Using the Z-bell℠ Test to Remediate Spatial Deficiencies in Non-Image-Forming Retinal Processing[1]

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Abstract. Preliminary evidence from a larger study is presented demonstrating that non-image-forming retinal processing takes place even through closed eyelids. The *Z-bell*℠ test, which has been in clinical use for more than twenty years shows that these processing channels affect how we perceive context in the space around us when forming visual imagery. By using therapeutic eyeglasses and pitched bells, we can measure changes in a subject's spatial processing, and remediate deficiencies among non-image-forming neural channels that operate in even the low-light conditions produced by closed eyelids. Using what we know of both the top-down feedback filtering of retinal input triggered purely by aural signals and also the characteristic difficulties that brain-injured patients have in organizing visual scenes (which the Z-bell℠ test links to difficulties with non-image-forming retinal processing), it is argued that the non-image-forming retinal channels demonstrated in this study may be critical in any human-centric model of computer vision. Spatial coding as a basis for human cognition is also briefly discussed.

Keywords: Peripheral Vision, Retina, Z-bell, Spatial Cognition, Context

1 Introduction

In working to develop models of computer vision we most naturally focus on what humans *see*. Indeed, the label "computer vision" itself tends to limit a broader view of how humans translate retinal images into cognitive meaning. In this paper, preliminary evidence is presented for a collection of non-image-forming retinal pathways that set the context for the peripheral and center vision systems, and also contribute to the forming of 3D spatial images derived from what we hear. The data presented shows that retinal spatial processing can be measured and altered through

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the filter of *closed eyelids*, which in turn suggests that any full human-based model of computer vision must account for retinal processing that takes place independently of the cognitive apprehension of visual artifacts. Our study is among the first attempts to gather scientific evidence for the efficacy of the *Z-bell*^{SM} test which is used to measure—and prescribe remediation for—deficiencies in this mode of sensory processing.

Deborah Zelinsky, O.D., F.N.O.R.A., F.C.O.V.D. is a recipient of the Founding Father's Award of the Neuro-Optometric Rehabilitation Association. She emphasizes neurodevelopmental optometric rehabilitation techniques in her clinical practice. Such techniques draw on a broad range of neuroscience findings and are based on the idea that retinal processing is a critical component of deeper brain processing, both at conscious—and also beneath conscious—levels. The Neuro Optometric Rehabilitation Association (NORA) has listed more than 500 research papers relating to neuro-otometric processing at their website [1]. As part of her work, Zelinsky developed the *Z-bell*^{SM} test to help her diagnose appropriate glasses for her patients who are experiencing post-concussion syndrome (PCS). The Z-bell^{SM} test has been in clinical use for over twenty years, and is now in use in more than ten countries worldwide. Zelinsky estimates that it has been used as a diagnostic tool in the treatment of more than 4,000 PCS cases. Optometrists and other rehabilitation neuroscientists from around the world come to Chicago for training in using Z-bell^{SM} testing in their practices.

Most optometrists mainly consider stimuli to the central eyesight retinal pathway; by contrast, developmental optometrists additionally focus on peripheral retinal processing. Peripheral processing can be divided into three components: the *peripheral eyesight*, the *non-image forming signals to the brainstem* (for controlling such processes as posture and spatial awareness, and on which this paper focuses) and the *non-image forming signals to the hypothalamus* (for controlling such processes as sleep cycles). Various optometrists emphasize each of these three portions of peripheral retinal processing. Zelinsky, and others that follow her work, extend these assessments by focusing on the diagnostic testing and selective stimulation of a set of non-image-forming retinal processes that she argues are critical for setting the context for both central and peripheral visual processes, and for integrating retinal processing with the internal visual 3D interpretation of audio input. The Z-bell^{SM} test, which filters out eyesight processing, is used to test this aspect of retinal processing.

In the Z-bell^{SM} test, a patient sits in a chair with her eyes closed throughout the duration of the test; the clinician rings a pitched bell in an area on each side of the patient (slightly to the front) asking the patient to reach out and touch the bell. The patient (with eyes closed throughout) is fitted with various prescription glasses (including possibly with tinted lenses, and glasses with partially translucent occlusions on the lenses) and the bell ringing is repeated. Different lighting conditions, different postures, and differently pitched bells are typically used in the test. If the prescription glasses are effective in correcting non-image-forming retinal processing problems, the patient's ability to reach and touch the bell improves. The key to this test is that the closed eyelids filter out the light used for eyesight processing, but let through enough light to trigger retinal responses in the non-image-forming retinal processes (which can operate at very low light levels).

Anecdotal clinical evidence—in the form of many PCS patients who have improved—suggests that the Z-bell℠ test, and the remediation of problems with the non-image-forming retinal processing as part of neuro-developmental rehabilitation, has been effective in the practices that use it. The principles of the non-image-forming retinal processes have also been discussed in the literature [1,2]. But there is an absence of empirical evidence about the kinds of processing the Z-bell℠ test measures. Such evidence may provide further insight to support models of retinal processing that can help us to build working systems that can be implemented on computers.

Humans use cognitive mapping to form 3D spatial representations that are the basis of thought [3,4]. We access this cognitive machinery when we form the symbols of thought (and the relationships between them), and when we interpret real-time input from our retinas as well as from our ears and our proprioceptive pathways. In this way we can consider one destination of all this input (including abstract creative input) as the 3D visual/spatial processing system. But an important piece of input that sets the context for knowing who we are, and where we are in space, is often overlooked. This non-image-forming input comes through the retinas but branches off to the brain stem and elsewhere before reaching the visual cortex. It affects visual processing, and also alters the way we *feel* the world around us and also *hear* that world.

The theory behind our interpretation of the following evidence is that closed eyelids filter out light to the peripheral and central visual systems so that as humans we can no longer see, but there is enough light passing through the closed-eyelid filters to affect how we form internal images based on our 3D interpretation of how we hear the world around us, how we form spatial images of that world, and how we reach for objects located within that 3D space.

In this study the following three hypotheses were explored: (1) that the Z-bell℠ test shows a repeatable pattern in how close a subject comes in touching various bell in space, in various (light, bell-tone) conditions; (2) that this pattern is repeatable with different non-communicating administrators (i.e. bell-ringers); and (3) that the pattern is altered in repeatable ways with various prescriptions (i.e. helpful versus non-helpful versus null prescriptions). In the following sections, our methods and our preliminary findings with 14 participants are summarized.

2 Methods

The study was approved by DePaul University's Internal Review Board. The data collection team included Dr. Deborah Zelinsky a neurodevelopmental optometrist, three graduate student research assistants (RAs), and DePaul professors Clark Elliott and Cynthia Putnam who acted as project supervisors. Prior to the study, Zelinsky worked with the three RAs to teach the bell-ringing techniques; the RA team practiced administering the test for five hours prior to conducting the first experiment. Elliott worked with the RA team on precise methods to guarantee absolute isolation in the knowledge of which glasses were which, making tester bias and inter-administrator telegraphing impossible.

When the Z-bell℠ test is observed in clinical settings it can be striking how differently clinical PCS (and other) patients will reach for the bell with prescription correction for the non-image-forming retinal processes compared to them reaching for the bell without correction—including with repeated glasses-on / glasses-off conditions. In designing this study to use primarily healthy young subjects and 96 bell-rings for each, it was understood that some of these dramatic effects would be lost. (Healthy young brains can adapt even within a few minutes.) Additionally, a trained clinician will find the "sweet spot" in the space around a patient that highlights differences in the two prescription conditions for that patient, whereas the RAs in this study used the same positioning throughout. But this model was chosen to guarantee absolute isolation of the effects. The study does, after all, support the claim that all people can "see" (perceive) through closed eyelids, and that this has important and measurable effects on cognitive appraisals of the world around us. It was felt that likely smaller effects using a general subject population and rigid bell positioning, but an iron-clad study design was a reasonable compromise design.

In the next sections we discuss our participants, our data collection, and our data analysis methods. During testing there were always at least five researchers present overseeing the environment.

2.1 Participants

41 participants were recruited between September and November 2017. Most participants (n = 38) were graduate and undergraduate students (mean age = 25.9 years, sd = 6.3 years) from the College of Computing and Digital Media at DePaul University; students were recruited through an online 'participant pool.' The participant pool allows DePaul students to gain extra credit in courses. Among the 38 student participants, 22 had uncorrected vision and the remaining 16 wore corrective glasses or contact lenses. Three additional participants were recruited by Zelinisky; all three had experienced a brain injury. They ranged in age from 57 to 73 (mean 64.6). All had uncorrected vision. Testing took place on five different dates.

At the time of this paper submission 14 of the 41 sessions have been analyzed, all with the student participants (mean age = 27.6 years, sd = 6.7 years). Among those 14 participants, 9 had uncorrected vision and the remaining 5 wore glasses or contact lenses.

2.2 Data Collection

Overview

All trials were conducted in the School of Computer Science building at DePaul University. Three physical stations were used in the study: an isolated foyer area, a clinical testing room, and an empirical testing room located across the hallway. None of the activity in any of the areas could be seen or heard from either of the others, though the hallway between them was shared. None of the three stations had external windows, so there were no complications from outside light. The three stations were typically used simultaneously, for the series of participants, with each participant moving from one station to the next in sequence. The clinical testing room and the empirical testing room each had identical five-bulb floor lamps used for illumination (bright light and dim light conditions), and pitch- and timber-identical sets of hand bells (pitched high and low). The clinical testing and empirical testing sessions were all recorded on video.

Two sets of two pairs of optometric frames were used (four frames). One set of frames were marked A and B (under paper flaps that hid the marking from casual view). The other set of frames were marked C and D. The frames held temporary lenses as randomly determined by Zelinsky, and she was the only person who ever knew whether a frame (A, B, C or D) held lenses intended to improve or impair retinal processing for a particular subject. Prescription lenses and (occasional) translucent partial occlusions were used, but although the Z-bell℠ test typically also works with tints they were not used in this study because of concerns about telegraphing which lenses were which. Zelinsky's clinical notes, which included which lenses and occlusions were used, were sealed until data collection was completed. Zelinsky had no access to the data or results until after her clinical notes were formally entered in the study archive, and data collection for all subjects was completed.

The three RAs rotated among three roles. The first RA role was the "glasses chooser," responsible for retrieving the box with the prepared glasses in it, bringing it along with the participant from the clinical testing room to the empirical testing room, and selecting the order the glasses would be tested based on rolls of a die. (E.g., for two pairs with markings [hidden under the flaps] of A and B we might get the order A, B, B, A—but also see below.) This role was also responsible for handing the succession of two glasses (four trials) to the tester in the right order so that the tester never knew what the marking was on frames. (And note that knowing the marking would still not give any information about the respective prescriptions.) Lastly, this role also watched to ensure that the participant's eyes were closed through the Z-bell testing.

The second RA role was that of "bell-ringer" who in addition to ringing the bells, was also responsible for communicating with the participant, giving instructions about when to reach for the bell. Communication additionally involved handing the optometry glasses to the participant, instructing participants to keep their eyes closed and their feet flat on the ground, and announcing for the recording which light and bell condition was being tested for which number participant.

The third RA role was responsible oversight which included also assuring that a participant's eyes were closed throughout and that all of the conditions (explained in the next sections) of the experiment were completed. Additionally, the third RA recorded a real-time casual assessment of how close the participant was to the bell for each condition. This data has not yet been coded.

Pre-processing

Elliott or Putnam greeted participants in the isolated foyer and explained the informed consent procedures. Participants were assigned a unique number chosen by drawing a name-tag from a box. They completed a pre-study questionnaire of fourteen questions relating to age, gender, prior head injuries, sleep and study preferences, organizational habits relative to ADHD, and etc. The questionnaire is included as an appendix. The questionnaire data has not yet been processed relative to the Z-bell℠ clinical test results or the experimental test results, and analysis is not included in this paper.

Clinical evaluation

Participants were taken to the clinical testing room, along with their completed questionnaire, each identified only by the tag-number. Zelinksy scanned each questionnaire to reduce the time it took her to determine therapeutic eyeglass prescriptions that would (a) improve the participant's ability to touch the bells (accurate non-image-forming retinal processing prescription) and (b) worsen the participant's ability to touch the bells (impaired prescription)—with their eyes closed. Zelinsky then administered the Z-bell℠ test for the participant, trying various sets of prescription lenses, in two light conditions, while taking clinical notes for later use. She determined the participant's two prescriptions (accurate and impaired) ultimately setting up the prescriptions in wearable optometry frames (i.e., creating eyeglasses that accepted temporary lenses of different prescriptions), which were labeled either A and B or C and D. (The two sets were used to keep the eyeglass sets sorted out during the simultaneous use of the clinical testing room and the experimental testing room). The determination of which label was used (e.g. randomly matching "A" with "impaired prescription") was made prior to the testing of the subject and entered into the clinical testing notes.

When testing was complete, the two pairs of appearance-identical, labeled glasses were placed in a closed box. The box and the participant were then taken to the experimental testing room by the "glasses chooser" RA.

Experimental testing

The RAs performed six cycles of bell ringing in two rounds of three: Cycles (1) and (6) were the baseline (neutral) condition in which participants wore optometry glasses with clear lenses (no prescription) so they presented as appearance-identical to the two test prescriptions. All the RAs knew that cycles (1) and (6) were with clear lenses, but the participants did not. Cycles (2) and (3), and independently cycles (4) and (5) each contained a pair of randomly assigned accurate and impaired prescriptions (one of each). The experimental conditions (accurate vs. impaired) were randomly chosen by the RA who was performing the ‘‘glasses chooser ‘role by using the rolled die to determine the order (accurate vs. impaired) for each of the four middle bell-ringing cycles. The design choice to use two random accurate/impaired sets rather than one random quad was made to reduce adaptation by—and the effects of testing fatigue on—the subject. See Table 1 for the four possible prescription assignment sequences for cycles (2) – (4).

Table 1. Four Possible Bell Ringing Sequences.

Round	**Sequence 1**	**Sequence 2**	**Sequence 3**	**Sequence 4**
One	Cycle 1: Neutral	Neutral	Neutral	Neutral
	Cycle 2: Accurate	Accurate	Impaired	Impaired
	Cycle 3: Impaired	Impaired	Accurate	Accurate
Two	Cycle 4: Accurate	Impaired	Accurate	Impaired
	Cycle 5: Impaired	Accurate	Impaired	Accurate
	Cycle 6: Neutral	Neutral	Neutral	Neutral

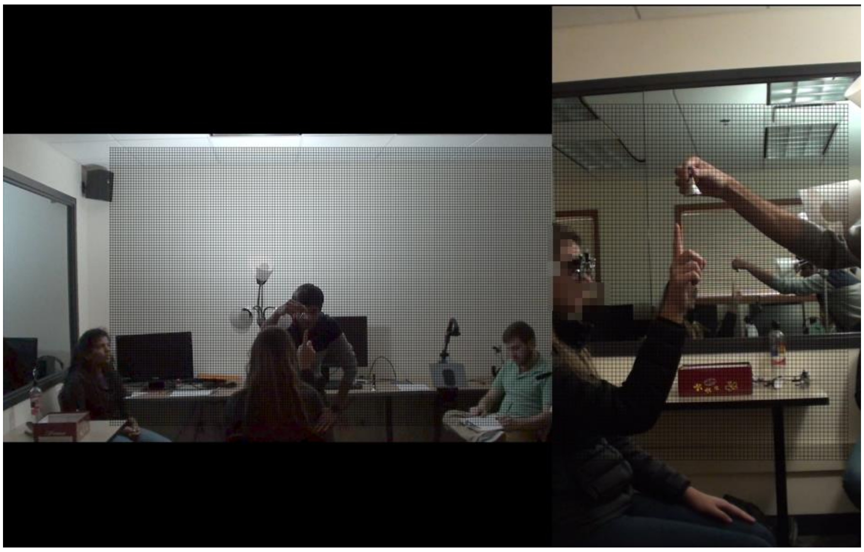
Each bell-ringing cycle included 16 bell rings that included two light conditions (dim vs. bright) and two bell-tone conditions (low vs. high). The "bell-ringer" RA located the bell rings in each of four quadrants: (quadrants 1 and 2) upper left and upper right—approximately aligned to the participant's knees and slightly above their shoulders; and (quadrants 3 and 4) lower left and lower right—approximately aligned to the participant's knees and waist. Thus, for each (accurate or impaired) cycle the bell was rung as follows: Each 16 rings: 8 rings in low light, 8 rings in bright light. Each 8 rings: 4 rings with the high-pitched bell, 4 rings with the low-pitched bell. Each 4 rings: 1 in each spatial quadrant.

As such, for each participant, data was collected for 96 bell rings (6 cycles x 16 rings). The sessions were videotaped (30 fps) from the side (for determining y and z measures) and the back (for determining the x measures); we therefore had a total of 288 measures (three dimensions x 96) per participant. *Participants' eyes were closed throughout testing during the experimental testing phase.*

Data Analysis

For each session, the back and side videos were imported into an *Adobe After Effects* editor in order to render them as a combined sequence. A grid was placed over each video that equated to an approximate ½ inch lattice for the combined renders; See Figure 1.

Figure 1. Rendered Image.



Additional graduate student RAs (who received independent study credit) were enlisted to assist with data analysis. They were not involved in the data collection. Combined renders (back + side with overlay grids) were used to identify the one second of video (i.e. the 30 frames) in which the participant made their first forward movement towards pointing to the bell. Those thirty frames were then rendered as still images and a single frame was determined capturing the point the participant ended their initial forward movement to the bell. (This technique mitigated issues with participants who waved around after not touching the bell initially.)

Once the frame that determined the end of the participant's forward motion was isolated, measurements were made of the x, y, and z distances from each participant's finger to the nearest point on the bell. That is, by counting the intervening squares in the overlay grids distances were calculated for the x (right-to-left), y (up-down) and z (in-out towards body) dimensions.

Some problems were encountered with estimating the x-distances for two reasons: (1) at times the bell ringer positioned the bell too low so the camera (from the back) could not see the bell and (2) the camera's auto-focus occasionally malfunctioned in the bright light condition. This occurred 34 times—about 5% of the bell-rings; as such, the decision was made to exclude the x-distance data. This approach is justified because there were minimal variances in the x-distances (as it was possible to measure) when compared to y and z distances—probably due to the alignment of the bell rings to the participants' knees and shoulders. The variance (sd^2) for the first 14 participants which this summary includes, in each dimension are as follows: (a) for x = 15.2 (mean = 3.2, sd = 3.9), (b) for y = 45.0 (mean = 5.9, sd = 6.7), and (c) for z = 31.0 (mean = 4.2, sd = 5.6).

For each bell-ring, the y and z distances were averaged (using approximately ½-inch units); we also noted if the participant touched the bell and assigned a subjective 'confidence' score from 1-3. A confidence score of 1 was assigned to bell-rings where the participant was tentative (e.g., waived around a lot) and assigned a 3 when participants directly pointed to where they felt the bell was (regardless of accuracy).

Five measures were then created for each participant per bell ringing cycle: (1) an average of y and z distances (in approximately ½-in units) when wearing the neutral, accurate and impaired glasses prescriptions; this equated two measures for each prescription because each prescription was tested twice—see Table 1; (2-3) average of the y and z distances under the dim light and bright light conditions for the corrected versus impaired prescriptions; and (4-5) average of the y and z distances under the high bell and low bell conditions for the corrected versus impaired prescriptions.

Six hypotheses were tested in this preliminary evaluation:

- H1 and H2: Participants will point closer to the bell (smaller distances) in the accurate prescription eyeglass conditions when compared to the neutral and (H2) impaired eyeglass prescriptions though their eyes are closed throughout the testing;

- H3: Participants will point farther from the bell (larger distances) in the impaired condition when compared to the neutral (and accurate) prescriptions;

- H4: Lighting (bright versus dim) will not have any significant effect on participants' performance when comparing the accurate versus the impaired prescription;

- H5: Bell tone (high and low) will not have any significant effect on participants' performance when comparing the accurate versus the impaired prescription;

- H6: There will be no significant changes from the first cycle (wearing neutral glasses) to the last bell-ringing cycle indicating minimal learning and/or fatigue.

For this initial analysis we evaluated our hypothesis through paired t-tests using SPSS version 22.

3 Preliminary Findings (n=14)

In this section, the findings for our six hypotheses for the initial 14 participants (28 data points) are presented.

3.1 Prescription differences

Recall, three-paired t-tests were used to explore if there were differences in combined y-z distances when comparing the neutral, accurate and impaired prescriptions.

- A statistically significant difference was found when comparing the distances in the neutral-accurate condition, $t_{(27)} = 2.12$, $p < .05$, $d = .404$ (a small to medium effect). The combined average distance for the neutral prescription was 5.06 (sd = 2.33) units (recall units were approximately 1/2 inch), while the average distance for the accurate prescription was significantly less at 4.42 units, sd = 2.31) indicating that the accurate glasses improved participants abilities to locate the bell in space.

- The differences between the accurate and impaired glasses narrowly failed significance, $t_{(27)} = 2.12$, $p = .073$; the combined average distance for the impaired prescription was 5.06 (sd = 2.72).

- Finally, the differences between the impaired and neutral glasses was not significant ($t_{(27)} = -\ 0.009$, $p > .05$); they had almost equivalent combined average distances.

3.2 Effect of light conditions

Recall, a paired t-test was used to explore if the two different light conditions (dim versus bright) had any effect on the average combined y-z distances in both the accurate and impaired conditions.

- Brightness of light did not appear to affect participants' accuracy. Differences were not significant between the bright or dim light conditions when wearing the accurate prescriptions ($t_{(27)}=0.71$, $p > .05$) or the impaired prescription ($t_{(27)}=0.29$, $p > .05$).

3.3 Effect of bell conditions

Recall, a paired t-test was used to explore if the two different bell conditions (high versus low) had any effect on the average combined y-z distances in both the accurate and impaired conditions.

- Bell tone did not appear to affect participants' accuracy. Differences were not significant between the low or high bell-tone conditions when wearing the accurate prescriptions ($t_{(27)}=0.47$, $p > .05$) or the impaired prescription ($t_{(27)}=1.14$, $p > .05$).

3.4 Learning/fatigue effects

Recall, we used paired t-test to explore if there were differences from the first baseline (i.e., first bell-ringing cycle—neutral prescription) to the last baseline (last bell-ringing cycle) in the average combined y-z distances to explore if there were any learning or fatigue effects.

- There did not appear to be significant learning or fatigue effects, ($t_{(27)}=1.17$, $p > .05$). The distances were slightly larger for the first baseline (mean = 5.4, sd = 2.3) than in the final bell-ringing cycle (mean = 4.7, sd = 2.4).

4 Discussion

Our findings indicated that with eyes closed throughout, accurate therapeutic lens prescriptions for non-image-forming retinal processing significantly improved participants' abilities to locate the bell in space when compared to the neutral prescriptions; additionally, participants performed much better when wearing the accurate prescription as compared to the impaired prescriptions. However, there was not any decrease in performance when comparing the impaired and neutral prescriptions. Combined, this indicated that the Z-bell^{SM} test could accurately assess a prescription to *improve* non-image-forming retinal processing but was not as successuful at assessing a prescription that would *worsen* non-image-forming retinal processing.

We also found that neither light nor bell tone significantlly changed participants' accuracy in locating the bell in the space. Finally, there did not appear to be any learning and/or fatigue effects (though it is our intuition that short-term adaptation probably did take place in these primarily healthy brains starting as early as the clinical testing; see below).

The central visual acuity is often tested as 20/20 in many brain-trauma patients (corrected as needed by prescription eyeglasses) and indeed the visual part of retinal processing is most often studied when looking at feedforward and feedback systems for scene understanding [5]. But, many such trauma patients still suffer mild to extreme deficits in being able to interpret the world around them, in organizing their thoughts[6], and in effecting normal movement through space [7]. External (and internal) visual scenes can easily deteriorate into a flattened collage of unrelated features—yet at such times PCS sufferers will still be able to completely describe the details of a visual scene with great accuracy and their (possibly corrected) central eyesight will also still test at 20/20 [8,9]. During these “context” breakdowns, such people may find it necessary to reconstruct meaning via intentional internal dialogs. For example in holding a printed page of this article in front of them, and while fully capable of reading, they might say to themselves, "OK. This is a white, flat object. I *know* that I know what it is used for, so I just have to retrieve that information. It has ninety-degree angled corners so it forms a rectangle. But the fact that it is a rectangle is not functionally important. It is flat and flexible and there are front and a back sides. It has printed writing on the front side. There is a top-to bottom orientation to the writing, and currently the top is more important than the bottom…"

A neurodevelopmental optometrist will test many non-central eyesight processes to find which parts of context-setting for (peripheral and) central eyesight are either not working correctly, or are not being integrated sufficiently with other processes. When deficiencies are identified, these can sometimes be remediated using therapeutic eyeglasses (of the kind described in this article) and other interventions, in the same way that central eyesight can be corrected. These processes, including the non-image-forming retinal processes, are important in scene understanding. Furthermore, Bellmund et al. [3] have viewed hippocampal-entorhinal place- and grid-processing mechanisms from a cognitive perspective to propose a neuroscience-based *spatial* representation for cognition. This approach is consistent with the complex difficulties in cognition described in the ten-year case study of PCS and retinal-based recovery described by Elliott [8].

So, for a full human-centered model of computer vision (including the internal spatial representation of cognition), we will also need to model the kind of spatial context-setting produced by the non-image-forming retinal processes. Important questions arise: (1) "How do we model non-image-forming retinal processing, such that bending the light entering into the retinas (e.g., using therapeutic eyeglasses)—while simultaneously filtering out visual image processing—alters the 3D internal visual/spatial representation of what we hear?" (2) "How do we model the relationship between the 3D world we see, and the 3D world we hear, based on non-image-forming retinal processing?" And lastly, (3) “How do these non-image-forming retinal processing systems help humans to set the context for the integration of disparate objects into a cohesive visual/spatial scene?”

Using fMRI Vetter, et al., [10] have shown that top-down cognitive pre-filtering of visual scenes depends in part in how we hear the world. They argue that because feedback filtering of input visual signals far outnumbers the feed-forward inputs themselves, that the "nonretinal influence of an early visual cortex" must critically be studied. They describe the use of auditory signals to bias visual input interpretation. But our data here suggest this is not a one-directional influence, because non-image-forming retinal inputs also bias the way we hear.

Some approaches to computer vision have hypothesized that we limit the search space for interpretation of scences through various forms of early visual processing that returns, e.g., basic visual features such as orientation, contrast and simple shape. Pylyshyn [11] has even argued that this takes place in a cognitively impenetrable module. Certainly whether or not this takes place in a separate module, this functionality is a necessary component of later cognitive interpretation. But the Z-bell℠ data suggests there is also a purely spatial (non-image) component to this early (possibly cognitively impenetrable) processing that relies on retinal input that helps set the context for how we interpret the 3D world around us. We might suppose that this argues in favor of Pylyshyn's theorized cognitively-impenetrable early vision module. Such a module would then also provide generalized, chunked information for the integration of retinal processing with the 3D spatial interpretation of aural images from our hearing system as well.

5 Limitations and Future Work

This initial analysis was conducted as a preliminary query into what we might find; obviously with only 14 participants (28 data points) there are limits on how much power can be used to find significance. However, these early findings are extremely promising and it is a reasonable expectation that with the increased power of the additional 24 student participants (48 more data points) we will find more definitive evidence of the Z-bell's ability to access an accurate prescription to improve non-image-forming retinal processes. Our preliminary results are consistent with clinical practice, and together these suggest the need for expanded models in computer vision research.

The inability to reliably find prescriptions that worsened non-image-forming processing could be related to the fact that all of the participants represented in these preliminary results reported themselves free of brain-injury and also were relatively young when compared to the entire adult population. This may indicate that younger, non-injured healthy people have an ability to rapidly adapt to the impaired prescriptions; i.e., these young subjects may have already have begun to significantly adapt to the experimental lenses by the end prescribing phase, before the testing phase began.

Along with evaluating the data from the remaining 24 student participants, we will also evaluate the three participants who had a brain-injury; however, because the samples are so small, we will only be able to do so descriptively. In future work, we would like to include a larger sample of people who have had brain injuries of different types [12] to explore how they might differ from people who have not had a brain injury as this may eliminate the quick adaptation and give us further insight into how healthy brains process non-image-forming retinal input.

In future similar studies it seems likely that using only the therapeutic prescription and baseline non-correcting lenses, limiting the number of bell-rings, and restricting the total time for the testing of each subject to just a few minutes will show stronger results. In addition to using prescriptions and occlusions, treatments using differently colored tints might also show increased results.

Lastly, we plan on assessing how participants' answers to the pre-study questionnaire (see Appendix) were associated with their performance in our study, and how questions regarding dispositional attention style may associate with clinical readings of the health of the non-image-forming retinal processing.

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Appendix—Pre-study questionnaire

Pre-study questionnaire **ID #__________**

Participant Initials ________ Date ___________________________ Time_________

Do you wear glasses? YES NO Do you wear contacts? YES NO

Birthday: Month _______ Year ________

Have you had (i.e., aware of) a head injury in the past? YES NO
If yes, can you provide some detail below including the date and type of your head injury.

Which statement best describes your sleep in the last six months? (Pick one)

- ○ I fall asleep as soon as I'm in bed and sleep solidly all night.
- ○ I have trouble falling asleep, because my mind won't turn off
- ○ I fall asleep easily, but can't stay asleep sleep through the night.

Which statement best describes your waking from sleep in the last six months if you do NOT set and alarm? (Pick one)

- ○ I wake up as soon as light comes into the room.
- ○ No matter what time I go to sleep, I wake up at the same time each morning.
- ○ I wake up whenever my body is rested; the light doesn't bother me.

Which statement best describes how you have fall asleep in the last six months? (Pick one)

- ○ I can easily fall asleep anywhere.
- ○ I have trouble falling asleep if not in my own bed.
- ○ I can easily fall asleep as long as there is no noise.

If you are involved in something you enjoy, do you forget to eat? In other words, would you NOT be aware of hunger pangs? (Pick one)

- ○ Yes, I would forget to eat and not feel hunger.
- ○ I would be aware of the hunger, but choose to ignore it
- ○ I would be aware of the hunger and have to stop what I was doing because my body has to eat.

Which statement best describes your current morning eating habits? (Pick one)

- ○ I love having a big breakfast.
- ○ I can't eat much in the morning.

- I'm not really too hungry when I wake up, but I eat because I'm supposed to eat.

Which statement best describes how you think? (Pick one)

- I prefer learning the big picture first. Details can come whenever.
- I prefer learning in small steps. Learning details first helps me organize information more accurately.

Which statement best describes how you learn? (Pick one)

- I learn best when I have a hands-on task.
- I learn best when I can listen to instructions.
- I learn best when I can watch an example.

How do you feel about clutter? (Pick one)

- I can ignore visual clutter around me and still concentrate.
- I need to have a clean desk in order to concentrate.
- I can tolerate visual clutter, but prefer a neat desk in order to concentrate.
- I actually concentrate better when there is clutter surrounding me.

How do you feel about auditory (sound) clutter? (Pick one)

- I can ignore auditory clutter around me and still concentrate.
- I need to have sounds (such as music in the background) in order to concentrate.
- I can tolerate surrounding sounds, but prefer quiet in order to concentrate.
- I cannot study well unless the room is silent. Sounds distract me, as I cannot tune them out.
- I actually concentrate better when there is noise surrounding me (such as a noisy restaurant).

Which statement best describes your relationship to rules: (Pick one)

- I object to silly or unfair rules and tend not to follow them.
- Rules can be annoying but I'll usually follow them if they make sense
- I follow rules
- I like the order that rules provide and rarely have problems with them

Which statement about singing best describes you? (Pick one)

- I am a poor singer, who can not sing on key.
- I am a good singer who can maintain my part and stay on key.
- I am a great singer who can maintain my harmony even when someone next to me is singing a different tune.

Which statement best describes how distracted you are when you work? (Pick one)

- I am easily distracted when I work. I have trouble focusing on any problem for long.

- ○ I prefer an environment with few distractions because otherwise sometimes I get distracted.
- ○ I don’t really notice getting distracted more than others do.
- ○ I can tolerate some chaos in the environment and can usually focus well anyway.
- ○ I am calm and focus well even when working on poorly defined problems. A chaotic environment around me doesn't matter.

What goes on in your head when reading fiction? (Select all that apply)

- ❑ I visualize the characters
- ❑ I hear a narration by a narrator
- ❑ I hear my own voice speaking for the characters
- ❑ I hear the characters speaking
- ❑ I both see and hear the characters
- ❑ I just see the words on the page.