Article • Who's on First? Is It Fixation That Drives Sensation? Or Is It Sensation That Controls Fixation?

Eric S. Hussey, OD • Spokane, Washington

ABSTRACT

Background: Fixation is the pause in saccadic eye movements that allows visual information to be sent to the cortex. Small fixational eye movements support stability of sensation during fixation, but yet to be established is whether stable sensation is required for properly controlled fixational eye movements.

Methods and Results: The vision science literature describes the motor side of fixation and how drifts and microsaccades work to keep the visual signal alive; that is, how they work to keep visibility intact. The clinical literature describing intermittent central suppression suggests possible effects on motor accuracy in fixation. Putting the vision science together with the clinical picture may help in understanding some of the problems associated with intermittent central suppression such as reading difficulty.

Conclusions: Understanding fixational eye movements allows description of probable eye-aiming errors that could occur during intermittent central suppression and that constitute a "spin-cycle" of aiming errors and sensory defects that interfere with accuracy in vision. The vision science provides the details of the motor and sensory parts of the spin-cycle.

Keywords: fixation, fixational eye movements, intermittent central suppression, magnocellular pathway, microsaccades, visibility

Introduction

Fixation: the necessary pause in ballistic saccadic motor activity during which visual information such as print on a page can be sent to the visual cortex. In fact, during a saccade, visual sensation and discrimination decrease, accompanied by and probably effectuated by a decrease in magnocellular firing rate of twenty percent or so.[1,2] The greatest detail (the sharpest visual acuity) and also the greatest retinal neural and ganglion cell involvement will occur if the fovea is aligned with the target of regard. In reading, that target is a word or words on the page. The precise positioning of the fovea on printed material may have an important role in visual memory and therefore learning.[3] At the very start, we have to state that accurate eye movements are necessary and responsible for getting the fovea, or in macular disease, the preferred retinal locus,[4] aligned with the target of regard. Without accurate eye movements leading to precise macular aim, information will likely be ignored or lost.

Fixational Eye Movements Supporting Visibility

The pause for fixation is not a true or complete cessation of motor activity. Rather than a suspension of action, a fixational pause actually includes a great deal of motor activity.[5] In fact, if the retinal image were truly stable (that is, no motor activity of any kind nor any passive drift in aim), the image would fade away in 80 msec or so.[6,7] That fading is probably a reduction in contrast to the point of disappearance.[8] Some retinal image motion or temporal modulation of the image

(on a receptor level, motion and temporal modulation may be the same stimulus[9]) is absolutely necessary for visibility, necessary for the retinal image to "stay alive" and make its way to the cortex to be perceived.[6,10] Three fixational eye movements are involved in keeping the image awake: fixation tremor, microsaccades, and drifts. Those fixational eye movements occur both monocularly and binocularly.[11] Virtually all of the studies on fixational eye movements assume fully intact, unimpaired visual neurology between the retina and the cortex. That is a luxury we may not have in the clinic.

Fast but small fixation tremor is a constant, except during saccades and microsaccades. Fixation tremor is very small and very fast, covering movements just a little less than the foveal inter-cone spacing.[12] Drifts are the variance in aim that occur between aim-correcting (to some degree) microsaccades, that variance on average taking foveal fixation away from the target of regard. Although much has been written on the neural pathway involving the superior colliculus for initiating saccades and microsaccades, little has been written on control of drifts.[13] As the term drift implies, this movement time between microsaccades may be a more passive oculomotor function, a function of ordinary, common instability in a complex neuromuscular system.[14] Although drifts apparently do have a random component, some active control may be involved since drifts move largely opposite to the direction of the prior microcassade, and vice versa: microsaccades move opposite to the direction of the last drift.[15] This contrasts with the typically more vertical drifts in blindness, suggesting, again, some level of active control when there is sight.[16]

Any presumed oculomotor passivity should not be taken to imply that the retinal image motion produced by drifts does not support maintenance of visual sensation.[17] In fact, V1 neurons respond to drift, and as a result, image detail improves, suggesting that perceptual enhancement in the foveal image must occur during drifts.[18] St. Cyr et al.[19] in a sense argue against the passivity of drifts in noting that drifts may contribute to aim correction when microsaccades show directional inaccuracy.

In the central retina, with small receptive fields and tightly packed receptors, drifts and tremor may produce enough transient-neurology motion input to keep the image from fading, to support and to retain visibility of the target of regard. This is not so when we move away from central vision, where the receptive fields are too large for tremor to move the image across receptive field borders.[17]

Microsaccades have received the bulk of attention in research on maintaining visibility since they are a reliable indicator of visibility change. Decreases in microsaccades precede fading/loss of visibility, and increases in microsaccades precede increases in visibility/reversal of fading. Changes in microsaccade rates anticipate changes in visibility or image strength.[11] Unexplained is what the trigger is for the microsaccade rate changes that anticipate or precede visibility changes. However, during fades from visibility, since microsaccades decrease, the gaps between microsaccades, or drifts, increase. Larger drift displacements of fixation during fades are more likely to trigger microsaccades.[13] This suggests that the drift-produced visual motion and/or retinal image displacement is at least one trigger for correcting microsaccades. Perhaps the combination of drifts and microsaccades is what sustains visibility and contrast.[13] McCamy et al. suggest that drifts sustain image visibility, while microsaccades are more efficacious at restoring visibility after an image fades.[20] Conversely, if visual sensation has faded and drift of aim has increased, that suggests that an increase of the neurological motion

signal beyond baseline must be necessary to reestablish visibility. Microsaccades apparently do that.

The transient visual neurology (magnocellular pathway) is responsible for neural signals controlling visibility changes. The magnocellular pathway is never truly silenced, always having background activity. Just a 20% drop from the normal background firing rate can trigger a loss of visibility.[10] The behavior of magnocellular saccadic and post-saccadic spike rates may well explain the efficacy of microsaccades in restoring visibility after a loss. Whereas a drop in the magnocellular spike rate of 20% mediates a loss of visibility, when a saccade lands fixation at a point, the magnocellular spike rate nearly doubles, measured at the lateral geniculate nucleus (LGN).[1] Therefore, drifts and microsaccades modulate activity and sustain the necessary activity level in the transient pathway, in turn controlling and sustaining visibility. In this sense, fixation controls sensation. A normal pattern of microsaccade-drift-microsaccade and sustained visibility would assume unimpaired motion sensitivity.

Adding to the motor mix is vergence, the simultaneous movement of both eyes in opposite directions to obtain single binocular vision.[21] Vergence has received much attention lately with the various Convergence Insufficiency Treatment Trials.[22] Those trials have made it clear that defective vergence has an unfavorable effect on visual tasks such as reading, tasks that require precision in eye aiming over time to assure the clearest single image possible. Fixation drifts may be part of maintaining vergence accuracy.[19] All of these fixation-related oculomotor functions – tremor, microsaccades, drifts, and vergence – are not isolated "snapshot" activities, but are part and parcel of the visual dynamic happening over time.

Unstable Sensation: Non-strabismic, Non-amblyopic Suppression

What about sensation? What is the effect of interference in sensation over time on those oculomotor functions? What if we view the events of fixation from the side opposite to oculomotor, from the side of visual sensation?

As discussed above, fixational eye movements keep the retinal image awake. Vergence probably contributes to retinal image motion and therefore to visibility, as do head movements,[23] even though the primary role of vergence is usually considered to be that of maintaining single vision. However, is a steady, unfluctuating retinal image involved in keeping fixation and vergence on target? Vergence and fixation accuracy maintain single binocular vision, but does single binocular vision sustained over time help maintain fixation accuracy and, by extension, vergence accuracy? Is this dance to maintain single, clear, stable visual sensation a one-sided affair, with motor effects in charge, or is another dancer – intact, stable visual sensation – also involved?

For example, non-strabismic, non-amblyopic intermittent central suppression (ICS) may cause small errors in vergence. ICS is a repetitive, intermittent, usually alternating dropout of central visual sensation following a typical temporal pattern of two to three seconds of loss of sensation (suppression) followed by three or so seconds of non-suppressed bilateral sensation. That sequence repeats over time, probably creating visual confusion and instability.[24] Logically, loss of central sensation would remove the sensory lock on vergence, and we could anticipate vergence drift. Then, when the suppression resolved for the few seconds of bilateral sight, correction of aim would have to occur to maximize accuracy for the best central image. All of this activity superimposes over or is coincident with saccadic jumps of fixation

down a line of print. The simulation of dropout of central sensation over time by Collewijn et al. supports the idea that interference in sensation negatively affects stable bilateral aim and vergence accuracy.[25]

Further complicating visual stability is the likely perceptual fill-in that occurs during loss of visibility/visual sensation.[8] Suppressors do not see a black spot during their suppressions. The cortex calculates a fill-in that is "surround," visual junk of about the same color and about the same texture as the target of regard. This fill-in, which serves to prevent a positive suppression scotoma, is a perceptual calculation without afferent retinal visual data.[8]

The more stealthy, and probably under-appreciated, part of the perceptual fill-in is that it is actually strong enough actively to interfere with the other eye's image through rivalry.[8] The first level of interference from the suppression and perceptual fill-in is from superimposition of the two images – one actual and one fill-in – in the same visual space. Although two images exist, the fill-in is unlikely to have any visual borders or other commonalities with the non-suppressed eye's image that would aid some level of precise motor fusion. Any fixation drift that might create a deviation in aim of either side means that the two images are now moving relative to each other. Added to those superimposed, moving images is rivalry, causing some direct but not consciously controlled switching from one image to the other.

Recent work on rivalry and attention suggests that this perceptual fill-in and potential rivalry might be even more relevant to children with reading problems. Attention is a difficult concept to define fully and accurately in a research sense, or even a clinical sense, once described as "the psychologist's weapon of mass explanation."[26] With that caveat, when visual attention is directed away from rivalrous images, binocular rivalry stops.[27,28]

Put that into the context of a child with reading problems, whose visual attention on a page of print quite likely will drift from the word at which they have been directed to look. Bilateral central visual areas (versus retinas/foveas, since the fill-in is probably cortically generated beyond V1[8]), during a loss of visibility/visual sensation, now are simultaneously sending visual images to the brain of one intact "correct" image and a moving perceptual fill-in. Rivalry may have stopped, but the strength of the fill-in is still there, so this is not one strong and one ghost image or one real image and one image that a novice reader can easily tell is not the real one. Over time, rivalry is less likely to reestablish naturally, rather than more likely,[29] suggesting that time and development are not going to "make it all go away." This also suggests that the visual world of a page of print may well be bewildering when dealing with ICS, as the visual percept repetitively moves through a cycle of bilateral alignment, suppression with a fill-in, movement out of alignment, resolution of the suppression with resultant diplopia, and movement back into alignment.

Neural plasticity allows reestablishment of rivalry in adults, probably through reestablishing magnocellular support for simultaneous activity of orientation and spatial frequency neurons (parvocellular neurons).[29] The good news is that neural plasticity is available in the visual neurology into adulthood. The bad news is that the fundamental error in fixation caused by the suppression, as well as the perceptual consequences of the fixation error, remain until actively treated. The central visual world of someone with ICS is probably confused and is constantly changing with moving, superimposed images, with final correction coming with the resolution of the suppression. All of that is repeated in a few seconds, and

virtually all of that is afferent. As Reudemann[3] says, "Anything that interferes with the foveal coordination shortens the span of attention and interferes with the memory process … foveal coordination is the nucleus of our learning process and our visual learning." Fixation is that foveal coordination. That pause in saccadic activity to allow transfer of visual information to the cortex is key to visual learning.

Intact Visual Motion as the Foundation for Sensation

Negating visual motion at the retinal level causes loss of visual sensation (perhaps more accurately, loss of visibility) through fading of the image.[10,30] A loss of visual motion sensitivity that would produce loss of visibility has been suggested as the underlying defect in ICS.[31] A neural defect reducing motion sensitivity would logically reside in large part in the magnocellular pathway.[32] A useful analogy for motion, M-pathway function and the effect of changes in detected motion on visibility, lies in the workings of the computer mouse and the computer. If the computer mouse is moved – if the mouse senses motion and transmits that motion signal to the computer – the computer screen stays awake. If the mouse stops moving and sending that mouse-based motion signal to the computer, the screen goes blank. It switches to screen-saver or sleep mode. The interplay between M- and P-pathways is analogous. If the motion-carrying M-pathway is defective, motion is harder to detect, and the result of the decrease in motion signal is a dropout of detail-carrying P-pathway. It is that dropout of detail that is implicated in or that constitutes ICS. The limitation to the analogy is that when the computer mouse is stopped, the motion signal to the computer stops completely; it does not simply decrease. In the visual neurology, "M" isn't "unplugged," with the M-signal shut off. Just a 20 percent decrease in "M" firing rate can cause a loss of detail (P-) to the 50% probability level in a recognition task,[1,2,8] probably through a loss of contrast.[8,13]

Why the suppression resolves in ICS to restore vision, or visibility, in the on-off visual sequence of ICS is an equally interesting question, and it must involve the same visual neurology. The switch from an "off" suppressed period to an "on" period, with the formerly suppressed eye seeing, may be a function of drifts during the loss-of-visibility suppression. It may also be a function of the change in the position of fixation reached during the suppression due to the drift away from accurate aim. Drift velocity increases when central vision laks detail;[15] drifts are longer, and microsaccade rates decrease, during losses of visibility.[13] V1 neurons respond to drift, and at least foveally, drift enhances the percept.[18] Microsaccades are triggered beyond the retina in the superior colliculus, as are other saccades.[13] Similarly, suppression occurs beyond the retina at a higher neurological level.

Although the visual cortex may not have an intact image or percept due to the suppression, light itself travels to the retinas unimpeded by the suppression. The suppression does not somehow prevent light from hitting the retinas, and the retinas are where the M and P ganglion cells originate. Therefore, that increased drift velocity and movement of detail across a wider range of M cells as the drifts shift the target across a broader area of retina may mean increased M firing as an afferent response to visual edges moving at increasing speed across retinal receptor and then ganglion cell receptive fields. The increased speed of drifts and less-frequent microsaccades also means increased displacements of the retinal image – increased positional error. Larger fixation displacements away from the target of regard are more likely to trigger correcting microsaccades.[13] Those microsaccades are associated with image

restoration after loss of visibility. Somehow, between the increased motion of target edges and detail across the retinas during a loss-of-visibility induced drift and the increased positional error from the same drift, enough motion is transmitted through M ganglion cells and microsaccade activity triggered by positional error that the fade in visibility is reversed, and the suppression recedes.

At first blush, having microsaccades preceding reestablishment of visibility suggests that positional error may outweigh drift motion as the trigger for a visibility-restorative microsaccade, since by definition drifts end with microsaccades that are more efficacious than drifts at restoring faded visibility. If a microsaccade precedes resolution of the suppression, then the image is not or has not been reestablished prior to the microsaccade. It cannot be both before and after the microsaccade that visibility is reestablished if microsaccades are the most efficacious fixational eye movements at image restoration.[20] Since the image itself is suppressed during a microsaccade, and then it is reestablished upon landing the microsaccade, changes in visibility must be post-saccadic. Another possibility is that a threshold for visibility is passed by increased magnocellular activity from the faster/larger drifts that then trigger a microsaccade based on error in aim, and we just do not have the ability to detect that initial increase in visibility. Either way, position is likely involved as a trigger for correcting microsaccades. Any positional error has to be corrected with microsaccades and vergence, perhaps including vergence-correcting drifts[19] to restore truly accurate bilateral – binocular – aim and vision.

This loss of visibility suggests a question regarding the neurological consequences of a loss of visibility occurring early in visual development, a particularly sensitive time during a period of rapid neural development. Is it possible that the same dropout of detail (contrast?) seen with non-strabismic, non-amblyopic ICS may be part of the falling sensory dominoes during early visual development, creating the cortical deprivation of amblyopia?[33] With a very early loss of visibility, could neurons be deprived of an intact post-synaptic signal to drive neural development from the LGN to the cortex? If so, the prospect of loss of neural development amounting to an amblyopic "internal deprivation" arises.

Importantly, the sensory "dropouts" discussed so far have been pre-cortical – they are afferent.[10] Therefore, the downstream neurology may be starved for activity in early development, not by an early cataract or ptosis, but actually by afferent loss of activity from loss of visibility. That loss of visibility may be triggered by only a 20% loss of magnocellular activity … of unknown cause. The cascade of effects would probably include a decrease in motor learning for accurate fixation since motor learning is believed to be activated by detection of errors by the visual system.[34] With impaired sensation through loss of visibility, less-accurate detection of error would be expected, which is supported by the loss of accuracy in vergence correction after saccades in a simulation paradigm.[25] That also suggests that with impaired sensation/visibility, fixation cannot learn truly accurate fixation behaviors.[35]

Afferent Sensory Defects

Clearly, fixational eye movements affect, and probably to some degree modulate, visual sensation. Less clear in research, but certainly implied by our understanding of visual sensation over time, is that stable visual sensation is also a part of the control of this dance between sensation and motor. Who leads in the dance may be up for debate. Fixational eye movements are complex, but visual sensation seems much more so.

Interruptions or defects in sensation can be afferent, such as in diagnoses like macular degeneration or in research paradigms that cover all or part of an eye's image. Defects can also be cortical, from V1 and beyond, ranging from strokes and other traumas to supposed cortical masking of one eye's image in strabismus and amblyopia.[7,36] Separating fixation patterns in experimentally produced afferent interferences ("defects") in sensation from fixation patterns seen in definite central neurological influences, as well as fixation patterns in pathologies just assumed to have central sensory influences (amblyopia), may show differences that could modify our traditional views of visual sensation and interferences in visual sensation.

If there is anything to the idea that afferent sensory defects could logically be expected to foster error in fixation, then experimental interruption of a visual target to produce an afferent sensory interruption, a "mimicked defect," might produce some consistent measurable errors. When Collewijn et al.[25] interleaved monocular and binocular conditions while measuring saccades and vergence, errors in those functions would be expected to increase under monocular versus binocular (perhaps more accurately, bilateral) conditions. They do document vergence errors at the end-point of saccades that would normally have been corrected with a combination of a version and vergence, but during the monocular conditions, those compensations during the intersaccadic fixation period didn't happen, as the non-seeing eye drifted toward a more central location. Also, saccades with the non-seeing eye tended to be smaller. Therefore, afferent loss of visual sensation in a completely vision-covering paradigm interferes with bilateral coordination of saccade dynamics.

A more recent afferent defect demonstration used visual stimuli computer-linked to eye movement monitoring in an attempt to mimic newer or more recently acquired macular degeneration.[4] Perhaps the most interesting experimental condition in Geringswald et al. was the 4-degree "warp" scotoma. With a little imagination, the warp scotoma condition might be considered similar to the perceptual fill-in during suppression that consists of "surround." In the experimental condition, all computer-superimposed central visual disturbances followed fixation in a computer-generated scene. Interfering with central visual sensation afferently reduced the number of fixations and increased saccade amplitudes, meaning more time with fixation in drifts. This echoes Bethlehem et al.'s finding that in juvenile macular degeneration, maintaining fixation is more difficult, and the instability in fixation is driven by drifts.[37]

Saccades were also less accurate in these experimental conditions, but there was no indication that saccade speed changed. Their findings on memory in the warp (and other) scotoma condition mirrors Reudemann's[3] assertion that visual learning and memory are related to foveation. Both short- and long-term visual memory suffered in these digitally produced scotoma conditions. Longer, more frequent fixations increase later memory, but this group showed less frequent, sloppier fixation with these visual memory impairments, accompanied by reduced detection of change in a visual scene.[4]

Geringswald et al. found that "the quality of long-term memory suffers when central vision becomes unavailable."[4] Further, they suggest that "the loss of foveal vision alone might [cause] problems in untrained observers."[4] As practitioners, then, we move this experience from the experimental world into the clinical world of intermittent suppressors. Unavailable or unreliable central vision is part and parcel of (intermittent) central suppression. A school child learning to read easily fits the parameters of an "untrained observer." The whole discussion of afferent disruption of central

sensation and fixation behavior suddenly is thrust into the clinical realm with untrained observers (children) saddled with unreliable central vision through suppression and the perceptual fill-in that occurs. The perceptual fill-in during a loss-of-visibility suppression may well push that unavailability of central vision to active interference with visibility of central vision.[8]

The distortion of fixational microsaccade behavior with afferent sensory defect may be related to contrast. Fixational saccades will be abnormal without observable contrast, and higher contrast increases fixational microsaccades.[38] Loss of visibility (Troxler's perceptual fading/intermittent central suppression?[39]) may be a reduction in contrast to the point of disappearance.[13] If accurate, and if loss of visibility is afferent, then microsaccade behavior during loss of visibility should match these afferent losses in experiments and in juvenile macular degeneration…and they do.[4,37]

During a Troxler's fade, microsaccade rates reduce and drifts increase in span. Similarly, looking at a uniform field without a fixation marker shows increased drift speeds and saccade amplitudes.[15] Since drift amplitude increases, microsaccade frequency has to decrease. Longer drifts mean fewer microsaccades.[39,40] Cherici et al.[13] also note that variance away from accurate aim in the uniform field condition is larger for inexperienced observers than for observers experienced as research subjects. Again, this data starts to intrude into the clinical setting with children. If something interferes with central sensation with a younger, less experienced reader, the variance in eye aiming away from accuracy is probably more than in an older, more experienced reader. They also suggest that peripheral vision may come into play in correction of aim, suggesting that position of the target away from the central visual area due to drifts may be part of reestablishment of aiming and resolution of visibility.

Afferent disruption of visual sensation decreases stability of fixation, increasing length of drifts and microsaccades while decreasing frequency of microsaccades, as well as impairing visual memory.

Neurologically Central Sensory Defects

Getting at visual sensory defects that we're sure are central and not afferent and how they affect fixational eye movement behavior is much tougher. The suppression of amblyopia may have a central component, but the afferent component apparently is much stronger than the central, cortical component,[41] fitting amblyopia more closely with the afferent defects than might be expected.

Cortical blindness certainly affects fixational eye movements, but on a much more significant scale than we discuss in microsaccadic behavior. Since small fixational eye movements prevent sensory adaptation that causes fading, when the cortex is inactive, that visibility-generating mechanism is profoundly affected, maybe losing any usefulness. In fact, after visual recovery in some of these formerly blind patients, visual motion can be perceived but cannot be used to prevent drifting in eye aiming, suggesting possible loss of part of the fundamental mechanism, perhaps related to contrast sensitivity (above).[16]

Drifts in loss of visual sensation are significantly faster, similar to those in amblyopia. Bilateral visual loss causes larger drifts than seen following monocular visual loss. Drifts become more vertical in blindness, termed the Heimann-Bielschowsky Phenomenon (HBP).[16] Most V1 neurons have drift responses, some with strong sustained activation,[18] so if V1 is unavailable, its neural response is probably unavailable, and drift behavior will change. Further, if visual sensation is gone bilaterally, correcting saccades and microsaccades go away.[16]

An imperfect way to get at central effects on fixational eye movements when blindness is not an issue might be to look at fatigue. Microsaccade rates reduce with relaxation; relaxation certainly wouldn't be considered an afferent visual defect.[16] Fatigue can also be considered central, possibly involving the brain's sleep centers (DiStasi et al. list those as nucleus raphe magnus, nucleus raphe dorsalis, and locus coeruleus.[42]) DiStasi et al.[42] used an air traffic control simulation paradigm to look at fatigue and fixational eye movements. Measurable fixational eye movement degradations occur fairly early in what would be a typical air traffic control shift. The relevant point, though, is that fatigue is not an afferent defect; therefore, these are not afferent vision neurology structures that would produce these changes in fixational behavior. It can certainly be said, however, that we probably don't know all the neural interconnections.

Microsaccade rates reduce with relaxation, and they apparently do in fatigue. Drift velocity increases with fatigue,[42] as it does in amblyopia.[43] A major difference is that in the central defect of fatigue, microsaccade velocity decreases, a velocity difference not seen in amblyopia.[42] Further, since drift velocity increases and microsaccade rates decrease in fatigue, we would expect that the drift-correcting microsaccade velocity would increase, since saccadic velocity increases with increasing saccadic amplitude necessary for correction of aim. Instead, a reduction in saccadic velocity with fatigue is the opposite of non-impaired or afferent sensory defect-associated microsaccadic behavior.[44]

As limited as this central versus afferent defect comparison is, it suggests first and foremost that interference in visual sensation negatively affects fixation. Fixation gets sloppy, and fixation is the information-input time for vision. The differences in microsaccade velocity between known afferent defects and known central influences suggest that microsaccade behavior may point very generally toward where the interruption of visual sensation is. If microsaccade velocity slows, the defect is more likely central. When microsaccade velocity stays intact, the primary sensory defect may well be afferent, which, for amblyopia, requires a shift from locating the sensory defect, suppression, entirely in the cortex to perhaps being strongly afferent, possibly near the lateral geniculate nucleus (LGN).[41] An intensely practical aspect from this investigation of fatigue suggests our need to pay close attention when patients, perhaps older patients in particular, complain about difficulty reading with fatigue. Particularly when any sensory issues are diagnosed, the fatigue effect becomes a very real hurdle for people who have enjoyed reading in the past.

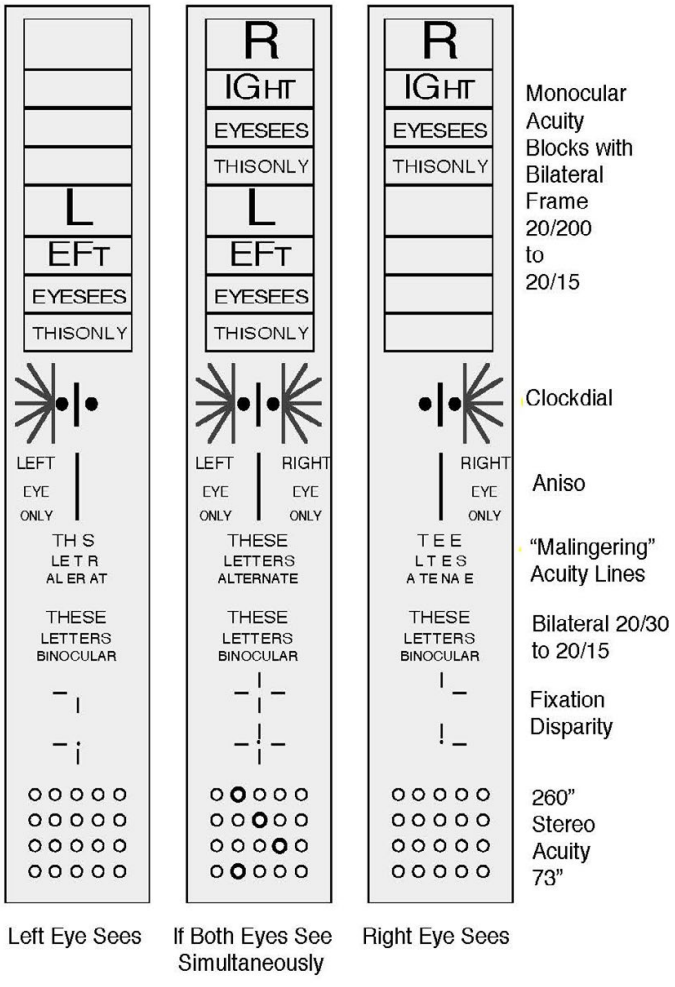

Figure 1. *Schematic of distance vectographic chart*

Time as a Component in Both Testing and Sensory Interference

These experimental paradigms generally test fixational eye movements and fixation dynamics over time. In testing fixational eye movements in fatigue, effects show over time. In clinical diagnosis, we routinely test eye movements over time. For example, the Developmental Eye Movement Test takes a few minutes to complete, as does the Maples Pursuit Test.[45] Although the time increments are not long compared to an air traffic control shift of two hours, they still take time.[42]

The typical clinical tests for evaluating visual sensation beyond acuity are more likely to be fast snapshots of sensation. For example, the 4-prism test for suppression should take literally a couple of seconds. However, we have seen that fixation behavior can vary over time, the root of which may be the state of sensation. Sensation over time can be routinely tested. A routine visual examination sequence that scans for loss of visual sensation over time through the use of vectographic targets at both distance and near has previously been described.[46]

An easy add-on for checking sensation over time might be to question further with a distance stereopsis test. On the classic AO/Reichert/Vision Assessment Corp adult vectographic distance test chart, four rows of rings provide the stereo stimulus (Figure 1). If the patient can determine the correct stimulus on the bottom row, suggesting what might be called normal binocular visual sensation, ask the patient to "watch just the bottom row. You say the second ring sticks out, is that correct? OK, now watch the bottom row, does the second ring ALWAYS stick out?" A report of "no, it doesn't" represents enough change in bilateral visibility that stereoacuity is at least intermittently reduced enough not

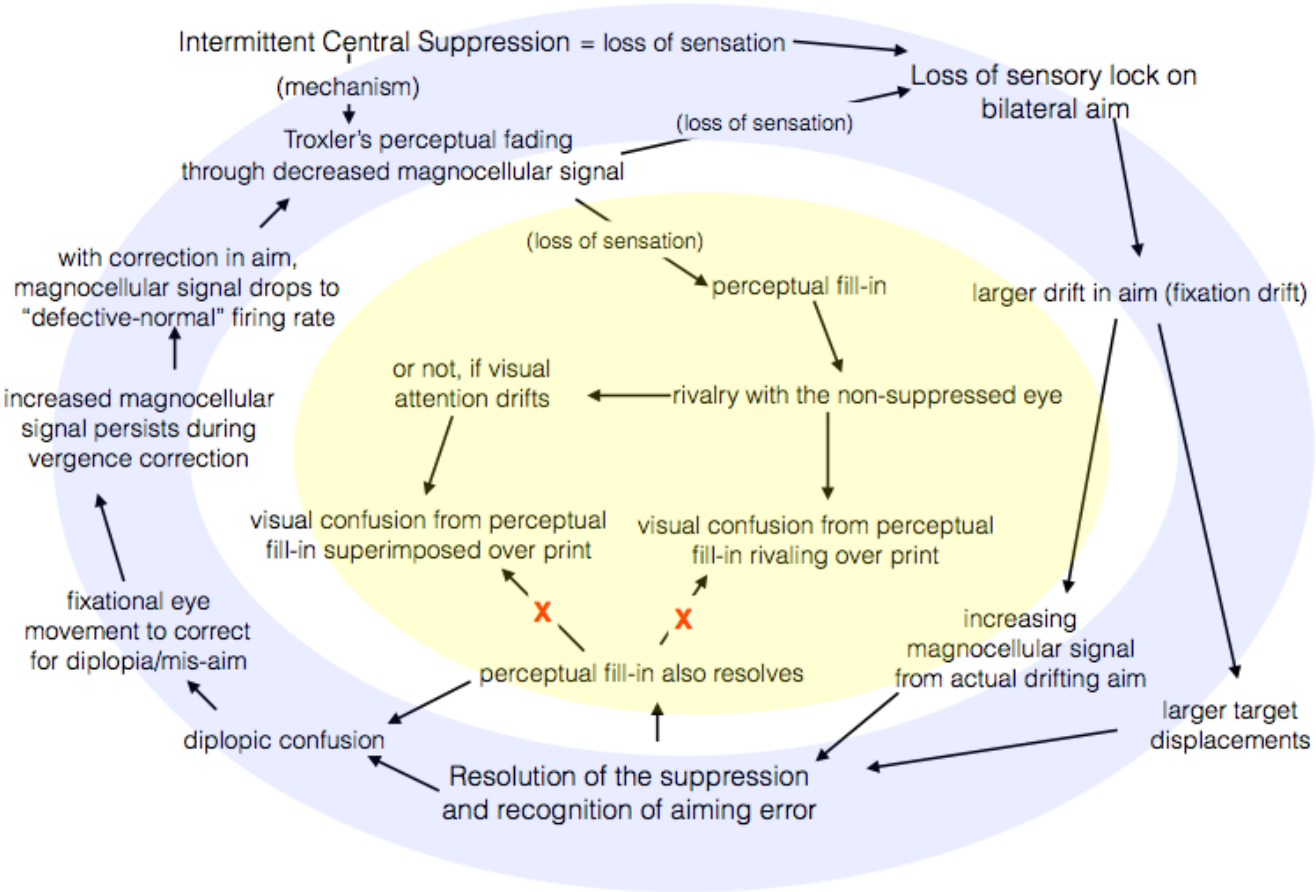

Figure 2. *The 5-second spin-cycle of intermittent central suppression*

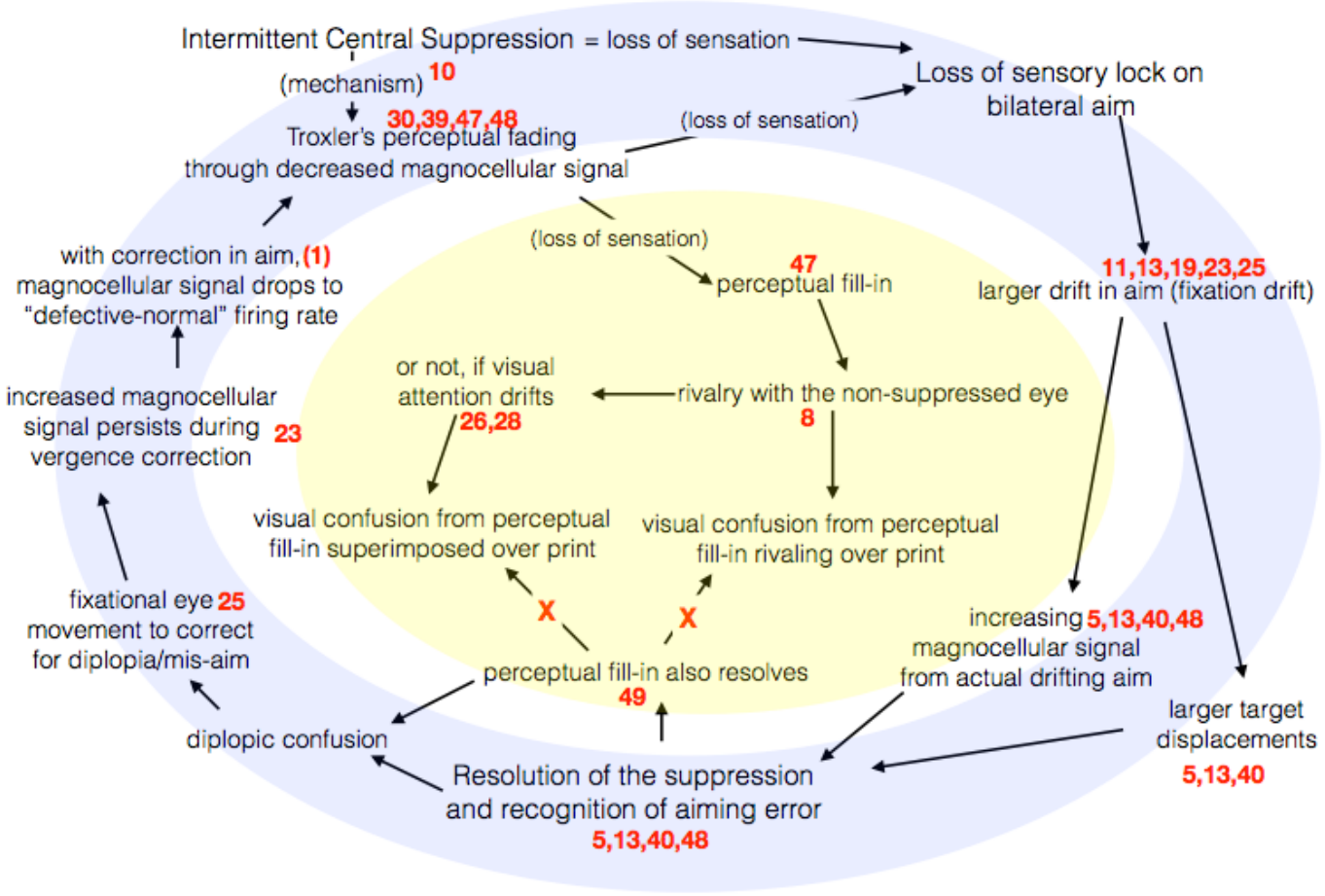

Figure 3. *Figure 2 graphic with references at appropriate points*

to allow recognition of a 73 arc second stereo stimulus.

Fixation behavior over time with variable sensation may provide all the justification necessary for testing sensation over time. Removing visual sensation intermittently may perhaps more accurately be decreasing contrast to the point of image disappearance.[10,13] If loss of contrast is accurate, then with reduced contrast, microsaccade rates will be reduced.[38] If visual sensation is variable over time, as in intermittent central suppression, microsaccade rates would also be expected to be variable, reflecting longer drift times and therefore more fixation variance. A pictorial of the possible fixation behavior in such a condition is seen in Figure 2.

Following the flow of fixation in Figure 2 shows that with loss of central sensation, the lock on fixation is gone, and drift in aim beyond typical non-impaired drift occurs. Longer drifts increase drift velocity,[15] so some increase in motion signal would be expected, and it is either this increase in motion signal with higher probability of image resolution or increased positional error[13,19] that triggers a correcting microsaccade. With the microsaccade and its spike in magnocellular signal, image resolution would be expected, so whether the increased motion signal happens via increased drift velocity or position error may be a moot point. Either way, the error must be corrected with fixational eye movements, probably also involving vergence.[25] While all of that is happening, the perceptual fill-in occurs with its complications amounting to direct interference with central sensation. A "spin-cycle" of loss of sensation, interference with sensation, and interference with normal fixational eye movement behavior is the

result. Figure 3 includes the references for those different points of aberrant fixational behavior with loss of visual sensation.

Conclusion

In this dance of sensation controlling fixational eye movements, and fixational eye movements supporting sensation, which leads the dance? Sensation or fixational eye movements? The answer may well be "yes." With no sensation, fixational eye movements get very random. Fixational eye movement behavior reflects stability of central sensation, but it also controls the stability of central sensation. If accurate, that does suggest further exploration of fixational eye movements when sensation is imperfect over time, such as in ICS, both experimentally and clinically. It also suggests the need to evaluate sensation over time. Sensation can be monitored over time with patient reporting. By its very nature, patient reporting is subjective, and it requires suspending a typically quick-moving test battery to watch and listen to patient reporting of changes in sensation, especially if evaluating with ICS in mind.

It is also readily apparent that central visual sensation must – MUST – be intact over time for fixation to be as accurate as possible. Further, normal development of visual motor control may be activated by detection of errors in fixation. The neural signal, probably foundationally carried by magnocellular neurons, maintains the necessary central visual sensation to teach the visual system both to fixate accurately and to maintain accurate fixation. Vergence therapy has been shown to reduce fixation duration, suggesting the possibility of some effect on fixational eye movements. However, the suggestion is also made that some of the effect may be attributable to vergence exercising, perhaps reducing fatigue effects. Beyond that possibility, no direct motor therapies for poor fixational drift and microsaccade behavior have been documented. Therefore, the one treatment available is in sensation; that is, treatment of central sensation, ideally treatment of the intermittent central suppression to extinction, apparently through bilateral stimulation of the foundational magnocellular pathway.

And why all this worry about accurate fixation sustained over time? Because fixation is the necessary pause in ballistic saccadic motor activity during which visual information such as print on a page can be sent to the visual cortex.

References

1. Reppas JB, Usrey WM, Reid RC. Saccadic eye movements modulate visual responses in the lateral geniculate nucleus. Neuron 2002;35:961-74. http://bit.ly/36YMhAx
2. Shioiri S, Cavanaugh P. Saccadic suppression of low-level motion. Vis Res 1989;29:915-28. http://bit.ly/38ZJTuY
3. Reudemann AD. Foveal coordination and the learning process. Kresge Eye Institute Bulletin 1957;8(1):4-10. http://bit.ly/2MuikAD
4. Geringswald F, Porracin E, Pollmann S. Impairment of visual memory for objects in natural scenes by simulated central scotomata. J Vis 2016;16(2):6. doi:10.1167/16.2.6 http://bit.ly/2MeTAMC
5. Martinez-Conde S, Macknik SL, Hubel DH. The role of fixational eye movements in visual perception. Nature Reviews/ Neuroscience 2004;5:229-40. http://bit.ly/1uwN7jp
6. Cornsweet TN. Visual Perception. New York: Academic Press, 1970:405. http://bit.ly/36RPPV4
7. Macknik SL, Livingstone MS. Neuronal correlates of visibility and invisibility in the primate visual system. Nat Neurosc 1998;1:144-9. http://bit.ly/2vTFdF7
8. Komatsu H. The neural mechanisms of filling-in. Nature Reviews/Neurosci 2006;7:220-31. http://bit.ly/2L6GTjg
9. Hussey ES. An idealized experiment on the effect of decreasing magnocellular signal on visual sensation. J Behav Optom 2005;16(5):119-24. http://bit.ly/2s5gUFz
10. Hussey E. Is anti-suppression the quest for visibility? Optom Vis Perf 2015;3(1):33-41. http://bit.ly/38Un8sB
11. Costela FM, McCamy MB, Coffelt M, Otero-Millan J, et al. Changes in visibility as a function of spatial frequency and microsaccade occurrence. Eur J Neurosci 2017;45(3):433-9. http://bit.ly/2Z6u1Cz
12. Ditchburn RW, Fender DH, Mayne S. Vision with controlled movements of the retinal image. J Physiol 1959;145:98-107. http://bit.ly/2PEs2SG
13. Poletti M, Rucci M. Eye movements under various conditions of image fading. J Vis 2010;10(3):1-18. http://bit.ly/2L2boaf
14. Cornsweet TN. Visual Perception. New York: Academic Press, 1970:400. http://bit.ly/36RPPV4
15. Cherici C, Kuang X, Poletti M, Rucci M. Precision of sustained fixation in trained and untrained observers. J Vis 2012;12(6):1-16. http://bit.ly/2Z8KyWx
16. Schneider RM, Thurtell MJ, Eisele S, Lincoff N, et al. Neurological basis for eye movements of the blind. PLoS ONE 2013;8(2): e56556. http://bit.ly/2ZeYCxJ

17. Martinez-Conde S, Macknik SL, Troncoso XG, Dyar TA. Microsaccades counteract visual fading during fixation. Neuron 2006;49:297-305. http://bit.ly/16LEFBN
18. Kagan I, Gur M, Snodderly DM. Saccades and drifts differentially modulate neuronal activity in V1: Effects of retinal image motion, position, and extraretinal influences. J Vis 2008;8(14):1-25. http://bit.ly/2EH6mio
19. St. Cyr GJ, Fender DH. The interplay of drifts and flicks in binocular fixation. Vision Res 1969;9:245-65. http://bit.ly/35D4vap
20. McCamy MB, Macknik S, Martinez-Conde S. Different fixational eye movements mediate the prevention and the reversal of visual fading. J Physiol 2014;592(19):4381-94. http://bit.ly/2ECjdCD
21. Solé Puig M, Pérez Zapata L, Puigcerver L, Esperalba Iglesias N, et al. Attention-related eye vergence measured in children with attention deficit hyperactivity disorder. PLoS ONE 2015;10(12):e0145281. http://bit.ly/2PHPLSc
22. Scheiman M, Mitchell GL, Cotter S, Cooper J, et al. A randomized clinical trial of treatments for convergence insufficiency in children. Arch Ophthalmol 2005;123:14-24. http://bit.ly/2Blqcc0
23. Collewijn H, Kowler E. The significance of microsaccades for vision and oculomotor control. J Vis 2008;8(14):1-21. http://bit.ly/2sJbOPp
24. Hussey ES. Remote treatment of intermittent central suppression improves quality of life measures. Optometry 2012;83(1):19-26. http://bit.ly/34FBiui
25. Collewijn H, Erkelens CJ, Steinman RM. Binocular co-ordination of human horizontal saccadic eye movements. J Physiol 1988;404:157-82. http://bit.ly/35Iqg8Q
26. Arnold DH. I agree: Binocular rivalry stimuli are common, but rivalry is not. Front Hum Neurosci 2011;5:157. http://bit.ly/35HJvzl
27. Platonov A, Goossens J. Eye dominance alternations in binocular rivalry do not require visual awareness. J Vis 2014;14(11):2:117. http://bit.ly/35Hx7PZ
28. Zhang P, Jamison K, Engel S, He B, He S. Binocular rivalry requires visual attention. Neuron 2011;71:362-9. http://bit.ly/2rcHmfX
29. Klink PC, Brascamp JW, Blake R, van Wezel RJA. Experience-driven plasticity in binocular vision. Curr Biol 2010;20(16):1464-9. http://bit.ly/2sQQs2g
30. Ditchburn RW. Eye movements in relation to retinal action. Optica Acta 1955;1:171-6. http://bit.ly/2PEFdD8
31. Hussey ES: The on-switch for seeing. J Optom Vis Devel 2003;34(2):75-82.
32. Hussey, ES. An idealized experiment on the effect of decreasing magnocellular signal on visual sensation. J Behav Optom 2005;16(5):119-24. http://bit.ly/2s5gUFz
33. Hussey ES. Visibility, suppression, and implications for downstream visual development. Optom Vis Perf 2018;6(4):222-4. http://bit.ly/2ZaEQDA
34. Yang Q, Kapoula Z. Binocular coordination of saccades at far and at near in children and adults. J Vis 2003;3:554-61. http://bit.ly/2r9pF0K
35. Kelly KR, Cheng-Patel CS, Jost RM, Wang Y, Birch EE. Fixation instability during binocular viewing in anisometropic and strabismic children. Exp Eye Res. Available from http://bit.ly/34FyLQD
36. Zihl J, Heywood CA. The contribution of LM to the neuroscience of movement vision. Front Integr Neurosci 2015;9(6) http://bit.ly/2sQVGep
37. Bethlehem RAI, Dumoulin SO, Dalmaijer ES, Smit M, et al. Decreased fixation stability of the preferred retinal location in juvenile macular degeneration. PLoS ONE 2014;9(6):e100171. http://bit.ly/2PEFMNj
38. Scholes C, McGraw PV, Nystrom M, Roach NW. Fixational eye movements predict visual sensitivity. Proc R Soc B 2015;282:20151568. Available from http://bit.ly/2sQVCeF
39. Troxler D. Uber das Verschwinden gegebener Gegenstande innerhalb unseres Geisichtskreises. In: Himly K, Schmidt JA, eds. Ophthalmische Bibliothek. Jena: Fromann, 1804:51-53.
40. Engbert R, Mergenthaler K. Microsaccades are triggered by low retinal image slip. PNAS 2006;103(18):7192-7. http://bit.ly/2PI6Nzn
41. Macknik SL, Martinez-Conde S. Dichoptic visual masking reveals that early binocular neurons exhibit weak interocular suppression: Implications for binocular vision and visual awareness. J Cog Neurosci 16;6:1049-59. http://bit.ly/35JNWcK
42. Di Stasi LL, McCamy MB, Catena A, Macknik SL, et al. Microsaccade and drift dynamics reflect mental fatigue. Eur J Neurosci 2013. Available from http://bit.ly/36DyWNL
43. Shaikh AG, Otero-Millan J, Kumar P, Ghasia FF. Abnormal fixational eye movements in amblyopia. PLoS ONE 2016;11(3):e0149953. http://bit.ly/2reDtr1
44. Zuber BL, Stark L. Microsaccades and velocity-amplitude relationship for saccadic eye movements. Sci 1965;150:1459-60. http://bit.ly/35HJEmv
45. Maples WC, Ficklin T. Comparison of eye movement skills between above average and below average readers. J Behav Optom 1990;1(4):87-91. http://bit.ly/35HRTyB
46. Hussey ES. Examination of binocular sensation over time with routine testing. J Behav Optom 2000;11(2):31-4. http://bit.ly/2uCACbQ
47. Troncoso XG, Macknik SL, Martinez-Conde S. Microsaccades counteract perceptual filling-in. J Vis 2008;8(14):1-9. http://bit.ly/35SxSpv
48. Olveczky BP, Baccus SA, Meister M. Segregation of object and background motion in the retina. Nature 2003,423:401-8. http://bit.ly/2r9rnzc
49. Magnussen S, Spillmann L, Sturzel F, Werner JS. Filling-in of the foveal blue scotoma. Vision Res 2001;41:2961-7. http://bit.ly/2EDPrxp

Correspondence regarding this article should be emailed to Eric S. Hussey, OD at spacegoggle@icloud.com.

Hussey ES. Who's on first? Is it fixation that drives sensation? Or is it sensation that controls fixation? Optom Vis Perf 2019;7(5-6):282-94.