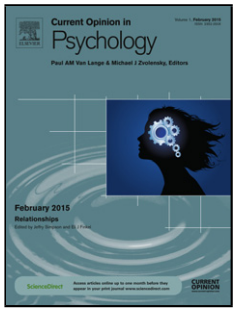

Title: Attention Deficits in Amblyopia

Authors: Preeti Verghese, Suzanne P McKee, Dennis M Levi

PII: S2352-250X(18)30268-9
DOI: https://doi.org/10.1016/j.copsyc.2019.03.011
Reference: COPSYC 811

To appear in:

Please cite this article as: Verghese P, McKee SP, Levi DM, Attention Deficits in Amblyopia, *Current Opinion in Psychology* (2019), https://doi.org/10.1016/j.copsyc.2019.03.011

Attention Deficits in Amblyopia

Preeti Verghese[1],
The Smith Kettlewell Eye Research Institute, San Francisco CA (email: preeti@ski.org)

Suzanne P McKee
The Smith Kettlewell Eye Research Institute, San Francisco CA (email: suzanne@ski.org)

Dennis M Levi,
Optometry and Vision Science, University of California Berkeley, CA (email: dmlevi@berkeley.edu)

1. Corresponding author

Abstract:

Amblyopia is a neuro-developmental abnormality associated with deficits in a broad range of both low- and high-level visual tasks. This is particularly true in strabismic amblyopia where fixation is unstable and there is an increased frequency of microsaccades. In light of the close association between eye movements and attention, we propose a novel hypothesis: that the cost of unstable fixation in amblyopia is a deficit in selective attention. The increased latency for saccades and manual response time with amblyopic-eye viewing is consistent with attention being distracted by unwanted fixational eye movements. We review other attention deficits in amblyopia and discuss whether they are explained by fixation instability, or whether they involve a form of neglect or suppression of the visual input from the amblyopic eye.

Keywords: strabismus, microsaccades, saccadic latency, manual latency, crowding, attentional blink, cueing, perceptual decision time.

Amblyopia ("lazy eye") is a common developmental abnormality that results in a loss of visual acuity in one eye that cannot be corrected by glasses or contact lenses. Typically, the acuity of the fellow eye is normal. Historically, the amblyopic deficit has been attributed to neural losses in early visual cortex, primarily V1 [1,2,3**]. While damage to both striate and extra-striate cortex undoubtedly contributes to the amblyopic loss, in this review we present a body of evidence that response latency is significantly impacted in amblyopia, suggesting a broader deficit than visual processing. Response latency has frequently been used as a metric of attention in studies ranging from the classic Posner cueing tasks [4] to performance in visual search tasks. We propose that the increased latency for saccades and manual

responses in amblyopia is due to an attentional deficit arising from poor fixation stability and an increased frequency of microsaccades, and review work that suggests that these factors impact the dynamics and the spatial allocation of selective attention.

Attention and eye movements

Goldberg and Wurtz [5] demonstrated a strong association between eye movements and attention. They showed that cells in the superficial layers of the superior colliculus respond more strongly when the animal attends to that location and prepares a saccade to a stimulus within the response field, compared to when the animal fixates or prepares a saccade to a location outside the response field. Rizzolatti and colleagues [6**] proposed the "premotor theory of attention" whereby attention is tightly linked to the saccade goal and the same cortical networks control attention as well as eye movements. This bold proposal is supported by neurophysiological studies in awake behaving primates as well as functional neuroimaging studies in humans that show that the same cortical structures in frontal, parietal and extrastriate cortex are involved in overt as well as covert attention [7-11].

The association between eye movements and attention is evident even when observers are required to maintain fixation and attend covertly to a cued location. Hafed and Clark [12*] showed that during a covert attention task, observers tend to make small eye movements (microsaccades with amplitude < 1°) in the direction of the cue. Furthermore, stimuli that appear at a location congruent with the direction of a microsaccade are discriminated better than those at incongruent locations, further supporting the link between saccadic eye movements and attention ([13], even when observers are required to fixate and attend covertly.

The attentional cost of fixational instability

Individuals with amblyopia, particularly those with strabismus, have poor fixation stability in their amblyopic eye [14, 15-16, 17*, 18-20]. In tasks that require fixation, the position of the amblyopic eye tends to drift from fixation and the frequency and amplitude of microsaccades is higher than for the fellow eye. This is particularly true of strabismic amblyopes, regardless of whether the viewing is binocular or with the amblyopic eye alone [17*, 21]. Critically, Chung et al. [14] used retinal imaging in a scanning laser ophthalmoscope to show that the greater error magnitude (the difference between the landing position of the microsaccade relative to the locus of the fixation marker on the retina) was the largest contributor to fixation instability of the amblyopic eye in strabismus. So rather than correcting for drift, the increased error magnitude often took the eye further from its intended landing position. For strabismic amblyopes the drift and associated microsaccades are mostly horizontal [22; also see 14 Fig. 1], whereas for anisometric amblyopes the drift patterns are more like a random walk, so the net deviation from fixation is smaller (23; 14).

The crux of our proposal is that this fixational instability manifests as an attention distractor [24]. The typical coupling of attention and eye movements implies that when a microsaccade occurs, attention is tied to the location of saccade goal [25**]. With the increased frequency of microsaccades in amblyopia, attention is being continuously shifted from one location to another, and is less available to respond to the appearance of a stimulus. This causes delays when the amblyopic observer is asked to maintain fixation on a marker and respond as quickly as possible to the appearance of a stimulus, as vigilance is compromised by frequent microsaccades [26]. This distracting component of attention could apply to all motor latencies, including eye and hand. Another factor that affects saccadic latency is the refractory period for saccades of about 150 ms [27,28], which places a lower bound on how quickly the eye can move following a preceding microsaccade. Previous work with non-amblyopic observers shows that microsaccades increase the initiation time of a saccade: saccadic latency increases by 40 ms when microsaccades occur within 150 ms before the presentation of a saccade target [29]. Thus, the increased frequency of microsaccades in amblyopia could add a further delay to saccadic latency as the eye is more likely to be in a saccade-related refractory period at any given time.

Increased Saccadic latencies in amblyopia

Both saccadic and manual latencies are slower in strabismic amblyopia [15,24,30-35, 36**]. Von Noorden [37] was the first to show increased latency of manual responses when viewing a central (rather than peripheral) target with the amblyopic eye. He also showed that the delay is even longer when the amblyopic eye is tested under conditions of binocular fixation. This additional delay may be the result of interocular suppression of the amblyopic eye by the dominant fellow eye [37]. The delay in both saccadic and manual reaction time is strongly correlated with the reduction in acuity in the amblyopic eye [24,32]. However, the increased delay is not simply a consequence of reduced acuity or contrast sensitivity. For example, Levi et al. [31] studied this manual latency difference as a function of contrast and fit the data with a power function as predicted by Pieron's law [38,39]. Their study showed that while response times decreased with increasing contrast in both eyes, the amblyopic eye needed higher contrast to reach asymptotic response time. McKee et al. [24] considered the possibility that the higher contrast required by the amblyopic eye might simply reflect its lower sensitivity and that the latency vs. contrast functions would superimpose if the latency were plotted against multiples of contrast threshold in each eye (effective contrast). They replotted one observer's data from Levi et al. [32] and showed that while the functions for the two eyes almost overlapped, there was still an irreducible difference in the asymptotic latency for manual response times, with the amblyopic eye having a 46 ms longer latency. To investigate this persistent difference thoroughly, Gambacorta et al. [36**] examined latency for saccades and hands when the effective contrasts in the two eyes were equated. They measured the latency vs. effective contrast for both anisometropic and strabismic amblyopes and found that equating contrast causes the latency vs. effective contrast function to superimpose for anisometropic and some strabismic amblyopes, especially for manual latencies.

However, for other strabismic amblyopes, the amblyopic eye has an additional delay with respect to the non-amblyopic eye of about 75 ms for saccades and a delay of about half of this amount for manual latencies, Moreover, Gambacorta et al. [31**] also showed that saccadic and manual reaction times are highly correlated (> 0.9) in the amblyopic eye, which indicates that common factors are producing a delay in both motor systems. They argue that the common factor involves attention whereby the increased frequency of microsaccades in strabismic amblyopes distracts attention from events such as target onset, resulting in an increase of both saccadic and manual latencies. The frequent microsaccades also increase the time that the amblyopic eye is in a refractory period from a previous saccade. Thus, saccadic latency suffers from two factors both due to microsaccades — distracted attention and the motor refractory period – and therefore exhibits a greater delay than manual latency.

Would the contribution of microsaccades to delays in saccadic latency be minimized if the demand for steady fixation were removed, by turning off the fixation point prior to test target onset, as in the 'gap' effect? Strabismic amblyopes do show the normal 'gap' improvement in saccadic latency in both their normal and amblyopic eyes, but the interocular difference in saccadic latency remains essentially unchanged by the introduction of a gap between fixation point and target (36**). Perhaps the pattern of drift followed by corrective saccades occurs in strabismic amblyopes, even in the absence of a fixation target. In fact, Schor and Hallmark [19] observed large drifts and saccades when their strabismic observers attempted to maintain fixation in darkness with their amblyopic eyes.

Other attentional deficits in amblyopia

Does poor contrast sensitivity and the distraction of attention by the increased frequency of microsaccades account for all reaction time delays, or could there be other factors that impose a general sluggishness in the processing of input from the amblyopic eye? For instance, we have shown that the time for a cue to reach peak effectiveness is delayed in strabismic amblyopia [40]. This is true for both peripheral and central cues. The delay for the amblyopic relative to the fellow eye was greater under binocular presentation, when the stimuli could appear randomly in either eye, compared to monocular presentation, when the stimuli appeared in one eye for a block of trials. However Roberts et al. [41] found no significant delay in response time for the amblyopic vs. the fellow eye for either anisometropic or strabismic participants. Differences in the stimuli used may explain the different pattern of results: the stimuli in Roberts et al. [41] were unmasked and observers were not under any time pressure to respond, resulting in latencies greater than 1 s. More importantly only 4 of the 14 participants were amblyopic, and of these 4 amblyopic participants, only one was strabismic.

The attention deficits due to fixation instability in strabismic amblyopia may not be the whole story. It is clear that amblyopia is associated with impaired performance at tasks that require attention such as multiple-object tracking [42] or detecting the change in direction of motion of multiple trajectories, particularly when the magnitude of change is small [43]. Studies suggest that in the case of strabismic amblyopia, attending to a cue produces a smaller enhancement for input in the amblyopic eye. Hou and coworkers [44] measured SSVEP responses to inputs in the amblyopic and fellow eyes in striate and extra-striate cortical areas while participants were cued to attend to a stimulus on the right or the left. In their study, strabismic amblyopes showed smaller attentional modulation to a cue than did controls and V1 responses were diminished for inputs to the amblyopic eye [44]. Extra-striate responses were diminished for inputs in both the amblyopic and fellow eyes. It is unclear whether this reduced gain is related to the common delay that exists for saccadic and manual reaction times or whether there is an additional mechanism that down-weights input from the amblyopic eye so that it is in a state of attentional neglect [45]. In another study that examined the effect of an attentional cue Pham, Carrasco and Kiorpes [46] measured direction discrimination as a function of contrast in monkeys with amblyopia. The animal was either validly cued to the location of the single vertical grating among seven patches of different orientations, or provided an uninformative neutral cue. Performance in amblyopic monkeys in response to an attentional cue increased both contrast gain and response gain. However, for strabismic monkeys a valid cue in the amblyopic eye did not increase response gain to the level of the fellow eye with a neutral cue. Thus, while the amblyopic eye can benefit from an attentional cue, the response to the cue does not compensate for the lower sensitivity of the amblyopic eye. The Hou et al. [44] and the Pham et al. [46] studies suggest that the input from the amblyopic eye may be habitually down weighted.

Other studies, such as undercounting features in a numerosity judgment task [47] when viewing with the amblyopic eye also point to deficits of attention. One possibility is that when the number of features is large (>5), observers are unable to switch attention to another cluster to subitize and estimate the number within the limited display time using their amblyopic eye. Sharma et al. [47] specifically tested whether extending the trial interval from 200 ms to 1 sec and removing the mask alleviated the undercounting deficit. The undercounting deficit decreased slightly but did not quite reach the performance of the fellow eye, suggesting that perhaps there maybe more than a temporal switching cost to the attention deficit in amblyopia.

The attentional blink is different in amblyopia [48]. The blink appears to be less finely tuned in the amblyopic eye, although the coarse (100 ms) sampling used in the study [48] makes it unclear whether it is delayed. Importantly, the pattern of errors is different than for controls. For the first target letter (T1), observers viewing with their amblyopic eye often report the letter that occurred before T1, suggesting delays in processing such that the previous letter was still being processed when T1 appeared. This effect is consistent with altered dynamics of spatial attention. However, when reporting the second

target letter (T2), amblyopic observers report letters that were never presented, suggesting an erroneous binding of letter features. This might be similar to a deficit in contour integration that we will discuss later, and might seem unrelated to the increased frequency of microsaccades, as only one letter was presented at a time. However, it is possible that the suppression associated with saccades prolongs the time required for evidence to accumulate to reach a perceptual decision [49]. Moreover, amblyopic individuals have longer integration times for higher spatial-frequency stimuli [50], and they show temporal crowding [51], both of which are consistent with frequent periods of suppression that might act like "time-outs".

Farzin and Norcia [52] reported that with the amblyopic eye viewing, choice response times to report the location of a gap (left/right) on a Landolt C are longer. They interpreted this as a consequence of attentional neglect; however an alternative explanation may be inappropriate spatial integration. Their finding, that a simple response-time task did not result in significantly longer delays with amblyopic-eye viewing, can be explained by the dependence of simple response time on stimulus contrast— the high contrast of the stimulus in Farzin and Norcia [52] probably made it clearly visible to the amblyopic eye of observers.

Contour integration and Crowding in Amblyopia

Normal observers can easily find a contour formed of roughly collinear Gabor patches presented amidst a dense background of randomly oriented patches. Amblyopic humans show difficulties in detecting contours in noise [53-58]. This deficit is not due to reduced visibility or increased positional uncertainty [59]. One possible explanation is that the amblyopic eye is impaired at using a contour as a cue. For control participants, Verghese [60] showed that parts of a contour act as a cue to other parts of the contour such that the presence of two or more aligned patches enhances contrast discrimination for a test patch that lies along the implicit path. This self-cueing effect is diminished in amblyopia [61]. While normal controls use a contour cue to find the test patch in an unknown location in noise and discriminate its contrast, amblyopic observers have great difficulty with the presence of noise, even when the test patch is in a fixed location. Interestingly, their contrast discrimination is unimpaired in the absence of noise. These studies suggest that spatial integration is impacted in amblyopia and may be due to the same underlying factors that result in abnormally large crowding zones in amblyopia. Crowding is the spatial pooling of information within a crowding zone that impairs the ability to detect an object in the periphery particularly when it is flanked by other objects. Crowding represents a bottleneck to object recognition and reading in amblyopia [62,63]. As noted above, in normal observers microsaccades can lead to shifts in attention; to the extent that similar attentional shifts occur when strabismic amblyopes make large microsaccades, this may result in increased crowding and substitution errors (i.e., mistakenly reporting a flanker rather than the target) because attention is erroneously directed at a flanker rather than the target [64]. For example, in a crowded acuity task with a 15 arcmin letter (20/60), a 15' microsaccade could result in fixation (and/or attention) on an abutting flank.

Conclusion

Several lines of evidence point to attention deficits in amblyopia. Here, we consider how much fixation instability and its contribution to distracting attention and increasing microsaccade-related refractory periods can explain these attention deficits. Clearly, attention deficits due to unstable fixation are highly consistent with increased latencies for both saccadic and manual latencies. It also possible that fixation-related attention deficits contribute to phenomena as diverse as undercounting, increased SOA for a cue to be effective, the attentional blink, contour integration and crowding deficits in amblyopia. However, there are clearly other results such as reduced response gain and reduced attentional modulation that suggest that fixation-related deficits are not the whole story, and that the attentional deficit in amblyopia may involve a habitual down-weighting of the input from the amblyopic eye, a form of attentional neglect.

Acknowledgments

NEI Grant RO1EY020976

References

1. Kiorpes L, McKee SP (1999). Neural mechanisms underlying amblyopia. Current Opinion in Neurobiology, 9: 480-486.
2. Levi DM (2006). Visual processing in amblyopia: Human studies. Strabismus, 14: 11-19.
3. **Levi DM (2013). Linking assumptions in amblyopia. Visual Neuroscience, 30: 277-287.This review examines the links between sensory deficits in amblyopia and single cell responses in area V1 and shows that many visual deficits in amblyopia are not easily captured by a simple loss of contrast sensitivity in V1 neurons. Other factors such as higher noise, poorer efficiency, and inappropriate pooling play a role and may involve higher cortical areas. This review indicates that the cortical neural losses that have been documented thus far do not completely account for the visual deficits in amblyopia.
4. Posner MI (1980). Orienting of Attention. Quarterly Journal of Experimental Psychology, 32:1,3 – 25.
5. Goldberg ME, Wurtz RH (1972). Activity of superior colliculus in behaving monkey.II. Effect of attention on neural responses. J Neurophysiol., 35(4): 560-74.
6. **Rizzolatti G, Riggio L, Dascola I, Umiltá C. (1987). Reorienting attention across the horizontal and vertical meridians: evidence in favor of a premotor theory of attention. Neuropsychologia 25: 31-40 . This is a landmark study that proposed the “premotor theory of attention” whereby overt and covert attention (without eye movements) share the same neural mechanisms. Interestingly the theory was proposed to explain experimental findings that manual latencies were longer at uncued target locations when observers covertly attended to a cued location. The authors went beyond the data to propose that a saccade is planned every time a cue indicates a target location, and attention accompanies the planning of the saccade. This theory can explain why it takes longer to respond manually when the target does not appear at the cued location.
7. Corbetta M, Akbudak E, Conturo TE, Snyder AZ, Ollinger JM, Drury HA, Linenweber MR, Petersen SE, Raichle ME, Van Essen DC, Shulman GL. (1998). A common network of functional areas for attention and eye movements. Neuron, 21: 761-73.
8. Nobre AC Gitelman DR, Dias EC, Mesulam MM. (2000). Covert visual spatial orienting and saccades: overlapping neural systems. Neuroimage, 11: 210-6.
9. Beauchamp MS, Petit L, Ellmore TM, Ingeholm J, Haxby JV. (2001). A parametric fMRI study of overt and covert shifts of visuospatial attention. Neuroimage 14(2): 310-21.
10. Moore T, Fallah M. (2001). Control of eye movements and spatial attention. Proc. Natl. Acad. Sci. USA. 98: 1273-6.
11. Moore T, Armstrong KM. (2003). Selective gating of visual signals by microstimulation of frontal cortex. Nature, 421: 370–373.

12. *Hafed ZM, Clark JJ. (2002). Microsaccades as an overt measure of covert attention shifts. Vision Res., 42(22): 2533-45. This is the first study to show a link between small eye movements during fixation (<1°) and the location of covert attention. The direction of these "micro" saccades was clearly biased toward the attended location, showing a link between attention and saccades.
13. Yuval-Greenberg S, Merriam EP, Heeger DJ. (2014). Spontaneous microsaccades reflect shifts in covert attention. Journal of Neuroscience, 34: 13693–13700.
14. Chung STL, Kumar G, Li RW, Levi DM. (2015). Characteristics of fixational eye movements in amblyopia: Limitations on fixation stability and acuity? Vision Research, 114: 87–99.
15. Ciuffreda KJ, Kenyon RV, Stark L. (l978) Increased saccadic latencies in amblyopic eyes. Investigative Ophthalmology & Visual Science, 17: 697–702.
16. Ciuffreda KJ, Levi DM, Selenow A. (l991). Amblyopia: Basic and clinical aspects. Boston: Butterworth-Heinemann.
17. *Gonzalez EG, Wong AMF, Niechwiej-Szwedo E, Tarita-Nistor L, Steinbach MJ (2012). Eye position stability in amblyopia and in normal binocular vision. Investigative Ophthalmology & Visual Science, 53: 5386–5394. This study measures fixation stability binocularly and shows increased instability in amblyopic eyes no matter whether viewing is monocular (with the fellow eye or the amblyopic eye) or binocular. This is relevant to showing that fixation instability is an issue under real-world conditions of binocular viewing.
18. Maxwell GF, Lemij HG, Collewijn H. (l995). Conjugacy of saccades in deep amblyopia. Investigative Ophthalmology & Visual Science, 36: 2514– 2522.
19. Schor CM, Hallmark W. (l978). Slow control of eye position in strabismic amblyopia. Investigative Ophthalmology & Visual Science, 17: 577–581.
20. Zhang B, Stevenson SS, Cheng H, Laron M, Kumar G, Tong J, Chino YM. (2008). Effects of fixation instability on multifocal VEP (mfVEP) responses in amblyopes. Journal of Vision, 8(3): 16, 1–14, doi:10.1167/8.3.16.
21. Raveendran RN, Babu RJ, Hess RF, Bobier WR. (2014) Tranisent fixation stability in strabismic amblyopes following bifoveal fixation and reduced interocular suppression. Ophthalmic Physiol Opt., 34: 214-25.
22. Subramanian V, Jost RM, Birch EE. (2013). A quantitative study of fixation stability in amblyopia. Invest Ophthalmol Vis Sci., 54(3): 1998-2003.
23. Koylu MT, Ozge G, Kucukevcilioglu M, Mutlu FM, Ceylan OM, Akıncıoglu D, Ayyıldız O (2007). Fixation Characteristics of Severe Amblyopia Subtypes: Which One is Worse? Seminars in Ophthalmology, 32(5): 553–558.
24. McKee SP, Levi DM, Schor CM, Movshon JA. (2016). Saccadic latency in amblyopia. J Vis., 16(5):3.
25. **Kowler E, Anderson E, Dosher B, & Blaser E. (1995). The role of attention in the programming of saccades. Vision Research, 35, 1897–1916. A rigorous set of studies

showing the tight link between attention and saccades. The authors demonstrated increased perceptual sensitivity at the saccade goal, facilitation of saccades to an attended location, and most importantly, that it was hard to decouple attention from the saccade goal—observers could not attend to a location and plan a saccade to a different location.

26. Betta E, & Turatto M (2006). Are you ready? I can tell by looking at your microsaccades. Neuroreport, 17: 1001–1004.
27. Carpenter RHS. (l977). Movements of the eyes. London: Pion Limited.
28. Otero-Millan J, Troncoso XG, Macknik SL, Serrano-Pedraza I Martinez-Conde S. (2008). Saccades and microsaccades during visual fixation, exploration, and search: Foundations for a common saccadic generator. Journal of Vision, 8(14): 21, 1–18, doi:10.1167/8.14.21.
29. Rolfs M, Laubrock J, Kliegl R. (2006). Shortening and prolongation of saccade latencies following microsaccades. Experimental Brain Research, 169: 369–376.
30. Mackensen, G. (1958). Reaktionszeitmessungen bei Amblyopia [Translation: Reaction time in amblyopia]. Graefes Arch Ophthalmol, 159: 636–642.
31. Levi DM, Harwerth RS, Manny RE. (1979). Suprathreshold spatial frequency detection and binocular interaction in strabismic and anisome- tropic amblyopia. Investigative Ophthalmology & Visual Science, 18: 714–725.
32. Hamasaki DI, Flynn JT. (l981). Amblyopic eyes have longer reaction times. Investigative Ophthalmology & Visual Science, 21: 846–853.
33. Niechwiej-Szwedo D, Chandrakumar M, Goltz HC, Wong AMF. (2012). Effects of strabismic amblyopia and strabismus without amblyopia on visuomotor behavior I: Saccadic eye movements. Investigative Ophthalmology & Visual Science, 53: 7458–7468.
34. Niechwiej-Szwedo D, Goltz HC, Chandrakumar M, Hirji ZA, Wong AMF. (2010). Effects of anisometropic amblyopia on visuomotor behavior, I: Saccadic eye movements. Investigative Ophthalmology & Visual Science, 51: 6348–6354.
35. Perdziak M, Witkowska D, Gryncewicz W, Przekoracka-Krawczyk A, Ober J. (2014). The amblyopic eye in subjects with anisometropia show increased saccadic latency in the delayed saccade task. Frontiers in Integrative Neuroscience, 8: 1–13, doi:10.3389/fnint.2014.00077.
36. **Gambacorta C, Ding J, McKee SP, Levi DM. (2018). Both saccadic and manual responses in the amblyopic eye of strabismics are irreducibly delayed. J Vis. 18(3): 20. This paper examines both saccadic and manual latencies in anisotropic and strabismic amblyopia after the contrast in the two eyes has been perceptually equated. Careful measurements of the response time vs. effective contrast show that even at the highest contrasts, some strabismic amblyopes show a persistent delay for both saccadic and manual response times. The correlation between saccadic latencies is high (>0.9) suggesting a common factor that underlies these two modalities. The authors propose that the increased fixational instability in strabismic amblyopia distracts attention and accounts for both these effects. They also

propose that the additional delay for saccadic over manual latencies may be due to the refractory period associated with saccades.

37. Von Noorden GK (1961) Reaction time in normal and amblyopic eyes. Archives of Ophthalmology, 66: 695–699.
38. Pie´ron H. (1914). Recherches sur les lois de variation des temps de latence sensorielle en fonction des intensite´s excitatrices [Translation: Research on the laws of variation of sensory latency as a function of stimulus intensity]. Anne´e Psychol, 22: 17–96.
39. Pie´ron H. (1952). The sensations: Their functions, processes and mechanisms. London: Frederick Muller Ltd.
40. Lai X, McKee S, Hou C, Verghese P. (2013). Cuing attention takes more time in strabismic amblyopes [Abstract]. Journal of Vision, 13(9): 470, doi:10.1167/13.9.470. [Abstract]
41. Roberts M, Cymerman R, Smith RT, Kiorpes L, Carrasco M. (2016). Covert spatial attention is functionally intact in amblyopic human adults. J Vis. 16(15):30.
42. Ho CS, Paul PS, Asirvatham A, Cavanagh P, Cline R, Giaschi DE. (2006). Abnormal spatial selection and tracking in children with amblyopia. Vision Res., 46(19): 3274-83.
43. Tripathy SP, Levi DM. (2008). On the effective number of tracked trajectories in human amblyopia. J Vis. 15;8(4): 8.1-22.
44. Hou C, Kim YJ, Lai XJ, Verghese P. (2016). Degraded attentional modulation of cortical neural populations in strabismic amblyopia. J Vis.,16(3):16.
45. Van Balen AT, Henkes HE. (1962). Attention and Amblyopia: an electroencephalographic approach to an ophthalmological problem. Br J Ophthalmol. 46(1): 12-20.
46. Pham A, Carrasco M, Kiorpes L (2018). Endogenous Attention improves perception in amblyopic macaques. J Vis. 18(3): 11.
47. Sharma V, Levi DM, Klein SA. (2000). Undercounting features and missing features: evidence for a high level deficit in strabismic amblyopia. Nature Neuroscience, 3: 496–501.
48. Popple AV, Levi DM. (2008). The attentional blink in amblyopia. Journal of Vision, 8(13): 1, 1–9, doi:10.1167/8.13.12.
49. Loughnane GM, Newman DP, Tamang S, Kelly SP, O'Connell RG. (2018) Antagonistic interactions between microsaccades and evidence accumulation proesses during decision formation. J Neurosci., 38(9): 2163-2176.
50. Harwerth RS, Levi DM (1978). A sensory mechanism for amblyopia: psychophysical studies. American Journal of Optometry and Physiological Optics, 5 (3): 151-162.
51. Bonneh Y, Sagi D, Polat U. (2007). Temporal and spatial crowding in amblyopia. Vision Res., 47(14): 1950-62.
52. Farzin F, Norcia AM. (2011). Impaired visual decision-making in individuals with amblyopia. Journal of Vision, 11(14): 6, 1–10, doi:10.1167/11.14. 6.
53. Chandna A, Pennefather PM, Kovács I, Norcia AM. (2001). Contour integration deficits in anisometric amblyopia. Invest Ophthalmol Vis Sci., 42(3): 875-8.

54. Hess RF, McIlhagga W, Field DJ. (1997). Contour integration in strabismic amblyopia: the sufficiency of an explanation based on positional uncertainty. Vision Res.,37(22):3145-61.
55. Kovács I, Polat U, Pennefather PM, Chandna A**,** Norcia AM. (2000). Anew test of contour integration deficits in patients with a history of disrupted binocular experience during visual development. Vision Res. 40(13): 1775-83.
56. Levi DM, Sharma V. (1998). Integration of local orientation in strabismic amblyopia. Vision Res., 38(6): 775-81.
57. Mussap AJ, Levi DM. (1999). Orientation-based texture segmentation in strabismic amblyopia. Vision Res. 39(3): 411-8.
58. Mussap AJ, Levi DM. (2000). Amblyopic deficits in detecting a dotted line in noise. Vision Res., 40(23):3297-307.
59. Levi DM, Yu C, Kuai SG, Rislove E. (2007). Global contour processing in amblyopia. Vision Res., 47(4): 512-24.
60. Verghese P. (2009). Contours in noise: a role for self-cuing? J Vis. 9(13):2 1-16.
61. Verghese P, Levi DM (2003). Meridional amblyopia impairs contour integration. ARVO annual meeting abstract. https://iovs.arvojournals.org/article.aspx?articleid=2414993
62. Levi DM, Song S, Pelli DG (2007). Amblyopic reading is crowded. J Vis., 7(2): 21.1-17.
63. Levi, DM (2008). Crowding—an essential bottleneck for object recognition: a mini-review. Vision Res. 48(5): 635-54.
64. Nandy AS, Tjan BS. (2012). Saccade-confounded image statistics explain visual crowding. Nat Neurosci. 15(3): 463-9, S1-2.
65. Kliegl R, Rolfs M, Laubrock J, Engbert R. (2009). Microsaccadic modulation of response times in spatial attention tasks. Psychological Research, 73: 136–146.