA, USA). Eye velocity was obtained by differentiation of the eye position over time and smoothed with a 3-sample window moving average filter, to reduce the additional noise arising from the differentiation process.[26]

Saccades were automatically detected with the adaptive threshold algorithm described in detail by Behrens et al. (2010). Briefly, this algorithm determines acceleration thresholds based on the standard deviation of the distribution of 200 preceding acceleration data values. Saccades are defined and detected as those data points that exceeded the established threshold. Saccade amplitudes were calculated, and saccades below 1^{o} amplitude were classified as microsaccades.[27, 28]

Periods of smooth pursuit that were free of saccades were plotted and further analysed. Some authors exclude periods of possible slowed smooth pursuit from their analysis.[29, 30] In contrast, other authors include all smooth pursuit segments, suggesting this may offer a better measurement of global smooth pursuit function.[31, 32] In any case, the difference in gain scores between these two measures has been reported to be less than 2% with a greater than 0.95 correlation.[32] In this study, we included all smooth pursuit segments, and the position gain for a given interval of smooth pursuit was defined as the ratio between the eye position and the target position for this interval. The position gains obtained from all smooth pursuit segments were averaged to obtain the mean position gain for each participant.

To obtain eye velocity for the constant velocity motions, a linear regression was performed on each segment of smooth pursuit data, and the slope of the fitted equation was defined as the eye velocity for that segment. The velocity of each segment was then weighted for the duration of the segment, then velocities were averaged together to obtain the mean time-weighted velocity for that smooth pursuit task and participant. Finally, velocity gain was calculated by dividing the time-weighted mean eye velocity by the stimulus velocity. For the sinusoidal motion paradigm, a polynomial fitting was performed along the eye position data without the saccades, and the velocity gain was defined as the coefficient of determination, R^2, between the smooth pursuit data and the polynomial fit.

The total proportion of smooth pursuit was defined as the total eye movement involving slow phase (i.e without saccades) divided by the total stimulus movement (20º for each smooth pursuit ramp).

Statistical analysis

The IBM SPSS software package version 18.0 (IMB SPSS Inc, Chicago, IL, USA) was used for statistical analysis. Normality tests were first performed on the data, including histograms and Shapiro-Wilk tests. In experiment 1, all parameters except the mean amplitude of the saccades (p<0.001) and the number of microsaccades (p<0.001) were normally distributed, while in experiment 2, only velocity gain appeared not to be normally distributed (p=0.004). Hence, parametric t-tests and non-parametric Wilcoxon test were used accordingly.

In experiment 3, only the number of microsaccades was not normally distributed. Parametric repeated measures ANOVA was still used to statistically analyse all the parameters in experiment 3, including the number of microsaccades, as ANOVA has been suggested to be robust to even moderate deviations from normality.[33, 34]

For statistical purposes, a p value lower than 0.05 was considered to be statistically significant in all three experiments.

Results

Experiment 1: Effect of stimulus type on smooth pursuit performance in young adults

Figures 4 and 5 show the smooth pursuit performance parameters obtained with the animated and the standard dot stimuli in each participant. The average smooth pursuit performance parameters for the animated and the dot stimuli are summarised in Table 2. The animated stimulus produced, on average, higher velocity gains and position gain, as well as a higher total proportion of smooth pursuit than the standard dot. These were significantly different from velocity gain (t=2.702; *p*=0.014), position gain (t=1.441; p=0.025) and the proportion of smooth pursuit (t=3.544; *p*=0.002) obtained with the standard dot stimuli. Additionally, fewer saccades were produced during smooth pursuit with the animated than with the standard dot stimulus (t=-2.957; *p*=0.008). In contrast, Wilcoxon tests revealed that stimulus type had no effect on the mean amplitude of the saccades (Z=-0.342; *p*=0.732) or the number of microsaccades (Z=-1.009; *p*=0.313).

Experiment 2: Effect of stimulus size on smooth pursuit performance in young adults

One participant recruited had an alternating strabismus, and data for this participant were excluded from the analysis. Figures 6 and 7 show the smooth pursuit performance parameters obtained from the nine participants. The average smooth pursuit performance parameters for the 1º and 2º standard dots are summarised in Table 3. Velocity and position gains as well as the proportion of smooth pursuit have similar values with each of the two stimuli sizes presented. A Wilcoxon test showed no differences in velocity gain (Z=-1.357; *p*=0.176), and paired t-tests did not reveal any significant differences in position gain (t=-0.223; p=0.829) or the proportion of smooth pursuit (t=-1.029; p=0.334) between the 1º and 2º standard dots.

Although the 1º standard dot produced on average fewer saccades and microsaccades than the 2º standard dot, neither difference was significant (number of saccades: t=1.397; p=0.211; number of microsaccades: t=0.185; p=0.858). Moreover, parametric paired t-tests revealed no significant differences in the mean amplitude of the saccades (t=-0.545; p=0.605) between the two stimuli sizes.

Experiment 3: Effect of stimulus motion paradigm on smooth pursuit performance in children

Figures 8 and 9 show the smooth pursuit performance parameters obtained in each participant following three different motion paradigms. Repeated measures ANOVA with a Greenhouse-Geisser correction for sphericity confirmed that velocity gain (F=1.689; p=0.222), position gain (F=1.479; p=0.243), and proportion of smooth pursuit (F=3.213; p=0.062) were not significantly different between the ramp, the step-ramp and the sinusoidal motion paradigms. Similarly, repeated measures ANOVA showed that the number of saccades (F=1.420; p=0.265), the mean amplitude of the saccades (F=1.137; p=0.341) and the number of microsaccades (F=2.824; p=0.083) were not significantly different between motion paradigms.

Discussion

Different stimuli can be used to study eye movements, but it is reasonable to suggest that changes in some of their characteristics may affect subjects' overall performance. A recent study has demonstrated that smooth pursuit and saccadic dynamics can be improved using cartoon-based stimuli.[13] Such improvement can be attributed to the fact that more meaningful targets increase attention and therefore impact on oculomotor performance. If this view is correct, the next logical step to further enhance attention would be to use not only more interesting but also more dynamic stimuli. While this can perhaps be more easily achieved for saccadic eye movements by using series of cartoon characters appearing at different locations, more complex and different stimuli might be needed to maintain attention during smooth pursuit eye movements. Hence, the first experiment investigated in young adults whether or not more complex and dynamic stimuli might be a better option to evaluate smooth pursuit eye movements than the traditional and static stimuli (e.g. dots, cartoons, light spots). The results revealed that smooth pursuit performance in a young adult population was significantly improved when using a customised animated stimulus if compared to a standard dot stimulus. For instance, smooth pursuit gains were found to be significantly higher and the number of saccades was found to be significantly lower when using the animated stimulus if compared to a standard dot in a young adult population. Although these results seem to contradict previous findings, which suggested that stimuli characteristics have little effect on smooth pursuit performance in adults,[13] our stimulus is qualitatively different from any stimuli used in previous eye movement research. For instance, the two stimuli compared by Irving et al. (2011) were similar in that they were “unchanging stimuli”, while the continuously changing (animated) stimulus presented here was designed to increase/maintain attention. Hence, our results suggest that using a dynamic stimulus could improve oculomotor performance in an adult population, and further studies using such stimuli are warranted.

In the first experiment, which aimed to investigate the effect of stimulus type on smooth pursuit performance, the presentation order of the stimuli was not alternated. Thus, the animated stimulus was always presented first followed by the unchanging dot stimulus. It could be argued that this design is not ideal, as maintaining the same presentation order in each participant could have affected the smooth pursuit performance for each stimulus type. However, the authors chose to always present the animated stimulus first so that the participants did not have previous experience with the smooth pursuit task, and therefore any learning effects were avoided when presenting this stimulus. Hence, if learning effects were present due to the repetition of the smooth pursuit task following the same motion and velocity, these would have appeared when presenting the unchanging dot stimulus, resulting in evidence for an improved performance.

It has been suggested that the size of the stimulus is also important when evaluating eye movements, so that large stimuli may elicit an optokinetic response rather than a voluntary smooth pursuit[35] or saccades might become less accurate.[22, 23] Hence, the second experiment was designed to evaluate the effect of stimulus size on smooth pursuit performance. The results showed no significant differences in any of the smooth pursuit parameters between a 1º and 2º standard dot following a ramp motion paradigm. These findings agree with previously published results, which suggest that smooth pursuit performance is independent of stimulus size, unless very large stimuli sizes are used.[13] Additionally, the smooth pursuit gains obtained for the standard dot stimuli reported here are similar to those reported in the literature for adults using dots or similar static stimuli at comparable velocities,[13, 36, 37] and confirm that our young adult population was not different from previously studied samples. One could argue that smooth pursuit performance using the dot stimuli was better in experiment 2 than in experiment 1 and that, therefore, some inconsistencies might be present. However, it is important to note that two different adult samples of different size (n=20 vs n=10) participated in each study, and therefore the results from both experiments should be compared carefully. In any case, there were no statistically significant differences between the results obtained using the 1º standard dot in experiments 1 and 2. In addition, the results from experiment 2 are in agreement with previous literature[22, 23] and further support the idea that eye movements are not dependant on stimulus size, at least for moderate stimulus sizes.

Finally, in the third experiment, we assessed the effect of different motion paradigms on smooth pursuit performance in a group of children using the animated stimulus. There were three reasons for undertaking this experiment in a group of children. First, the characteristics of our novel animated stimulus were designed to increase/maintain participants' attention, with the expectation that this stimulus might be particularly salient to children. Second, stimulus characteristics seem to have a higher impact in children than in adults,[13] and thus our stimulus might be expected to improve their oculomotor performance. Third, while most studies have used ramp paradigms to investigate smooth pursuit in adults,[15-17] studies in children have used various motion paradigms, and therefore their results are often not comparable.[6-8, 18, 19] Further complicating matters, it has been suggested that step-ramp motions are more appropriate for infants and young children,[38] while sinusoidal motions are a better option for school age children.[6, 20] However, these suggestions seem to be based more on the authors' opinions and preferences than on scientific evidence. Interestingly, the values obtained for all the smooth pursuit parameters studied here were similar across the three different motions presented, and in fact, no significant differences were found between any of the motion paradigms. Hence, the motion paradigm used seemed to have little or no effect on smooth pursuit performance in children, at least with the animated stimulus presented here.

Overall, our results demonstrate that, contrary to previous studies, smooth pursuit performance can be improved in young adults with a more interesting and/or interactive stimulus. Of course, one could argue that the differences in smooth pursuit performance found in experiment 1 between the animated and the unchanging dot stimuli could arise from the stimulus size, as these two were different in size. However, the results from experiment 2 showed that size of the stimulus (1° vs 2°) did not significantly affect smooth pursuit performance in a young adult population, supporting the view that the differences found in the previous experiment were due to the type rather than the size of the stimulus. Although the effects of stimulus type were studied here only in a young adult population, the improvement is likely to be even more evident in children.

Conclusion

Finally, this is an innovative and unique study as, to our knowledge, it is the first time that an animated stimulus has been utilised to study eye movements in adults and children. Although this study has focussed on smooth pursuit eye movements, the results may well be extrapolated generally to other eye movements and offer the possibility that performance can be improved significantly with attention-grabbing and dynamic (i.e. animated) stimuli. Therefore, we recommend the use of animated stimuli for the evaluation of smooth pursuit and fixation stability and further support the idea of using cartoon pictures as stimuli for saccades,[13] especially in children. Of course, the importance of the choice of stimuli to evaluate eye movements should not only be considered for research purposes but also in clinical settings.

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References

1. Leigh RJ, Zee DS. Smooth pursuit and visual fixation. In: The Neurology of Eye Movements. 3rd ed. New York: Oxford University Press; 1999.

2. Flechtner KM, Steinacher B, Sauer R, Mackert A. Smooth pursuit eye movements of patients with schizophrenia and affective disorder during clinical treatment. Eur Arch of Psychiatry Clin Neurosci 2002;252:49-53.

3. Yang Q, Bucci MP, Kapoula Z. The latency of saccades, vergence, and combined eye movements in children and in adults. Invest Ophthalmol Vis Sci 2002;43:2939-49.

4. Judge J, Caravolas M, Knox PC. Smooth pursuit eye movements and phonological processing in adults with dyslexia. Cogn Neuropsychol 2006;23:1174-89.

5. Kowler E, Martins AJ. Eye movements of preschool children. Science 1982;215:997-9.

6. Accardo AP, Pensiero S, Da Pozzo S, Perissutti P. Characteristics of horizontal smooth pursuit eye movements to sinusoidal stimulation in children of primary school age. Vision Res 1995;35:539-48.

7. Salman MS, Sharpe JA, Lillakas L, Dennis M, Steinbach MJ. Smooth pursuit eye movements in children. Exp Brain Res 2006;169:139-43.

8. Lions C, Bui-Quoc E, Wiener-Vacher S, Seassau M, Bucci MP. Smooth pursuit eye movements in children with strabismus and in children with vergence deficits. PLoS ONE 2013;8.

9. Roucoux A, Culee C, Roucoux M. Development of fixation and pursuit eye movements in human infants. Behav Brain Res 1983;10:133-9.

10. Von Hofsten C, Rosander K. Development of smooth pursuit tracking in young infants. Vision Res 1997;37:1799-810.

11. Shagass C, Roemer RA, Amadeo M. Eye-tracking performance and engagement of attention. Arch Gen Psychiatry 1976;33:121-5.

12. Sweeney JA, Haas GL, Li S, Weiden PJ. Selective effects of antipsychotic medications on eye-tracking performance in schizophrenia. Psychiatry Res 1994;54:185-98.

13. Irving EL, Gonzalez EG, Lillakas L, Wareham J, McCarthy T. Effect of stimulus type on the eye movements of children. Invest Ophthalmol Vis Sci 2011;52:658-64.

14. Barnes GR. Ocular pursuit movements. In: Liversedge S, Gilchrist I, Everling S, ed. The Oxford Handbook of Eye Movements. New York: Oxford University Press, 2011; 115-34.

15. Ross RG, Olincy A, Harris JG, Sullivan B, Radant A. Smooth pursuit eye movements in schizophrenia and attentional dysfunction: adults with schizophrenia, ADHD, and a normal comparison group. Biol Psychiatry 2000;48:197-203.

16. Knox PC, Davidson JH, Anderson D. Age-related changes in smooth pursuit initiation. Exp Brain Res 2005;165:1-7.

17. Straube A, Scheuerer W, Eggert T. Target velocity and age influence the initial smooth pursuit response in humans. Neuro-Ophthalmology 1997;18:191-8.

18. Ross RG, Radant AD, Hommer DW. A developmental study of smooth pursuit eye movements in normal children from 7 to 15 years of age. J Am Acad Child Adolesc Psychiatry 1993;32:783-91.

19. Ingster-Moati I, Vaivre-Douret L, Bui Quoc E, Albuisson E, Dufier JL, Golse B. Vertical and horizontal smooth pursuit eye movements in children: a neuro-developmental study. Eur J Paediatr Neurol 2009;13:362-6.

20. Rashbass C. The relationship between saccadic and smooth tracking eye movements. J Physiol 1961;159:326-38.

21. Lundy BL, Jackson JW, Haaf RA. Stimulus properties, attentional limitations, and young children's face recognition. Percept Mot Skills 2001;92:919-29.

22. Kowler E, Blaser E. The accuracy and precision of saccades to small and large targets. Vision Res 1995;35:1741-54.

23. Dick S, Ostendorf F, Kraft A, Ploner CJ. Saccades to spatially extended targets: the role of eccentricity. Neuroreport 2004;15:453-6.

24. Ego C, Orban de Xivry JJ, Nassogne MC, Yuksel D, Lefevre P. The saccadic system does not compensate for the immaturity of the smooth pursuit system during visual tracking in children. J Neurophysiol 2013;110:358-67.

25. Tobii Technology. Tobii TX300 Eye Tracker Product Description. Stockholm; 2010. Available at: http://www.tobiipro.com/product-listing/tobii-pro-tx300/#Specifications. Accessed: 26 October 2016];

26. Behrens F, Mackeben M, Schroder-Preikschat W. An improved algorithm for automatic detection of saccades in eye movement data and for calculating saccade parameters. Behav Res Methods 2010;42:701-8.

27. Martinez-Conde S, Macknik SL, Hubel DH. The role of fixational eye movements in visual perception. Nat Rev Neurosci 2004;5:229-40.

28. Martinez-Conde S, Macknik SL, Troncoso XG, Hubel DH. Microsaccades: a neurophysiological analysis. Trends Neurosci 2009;32:463-75.

29. Clementz BA, Sweeney JA. Is eye movement dysfunction a biological marker for schizophrenia? A methodological review. Psychol Bull 1990;108:77-92.

30. Lisberger SG, Pavelko TA. Topographic and directional organization of visual motion inputs for the initiation of horizontal and vertical smooth-pursuit eye movements in monkeys. J Neurophysiol 1989;61:173-85.

31. Radant AD, Hommer DW. A quantitative analysis of saccades and smooth pursuit during visual pursuit tracking. A comparison of schizophrenics with normals and substance abusing controls. Schizophr Res 1992;6:225-35.

32. Ross RG, Harris J, Olincy A, Radant A, Adler L, Freedman R. Smooth pursuit eye movements in parents of schizophrenic probands; a most likely carrier approach. Schizophr Res 1997;24:244-5.

33. Lix LM, Keselman JC, Keselman HJ. Consequences of assumption violations revisited: a quantitative review of alternatives to the one-way analysis of variance "F" test. Rev Educ Res 1996;66:579-619.

34. Glass GV, Peckham PD, Sanders JR. Consequences of failure to meet assumptions underlying the fixed effects analyses of variance and covariance. Rev Educ Res 1972;42:237-88.

35. Pola J, Wyatt HJ. Active and passive smooth eye movements: effects of stimulus size and location. Vision Res 1985;25:1063-76.

36. Tajik-Parvinchi DJ, Lillakas L, Irving E, Steinbach MJ. Children's pursuit eye movements: a developmental study. Vision Res 2003;43:77-84.

37. Ke SR, Lam J, Pai DK, Spering M. Directional asymmetries in human smooth pursuit eye movements. Invest Ophthalmol Vis Sci 2013;54:4409-21.

38. Shea SL, Aslin RN. Oculomotor responses to step-ramp targets by young human infants. Vision Res 1990;30:1077-92.

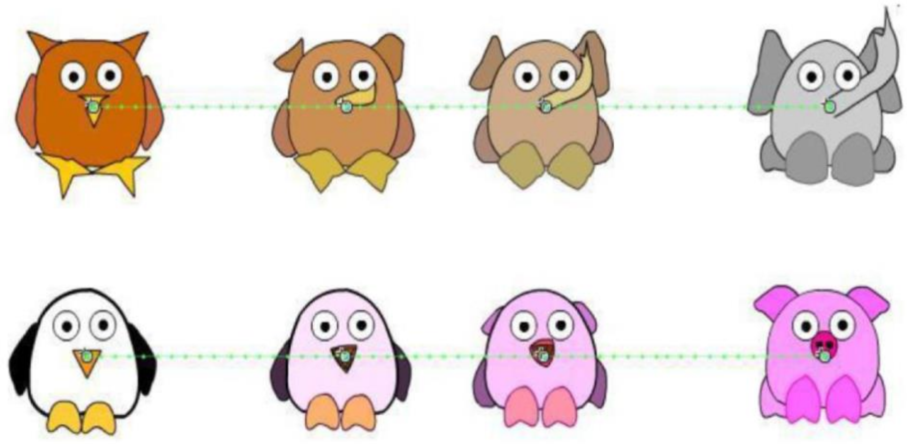

Figure 1. Cutomised animated stimulus.

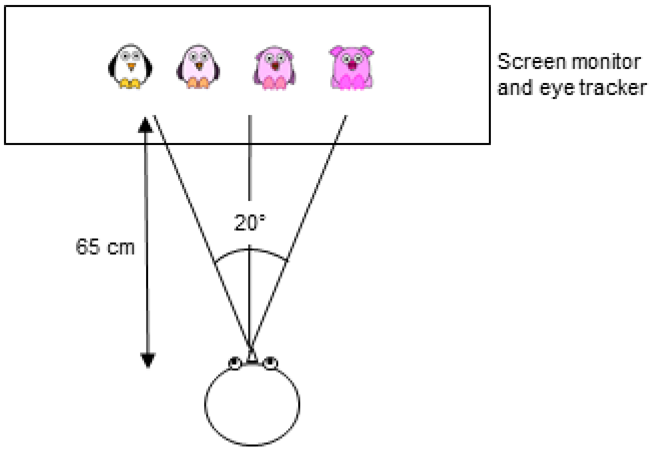

Figure 2. Diagram of the setup illustrating the distance of the eye-tracker from subject and the amplitude of the stimulus movement.

Figure 3. Customised child-friendly head stabiliser.

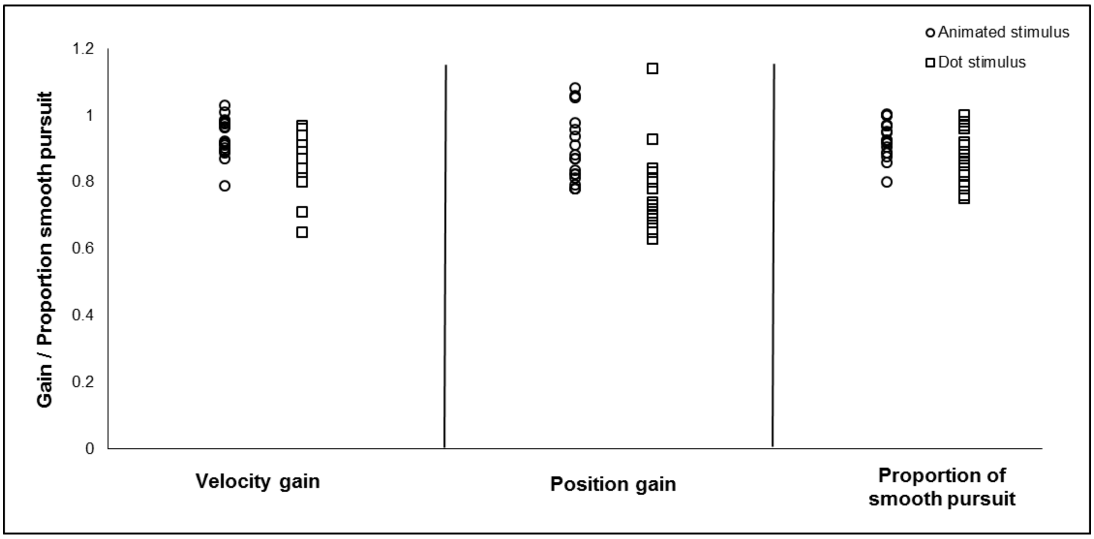

Figure 4. Velocity gain, position gain and proportion of smooth pursuit obtained from 20 young adults using the 2º animated stimulus (circles) and the 1º standard dot (squares).

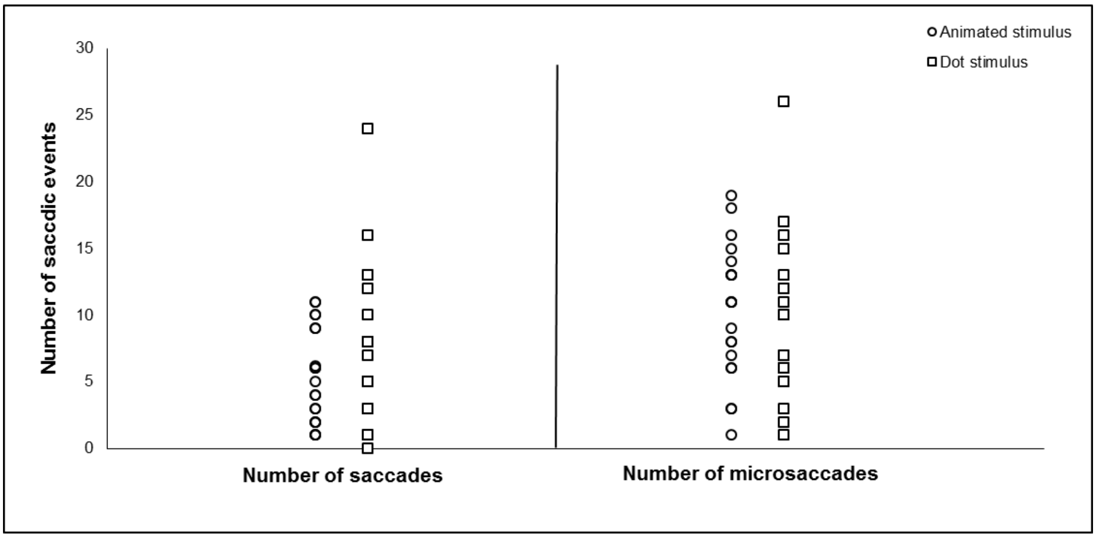

Figure 5. Number of saccades and microsaccades obtained from 20 young adults using the 2º animated stimulus (circles) and the 1º standard dot (squares).

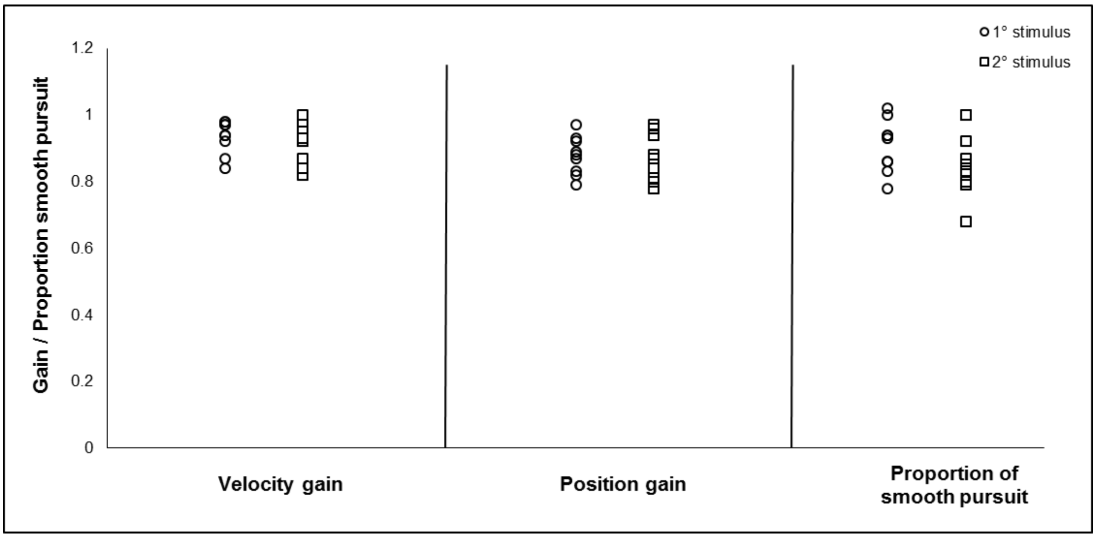

Figure 6. Velocity gain, position gain and proportion of smooth pursuit obtained from 9 young adults using the 1º dot (circles) and for the 2º dot stimulus (squares).

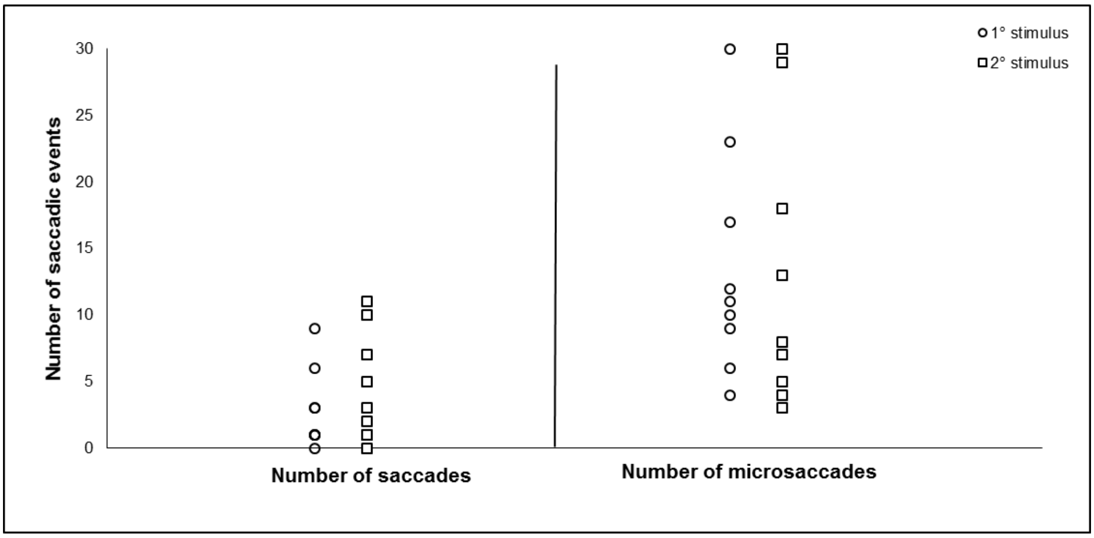

Figure 7. Number of saccades and microsaccades obtained from 9 young adults using the 1º standard dot (circles) and for the 2º standard dot stimulus (squares).

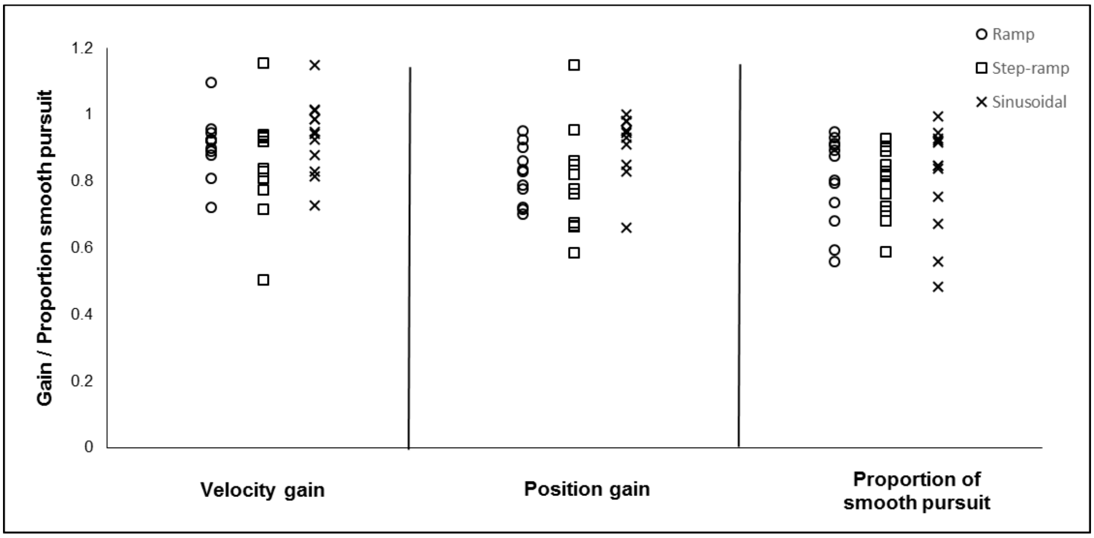

Figure 8. Velocity gain, position gain and proportion of smooth pursuit obtained from 12 children using the animated stimulus following a ramp (circles), step-ramp (squares) and sinusoidal (crosses) motion paradigms.

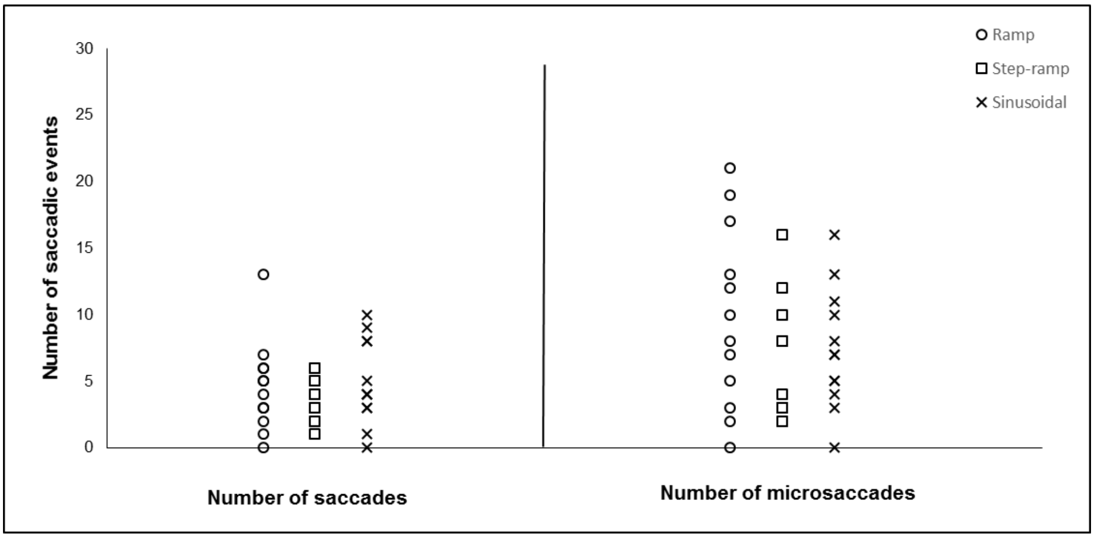

Figure 9. Number of saccades and microsaccades obtained from 12 children using the animated stimulus following a ramp (circles), step-ramp (squares) and sinusoidal (crosses) motion paradigms.

Supplemental Digital Content 1. Video that shows the eye movement recording of a 4 year old child using our customised setup and animated stimulus. mov

Table 1. Summary of the participants taking part, stimulus type and motion presented in each experiment

	Participants	Stimulus type	Stimulus motion
Experiment 1	20 adults	2º animated 1º standard dot	6º/sec ramp
Experiment 2	10 adults	1º standard dot 2º standard dot	6º/sec ramp
Experiment 3	12 children	2º animated	6º/sec ramp 6º/sec step-ramp Sinusoidal

Table 2. Mean values for each smooth pursuit parameter obtained from twenty young adults using the animated and the dot stimuli.

Smooth pursuit parameters	Animated stimulus Mean; 95% CI	Dot stimulus Mean; 95% CI	p
Velocity gain	0.93; 0.90-0.96	0.87; 0.82-0.92	***p*=0.014**
Position gain	0.93; 0.85-1	0.82; 0.72-0.92	***p*=0.025**
Proportion of smooth pursuit	0.94; 0.91-0.96	0.872; 0.83-0.90	***p*=0.002**
Number of saccades	5.30; 3.64-6.96	7.75; 5.03-10.46	***p*=0.008**
Mean amplitude of saccades	1.41; 1.16-1.66	1.34; 1.13-1.55	*p*=0.732
Mean number of microsaccades	10.25; 7.90-12.60	9.50; 6.68-11.31	*p*=0.313

Table 3. Mean values for each smooth pursuit parameter obtained from nine young adults using a 1º and a 2º dot stimuli.

Smooth pursuit parameters	1º dot stimulus Mean; 95% CI	2º dot stimulus Mean; 95% CI	p
Velocity gain	0.93; 0.89-0.97	0.91; 0.86-0.96	p=0.176
Position gain	0.87; 0.83-0.92	0.87; 0.81-0.92	p=0.829
Proportion of smooth pursuit	0.90; 0.84-0.96	0.86; 0.78-0.93	p=0.334
Number of saccades	2.77; 0.51-5.04	4.44; 1.31-7.56	p=0.211
Mean amplitude of saccades	1.23; 1.07-1.39	1.19; 1.09-1.28	p=0.605
Mean number of microsaccades	14.22; 6.57-21.86	15.55; 3.15-27.95	p=0.858