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Refractive Intervention

The Initial Progression of Physical and Perceptual Symptoms Associated With Aniseikonia

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Purpose: We aimed to evaluate the initial progression of physical and perceptual symptoms associated with wearing spectacles that produce unequal retinal image sizes in the two eyes (aniseikonia).

Methods: A within-subjects experiment (n = 20) was conducted to assess how symptoms change over one hour. Participants wore spectacles that contained a minifying lens (4%) over one eye and a plano lens over the other. They reported their physical and perceptual symptoms on Likert scales while performing activities that involved hand-eye coordination, locomotion, and viewing at distance and near. The main session included a one-hour adaptation period with symptom measurements taken before, during, and after. In a control session on a separate day, participants repeated the same activities but wore plano lenses over both eyes during the one-hour period.

Results: There was a general trend for participants' symptoms to compound over time. During the one-hour adaptation period, when participants wore aniseikonic spectacles they reported significantly elevated symptoms, such as blurry vision, distorted percepts, and eyestrain. After adaptation, physical symptoms trended toward being similar or worse than in the control session, but most perceptual symptoms trended slightly better. However, these differences between sessions were not statistically significant.

Conclusions: Our results suggest that the initial progression of symptoms associated with aniseikonia includes a decrease in perceptual symptoms and a persistence of physical symptoms.

Translational Relevance: By anticipating the symptoms that people experience, we hope to improve patient outcomes as people adapt to new aniseikonic spectacles.

Introduction

Prescription spectacles help improve the vision of individuals with refractive errors, but they can also produce troublesome optical distortions. Depending on the refractive correction, spectacle lenses may produce changes in both the size and shape of the retinal images of the wearer.[1] Myopia and hyperopia, which together affect more than half of the global population, are corrected with spectacle lenses that minify and magnify the retinal images, respectively.[2,3] Previous research has shown that people's initial experience of these optical distortions is associated with a constellation of perceptual and physical symptoms.[4–10] While many people adapt successfully to prescription spectacles (i.e., they get used to them), failures of adaptation remain an ongoing concern in vision correction.[11,12] Inability to adapt to spectacles, for example, is estimated to account for about 10% of non-tolerance issues in prescription lens wearers.[11]

Here, we aim to understand the symptoms that people experience within the first hour of wearing new spectacles that produce optical distortions. By anticipating the most likely pattern of symptoms, we hope to provide guidance that can improve patient outcomes as people adapt to new spectacle lenses. In this study, we focus on adaptation to spectacles that create interocular differences in retinal image size called aniseikonia. It has long been appreciated that aniseikonic distortions are particularly problematic.[11–16] Clinically, these image size differences can often occur when patients with anisometropia—a difference in refractive error between their eyes—receive a new pair of spectacles with different optical powers in the two lenses.[17–19] Prescription spectacles for anisometropia likely cause particularly strong discomfort because aniseikonia can have a constellation of effects on binocular perception of space and can drive changes in eye alignment.[20]

In a recent study, we characterized the range and severity of physical and perceptual symptoms that people report in the first few minutes of wearing spectacles that produce aniseikonia.[4] We found that spectacles with interocular differences in minification of 2% and 4% were associated with various symptoms, such as dizziness, eyestrain, and distortions in visual motion.[4] The data suggested that similar symptoms can be also elicited when optical minification is equal in both eyes, but that these symptoms tend to be exacerbated by spectacles with an interocular difference in minification. Importantly, it is not yet known whether these symptoms persist or dissipate over time. An understanding of how the symptoms of spectacle wearers tend to change over time is essential for giving clinical advice about how to support adaptation to new prescriptions. Moreover, wearable augmented and virtual reality systems also produce optical distortions, so this question is relevant for improving emerging consumer technologies.[21–24] Thus here we report an investigation of how interocular differences in optical minification experienced for one hour affect the symptoms that people report while performing naturalistic tasks.

Methods

Participants

Twenty adults completed the study (average age of 23 years, range 18-29; eight males, 12 females). Based on our prior work,[4] we judged that a sample size of 20 participants would allow us to adequately assess short-term effects of aniseikonia, but we did not conduct a formal power analysis. Exclusion criteria included wearing corrective spectacles or contact lenses more than once a month, because we wanted to simulate the experience of a novice spectacle wearers. We conducted visual acuity and binocular vision (Randot) tests to ensure that all participants had normal vision. We required participants to have 20/25 monocular and 20/20 binocular visual acuity. Acuity was measured at 10 feet and converted to the 20-foot equivalent. Participants were also required to have 50 arc seconds or better stereo acuity. Seven out of 27 recruited individuals were disqualified as a result of their inability to meet these criteria, yielding the desired sample size of 20. Qualified participants completed a demographics form, an eye dominance test, and a motion sickness susceptibility questionnaire (MSSQ). Informed consent was obtained from all participants, the experimental procedure was approved by the University of California, Berkeley Institutional Review Board, and all procedures complied with the Declaration of Helsinki. Participants were compensated at the end of each session.

Spectacles

The lenses used in this study were designed to have zero optical power (i.e., size lenses). A pair of these lenses were placed in spectacle frames to induce approximately 4% minification in the right eye and 0% in the left eye. Previous research using these lenses outlines their optical specifications in greater detail.[4] Each participant was fitted with an adjustable spectacle frame that was customized to their facial features. For consistency with previous research using these lenses, fitting of the frame was performed with a set of lenses of intermediate minification strength (2%).[4] The pupillary distance of each participant was measured using a pupillometer and the optical center of the lenses was centered both horizontally and vertically. The pantoscopic tilt of each lens and frame fit was set to be as close to 0° as possible ($M = 0.06°$, $\pm$ 0.49°). The vertex distance between the eye and the lens was set to be as close to 10 mm as possible ($M = 10.2$ mm $\pm$ 0.55 mm). These settings were chosen to ensure that each participant experienced a level of optical distortion that was as close to the intended levels as possible. These spectacles were used because we aimed to examine people's experience with aniseikonia. However, it is also possible that some of the reported symptoms in this study are caused by minification irrespective of interocular differences (e.g., people may have reported similar symptoms if they viewed monocularly through a 4% minifier or wore 4%

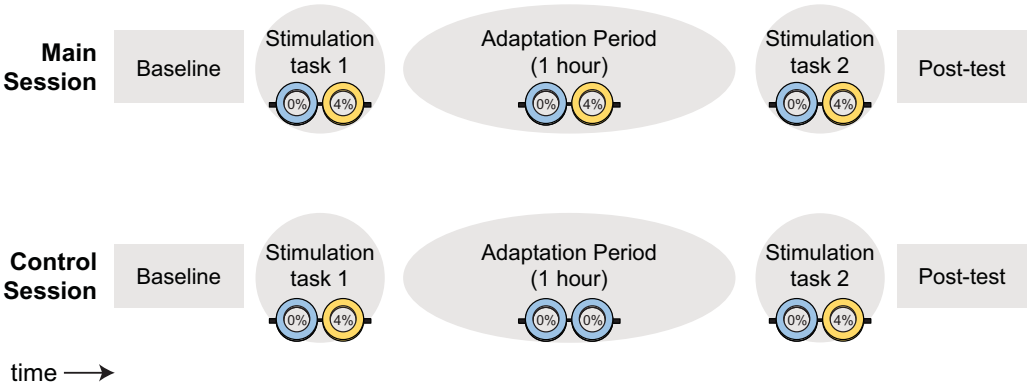

Figure 1. Experimental procedure and measurements for the main session and the control session. *Gray ovals* represent tasks that were performed, and *squares* represent time periods where only measurements were taken. *Colored circles* under the tasks represent the spectacles that were worn during the session, with numbers indicating the percent minification worn over the right and left eyes.

minifiers over both eyes). We return to this issue in the Discussion.

Experimental Procedure

The experiment consisted of a within-subjects design with two sessions (main and control) performed in a randomized order on two different days. The control session was included to ensure that any measured adaptation effects to the spectacles were due to participants getting used to the spectacles and not simply due to the passage of time, the experience of wearing the frames, or the effects of the adaptation activities themselves. Each main and control session was broken up into five segments, described below and illustrated in Figure 1.

Baseline Measures

The purpose of the baseline measures was to gather information about initial symptoms and eye alignment. Participants completed a customized questionnaire about their current physical and perceptual symptoms before putting on the spectacles (see below for questions). Horizontal and vertical phoria (the natural resting state of the eyes) were also measured with the spectacles and without the spectacles at viewing distances of 40 cm and 6 m.[25] We had initially hoped to assess changes in phoria associated with the spectacles, however, due to issues in the phoria measurements we were unable to obtain reliable data for this analysis. As such, we forgo an investigation of phoria adaptation in the current study. If it was the first session, vertical and horizontal fusional vergence ranges were also measured (without the spectacles) using prism bars at 40 cm and 6 m to understand the range of vergence over which the participant could maintain a single clear image.

First Stimulation Task

After the baseline measures were completed, participants wore the spectacles and performed a stimulation task. The purpose of this task was to stimulate the perceptual and physical symptoms associated with doing typical activities while experiencing aniseikonia. The task includes elements of daily activities that are likely to provoke discomfort, such as reading, hand-eye coordination, and body movement. Our previous study showed that this task can elicit elevated symptoms within a few minutes.[4] Participants were given a basket of 12 common household items that were placed on the floor (items were randomized across sessions). There were eight letter markers labeled A through G randomly scattered in a room with dimensions 3.87 × 3.87 m. Participants were instructed to place the items one at a time on a designated letter marker indicated by a sign posted on the wall. After all items were placed, participants put each item back in the basket one by one. Participants were not timed and took approximately two to three minutes to complete the task. Then participants reported their physical and perceptual symptoms. The task did not differ between the two sessions (main and control), and participants always wore the aniseikonic spectacles while performing the task.

Adaptation Period/Control Period

This was the only period that differed between the main and control sessions. In the main session, the purpose of the adaptation period was to test whether individuals would experience a benefit (i.e.,

an improvement in their initial physical or perceptual symptoms) or a disadvantage (i.e., a worsening in their initial physical or perceptual symptoms) after wearing the spectacles for one hour. Adaptation, particularly in binocular vision, has been shown to occur over multiple timescales from seconds to days.[26] The one-hour duration of the adaptation period in this experiment was selected so as to be long enough to plausibly support sustained adaptation based on prior work, while still supporting practical considerations for participant recruitment and scheduling. The tasks during the adaptation period were designed to simulate natural activities and allow participants the opportunity to get used to the spectacles if possible. In the main session, participants continued to wear the spectacles during this period, but in the control session they wore plano lenses in front of both eyes instead. Participants completed three tasks: a scavenger hunt, crossword puzzle, and building a three-dimensional structure (marble maze or LEGO puzzle). Each task has two versions that were counterbalanced across the sessions. Halfway through this period, participants were asked the physical and perceptual symptom questionnaire to obtain an interim measure of how their symptoms were changing.

Second Stimulation Task

After the adaptation/control period, participants repeated the stimulation task while wearing the aniseikonic spectacles so that we could examine whether the symptoms associated with the stimulation activity had improved, worsened, or stayed the same.

Post-Test

The purpose of the post-test was to assess the symptoms soon after lens removal. Horizontal and vertical phoria were measured again at 40 cm and 6 m with the spectacles on, then the spectacles were removed, and the phoria measurements were repeated. Then participants reported their physical and perceptual symptoms a final time.

Physical and Perceptual Symptom Questionnaires

To track symptoms throughout the experiment, a customized physical and perceptual questionnaire was administered several times. The questionnaire was repeated at five different time points: the baseline measures, after the first stimulation task, in the middle of the adaptation/control period, after the second stimulation task, and in the post-test. Responses were made on a 1–5 Likert scale with 1 indicating "not at all," 2 indicating "mild," 3 indicating "moderate," 4 indicating "bad," and 5 indicating "severe." The questions were as follows:

Physical Symptoms

- Are you experiencing a headache?
- Are you experiencing dizziness?
- Are you experiencing nausea?

Perceptual Symptoms

- Do you find it difficult or uncomfortable to pick up or interact with objects?
- Do objects look distorted in shape or size?
- Do the objects appear to be in a different location?
- Does the world appear to move or "swim" when your body, head, or eyes move?
- Do you experience any blurry vision?
- Do you experience any "double vision?"

Eyestrain (Physical and Perceptual)

- Do you experience any eyestrain or eye tiredness?

Control Question

- Do you experience any shoulder or neck pain?

The neck/shoulder pain question was included as a control question because we did not expect participants to experience this symptom during the experiment nor for there to be any differences in this symptom between the sessions. Consistent with our hypothesis, participants did not report any significant neck/shoulder pain symptoms at any measurement time point, and there was no significant difference between the sessions. Two additional physical symptom-only measurements were originally taken for consistency with the standard VOMS test[27]; however, for analysis we focus on five main time points when all questions were asked.

Analysis

Statistical analyses were conducted in R. Statistically significant symptoms were assessed by evaluating differences between the symptoms in each session versus a null hypothesis of no symptoms (response of 1) using single-sample Wilcoxon signed-rank tests. Differences in symptoms between the main session and the control session were measured using paired Wilcoxon signed-rank tests. Effect sizes for each of these tests are reported in terms of r values.[28] We corrected for multiple comparisons using a false discovery rate of 5%. Correction was applied to each subset

of physical and perceptual symptoms at each time point that measurements were taken; these subsets are grouped together in the panels of each of the statistical tables. Changes between symptoms at specific time points within a given session were also used to examine how symptoms progressed over time (difference scores). Statistics on difference scores were calculated in the same manner as described above. For clarity of visualization, in figures we plot the mean and 95% confidence intervals even though all statistical tests were nonparametric.

Results

The Initial Experience of Aniseikonia Produced a Range of Physical and Perceptual Symptoms

The physical and perceptual symptoms reported across five time points during each session are summarized in Figure 2. Recall that both sessions were identical for the baseline measures and for the first

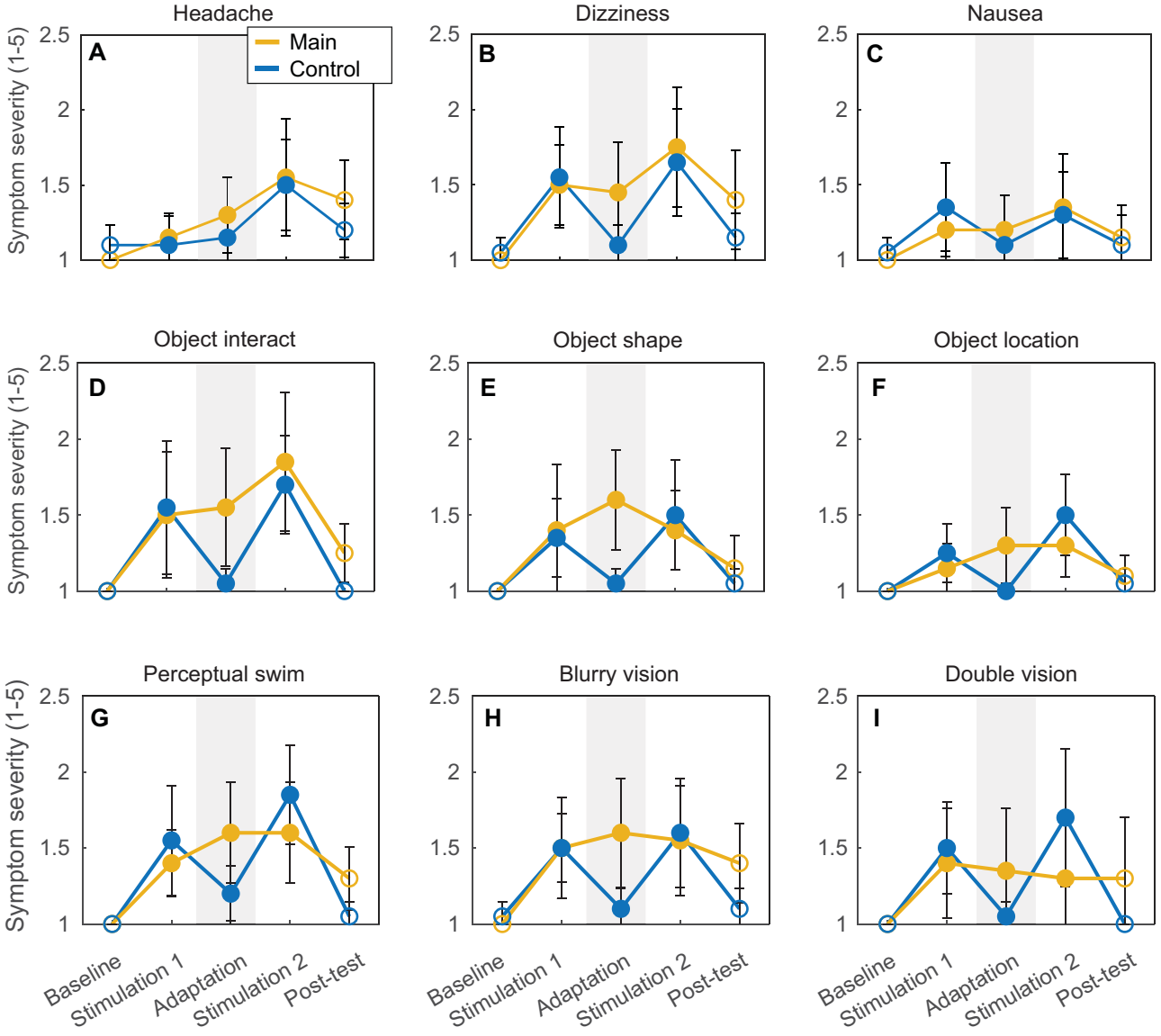

Figure 2. Physical and perceptual symptoms measured on a five-point Likert scale. Means and 95% confidence intervals from a 1 to 5 scale are plotted. *Blue* represents symptoms measured during the main session, and *yellow* represents symptoms measured during the control session. The symptoms reported in this plot include (**A**) headache, (**B**) dizziness, (**C**) nausea, (**D**) difficulty interacting with objects, (**E**) a change in perceived object shape, (**F**) a change in perceived object location, (**G**) perceptual swim, (**H**) blurry vision, and (**I**) double vision. *Filled markers* indicate that the measurements were made with the spectacles on, whereas *unfilled markers* indicate that the spectacles were off. *Shaded regions* indicate when the spectacles differed between the main and control sessions (aniseikonic spectacles in the main session and plano lenses in the control session).

Table 1. Symptoms During the Baseline Measurements

	Main			Control			Comparison		
	V	*P*	*r*	*V*	*P*	*r*	*V*	*P*	*r*
Physical symptoms									
Headache	—	—	—	3	1.000	0.21	3	1.000	0.21
Dizziness	—	—	—	1	1.000	0.00	1	1.000	0.00
Nausea	—	—	—	1	1.000	0.00	1	1.000	0.00
Perceptual symptoms									
Object interaction	—	—	—	—	—	—	—	—	—
Object shape	—	—	—	—	—	—	—	—	—
Object location	—	—	—	—	—	—	—	—	—
Swim	—	—	—	—	—	—	—	—	—
Blur	—	—	—	1	1.000	0.00	1	1.000	0.00
Double	—	—	—	—	—	—	—	—	—

The results of single-sample or paired-sample Wilcoxon signed-rank tests, with test statistics (*V*), significance levels (*P*) and effect sizes (*r*). Significant *P* values are bolded, and the dashes indicate that either no symptoms were reported or both sessions produced identical symptoms such that a Wilcoxon test could not be run.

Table 2. Symptoms After the First Stimulation Task

	Main			Control			Comparison		
	V	*P*	*r*	*V*	*P*	*r*	*V*	*P*	*r*
Physical symptoms									
Headache	6	0.179	0.32	1	1.000	0.00	2	0.777	0.06
Dizziness	**45**	**0.029**	**0.63**	**36**	**0.035**	**0.56**	16	0.777	0.06
Nausea	10	0.108	0.40	15	0.107	0.43	8	0.777	0.21
Perceptual symptoms									
Object interaction	**28**	**0.029**	**0.55**	**28**	**0.031**	**0.53**	25	0.989	0.06
Object shape	10	0.106	0.37	**21**	**0.039**	**0.50**	9	0.989	0.05
Object location	6	0.149	0.32	**15**	**0.049**	**0.47**	3	0.968	0.21
Swim	**36**	**0.025**	**0.61**	**36**	**0.025**	**0.57**	24	0.968	0.19
Blur	**36**	**0.025**	**0.59**	**55**	**0.023**	**0.69**	22.5	1.000	0.00
Double	15	0.065	0.43	**36**	**0.025**	**0.57**	14	0.968	0.16

The results of single-sample or paired-sample Wilcoxon signed-rank tests, with test statistics (*V*), significance levels (*P*) and effect sizes (*r*). Significant *P* values are bolded.

stimulation task (they only differed once the adaptation/control period started). Because the baseline measures were taken before any tasks were performed, we therefore expected participants to report essentially no baseline symptoms in both sessions. Consistent with these expectations, there were no significant baseline physical or perceptual symptoms reported in either session nor any significant differences between the main and control sessions (Table 1).

At the first stimulation task, participants performed an activity that has been previously shown to produce symptoms while wearing aniseikonic spectacles.[4] Consistent with this previous work, in both sessions participants reported several significant physical and perceptual symptoms, including dizziness, difficulty interacting with objects, visual swim, and blurry vision (Table 2). Although object shape/location distortions and double vision qualitatively increased in both sessions, these only reached statistical significance in the control session. As expected, the symptoms in the main and control sessions did not significantly differ (Table 2).

During the Adaptation Period, Many of These Symptoms Persisted

We next examined whether the symptoms continued when participants wore the aniseikonic spectacles

Table 3. Symptoms During the Adaptation/Control Periods

	Main			Control			Comparison		
	V	*P*	*r*	*V*	*P*	*r*	*V*	*P*	*r*
Physical symptoms									
Headache	15	0.143	0.44	6	0.260	0.32	0	0.223	0.32
Dizziness	28	0.088	0.55	3	0.346	0.21	0	0.079	0.50
Nausea	6	0.260	0.30	3	0.346	0.21	0	0.346	0.21
Perceptual symptoms									
Object interaction	28	0.055	0.52	1	1.000	0.00	**0**	**0.036**	**0.53**
Object shape	**45**	**0.025**	**0.60**	1	1.000	0.00	**0**	**0.036**	**0.61**
Object location	15	0.105	0.44	—	—	—	0	0.057	0.44
Swim	**55**	**0.025**	**0.67**	10	0.132	0.40	**0**	**0.036**	**0.55**
Blur	**45**	**0.025**	**0.61**	3	0.475	0.21	**4**	**0.037**	**0.50**
Double	10	0.140	0.38	1	1.000	0.00	0	0.089	0.38

The results of single-sample or paired-sample Wilcoxon signed-rank tests, with test statistics (*V*), significance levels (*P*) and effect sizes (*r*). Significant *P* values are bolded, and the dashes indicate that either no symptoms were reported or both sessions produced identical symptoms such that a Wilcoxon test could not be run.

Table 4. Symptoms Produced After the Second Stimulation Task

	Main			Control			Comparison		
	V	*P*	*r*	*V*	*P*	*r*	*V*	*P*	*r*
Physical symptoms									
Headache	**28**	**0.030**	**0.52**	**36**	**0.021**	**0.57**	16	0.890	0.05
Dizziness	**55**	**0.014**	**0.63**	**55**	**0.014**	**0.65**	7	0.890	0.16
Nausea	10	0.098	0.37	10	0.098	0.37	6.5	0.890	0.03
Perceptual symptoms									
Object interaction	**66**	**0.011**	**0.67**	**78**	**0.006**	**0.74**	8	0.447	0.23
Object shape	**28**	**0.020**	**0.55**	**28**	**0.021**	**0.53**	17.5	0.705	0.12
Object location	**21**	**0.021**	**0.52**	**45**	**0.014**	**0.63**	12.5	0.406	0.28
Swim	**45**	**0.014**	**0.60**	**91**	**0.006**	**0.73**	24	0.395	0.40
Blur	**36**	**0.018**	**0.57**	**36**	**0.018**	**0.56**	21	0.714	0.08
Double	6	0.173	0.30	**45**	**0.014**	**0.60**	29	0.395	0.34

The results of single-sample or paired-sample Wilcoxon signed-rank tests, with test statistics (V), significance levels (*P*) and effect sizes (r). Significant *P* values are bolded.

during the adaptation period. In the main session, several symptoms were significantly elevated during adaptation: distortions of object shape, visual swim, and blurry vision (Table 3). Other symptoms (dizziness and difficulty interacting with objects) were marginal. No symptoms were statistically significant in the control session during which the spectacles were swapped out for plano lenses for this period. A direct comparison of the main and control sessions further supported the conclusion that wearing the aniseikonic spectacles caused symptoms to persist: All perceptual symptoms except distorted object location and double vision were significantly greater in the main session, and one physical symptom (dizziness) was marginally greater (Table 3). Thus the results from questionnaires taken during adaptation suggest that wearing aniseikonic spectacles continued to cause discomfort midway through the one-hour period.

After Adaptation, Symptom Trends for Physical and Perceptual Symptoms Differed

Symptoms were clearly elevated when participants were wearing the spectacles during the adaptation period. However, participants may have also had time

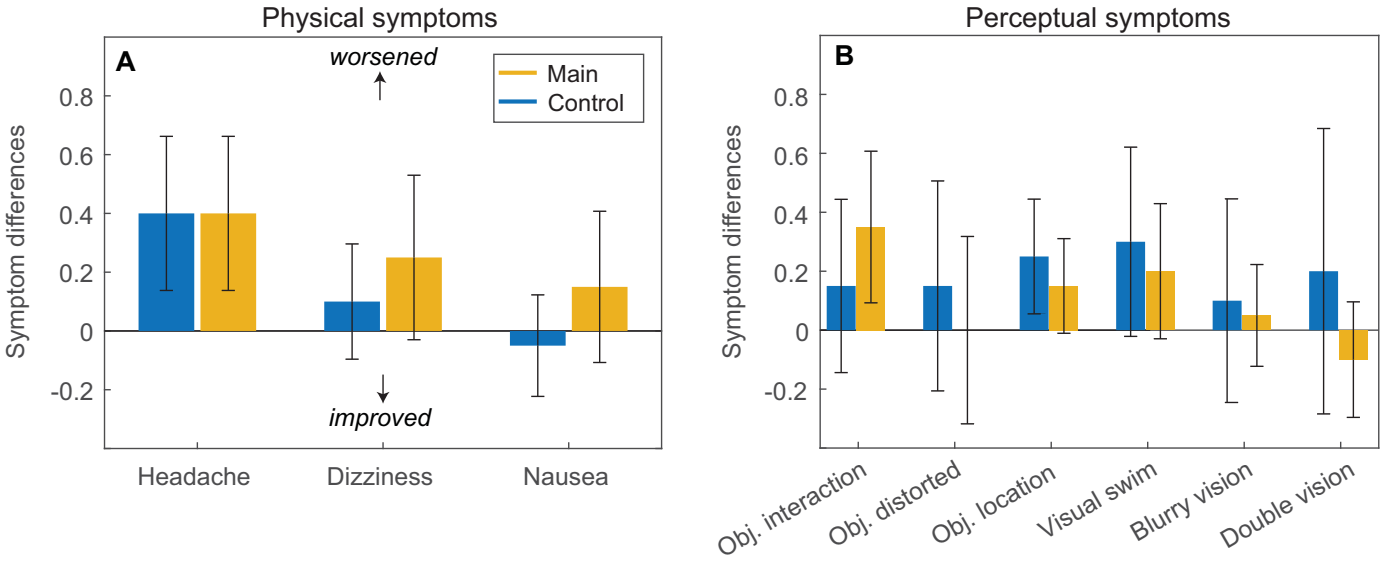

Figure 3. Differences between the symptoms reported during the second and first stimulation tasks. (**A**) Difference scores for the three physical symptoms. *Bar heights* and *error bars* indicate the mean and 95% confidence interval, respectively. *Blue bars* represent difference scores calculated for the control session, and *yellow bars* represent differences from the main session. (**B**) Difference scores for the perceptual symptoms plotted in the same manner as in panel A.

to get used to the spectacles such that after this period was completed, they would be more comfortable than before. Thus, after one hour we asked participants to repeat the stimulation task while wearing the spectacles. This second stimulation task aimed to determine whether participants experienced a reduction or an increase in their symptoms as a result of wearing the spectacles during the adaptation period.

Almost all symptoms were significantly elevated following this second stimulation period across both the main and control sessions, suggesting that performing the stimulation task twice was a strong trigger for symptoms regardless of whether an adaptation period had been experienced (Table 4). We next examined the differences between the main and control sessions, which are the key comparisons for determining whether the adaptation period had a specific effect on symptoms. None of these differences were statistically significant (Table 4). However, qualitatively at the second stimulation task we observed that the physical symptoms were similar or worse in the main session relative to the control (Figs. 2A–C), and most of the perceptual symptoms were better (Figs. 2E–I). Although preliminary, this raises the possibility that one hour of adaptation was sufficient to begin a process of perceptual adjustment but not sufficient to mitigate physical symptoms.

To further assess the possible effects of adaptation, we also examined the difference between the symptoms experienced in the first and second stimulation tasks. The average of these difference scores across participants for the main session and control session are plotted in Figure 3 (statistics in Table 5). These scores indicate that participants had significantly increased headache severity over time in both sessions. There were no other significant increases or decreases in symptoms over time, nor were there significant differences between the sessions. Descriptively, we again observed that the other physical symptoms (dizziness and nausea) were worse on average in the main session (Fig. 3A), whereas most of the perceptual symptoms were better on average (Fig. 3B) as compared to the control session. Although not yet conclusive, one potential interpretation of this pattern of results is that the experience of adapting to the aniseikonia over the short term might confer some perceptual benefit, for example, as the oculomotor system adjusts to the new demands created by the lenses, while also exacerbating some elements of physical discomfort.

The Effect of the Entire Experiment on Symptoms

The purpose of the post-test measurement was to evaluate the symptoms that remained once the spectacles were removed. No post-test symptoms were statistically significant (Table 6). Descriptively, all symptoms were worse at this time point during the

Table 5. Symptom Difference Scores Between the First and Second Stimulation Tasks

	Main			Control			Comparison		
	V	*P*	*r*	*V*	*P*	*r*	*V*	*P*	*r*
Physical symptoms									
Headache	**28**	**0.044**	**0.55**	**28**	**0.044**	**0.55**	22.5	1.000	0.00
Dizziness	35	0.219	0.36	7.5	0.508	0.18	6	0.561	0.20
Nausea	8	0.508	0.21	2	0.773	0.06	5	0.561	0.24
Perceptual symptoms									
Object interaction	40	0.221	0.51	30	0.701	0.21	22	0.780	0.23
Object shape	14	1.000	0.00	10	0.729	0.13	14	0.780	0.14
Object location	6	0.357	0.32	15	0.221	0.47	7.5	0.780	0.18
Swim	17.5	0.357	0.34	36	0.357	0.37	21	0.850	0.08
Blur	4	0.843	0.06	27	0.729	0.11	35.5	0.850	0.04
Double	2.5	0.726	0.18	13.5	0.729	0.12	30.5	0.780	0.21

The results of single-sample or paired-sample Wilcoxon signed-rank tests, with test statistics (*V*), significance levels (*P*) and effect sizes (*r*). Significant *P* values are bolded.

Table 6. Symptoms Remaining During The Post-Test

	Main			Control			Comparison		
	V	*P*	*r*	*V*	*P*	*r*	*V*	*P*	*r*
Physical symptoms									
Headache	28	0.079	0.55	10	0.144	0.40	9	0.272	0.30
Dizziness	21	0.079	0.50	6	0.223	0.32	3	0.272	0.35
Nausea	3	0.445	0.20	1	1.000	0.00	0	1.000	0.00
Perceptual symptoms									
Object interaction	15	0.123	0.47	—	—	—	0	0.111	0.47
Object shape	3	0.530	0.20	1	1.000	0.00	0	1.000	0.00
Object location	3	0.530	0.21	1	1.000	0.00	2	0.927	0.06
Swim	21	0.098	0.52	1	1.000	0.00	4	0.145	0.40
Blur	28	0.098	0.55	3	0.530	0.21	0	0.111	0.52
Double	6	0.434	0.30	—	—	—	0	0.260	0.30

The results of single-sample or paired-sample Wilcoxon signed-rank tests, with test statistics (*V*), significance levels (*P*) and effect sizes (*r*). Significant *P* values are bolded, and the dashes indicate that either no symptoms were reported or both sessions produced identical symptoms such that a Wilcoxon test could not be run.

main session as compared to the control session, suggesting that symptoms increased overall when participants removed the spectacles after a longer amount of time wearing them (Fig. 2). However, there were no significant differences between the symptoms reported in the two sessions (Table 6). One potential interpretation of this pattern of results is that the physical symptoms elicited by the adaptation period persisted, whereas the alleviated perceptual symptoms returned once the spectacles were removed. However, additional tests will be necessary to assess this hypothesis.

Eyestrain

The experience of eyestrain is thought to include both physical and perceptual components, so we considered the eyestrain results separately. Participants reported significant eyestrain at every time point during both the main session and control session, including

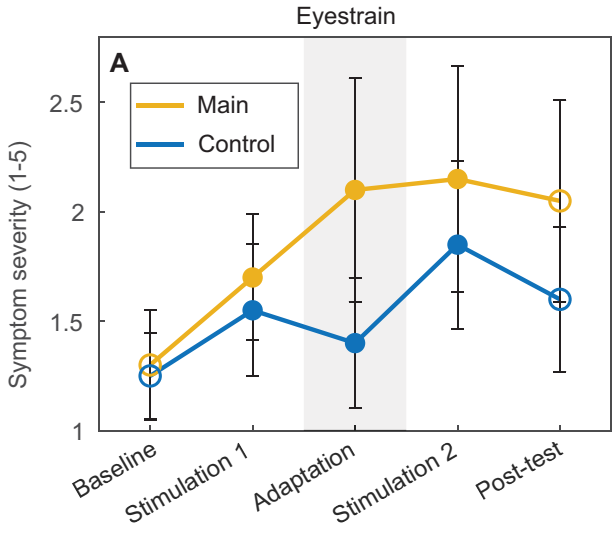

Figure 4. Eyestrain across the main session and control session with the mean and 95% confidence intervals plotted. *Open circles* indicate time points when no spectacles were worn, and *closed circles* represent time points when spectacles were worn.

at baseline (Fig. 4; Table 7). Eyestrain tended to be greater in the main session, but this difference was only statistically significant during the adaptation period and post-test. As with the other symptoms, difference scores were computed between the second and first stimulation task to assess adaptation; however, the differences for eyestrain were not significant in either session, and there was no significant difference between the sessions (Table 7). Together, these data show that eyestrain was experienced throughout both sessions. This is perhaps due to the combination of the fact that the research participant pool was largely composed of students (who might have some baseline eyestrain from computer work) whose symptoms were exacerbated by a combination of both the experiment tasks and the spectacles.

Discussion

Changes in Symptomatology From Aniseikonia Over Time

If prescription spectacles cause discomfort, people may not wear them. Clinically, it is relatively common for people to have refractive errors with an interocular difference of 1.0 diopter or more (termed *anisometropia*).[17,18] Here, we simulated the aniseikonia associated with spectacles that correct for a large anisometropia that is known to produce notable symptoms: approximately a 4.0 diopter difference in prescription between the eyes.[4,29] Consistent with previous literature, we found that people initially experienced a constellation of physical and perceptual symptoms while wearing these aniseikonic spectacles.[4,29] These symptoms are likely related to disruptions in binocular visual processing and eye movements that result when the retinal image sizes differ between the two eyes.

Although we did not find strong evidence for perceptual adaptation to aniseikonic spectacles over one hour, our data are consistent with a small but broad perceptual improvement. Several perceptual symptoms were on average lower during the main session compared to the control session after adaptation (at the second stimulation task), both in terms of their absolute rating and their change over time. While this trend was not statistically significant, it suggests that participants may have experienced a benefit or reduction in perceptual symptoms during the main session as a result of wearing the aniseikonic spectacles. A different trend was observed in the physical symptomatology and eyestrain: The evidence suggests that these symptoms were unaffected or slightly exacerbated by the one-hour adaptation period. Although

Table 7. Eyestrain Reported at Each Time Point

	Main			Control			Comparison		
	V	*P*	*r*	*V*	*P*	*r*	*V*	*P*	*r*
Time point									
Baseline	**15**	**0.048**	**0.44**	**15**	**0.037**	**0.47**	9	0.824	0.05
Stimulation 1	**78**	**0.001**	**0.72**	**45**	**0.006**	**0.61**	20	0.437	0.17
Adaptation	**78**	**0.002**	**0.69**	**21**	**0.031**	**0.48**	**5**	**0.006**	**0.62**
Stimulation 2	**78**	**0.002**	**0.69**	**78**	**0.002**	**0.70**	22.5	0.179	0.30
Post-test	**91**	**0.001**	**0.72**	**45**	**0.007**	**0.60**	**8**	**0.044**	**0.45**
Difference score	69.5	0.087	0.38	18	0.120	0.35	24.5	0.457	0.17

The results of single-sample or paired-sample Wilcoxon signed-rank tests, with test statistics (*V*), significance levels (*P*) and effect sizes (*r*). Significant *P* values are bolded. Note that eyestrain symptoms did not undergo *P* value correction for multiple comparisons with the other symptoms because they are considered both perceptual and physical.

these were also not statistically significant changes, this trend suggests that physical symptoms may initially worsen over time when people wear aniseikonic spectacles.

The persistence of physical and perceptual symptoms once spectacles are removed can also be an important contributor to adherence to prescription spectacles. Even if the patient adapts to the spectacles and their discomfort goes away, if discomfort reappears after removal, this could be a strong deterrent. Although there was no significant difference between the physical and perceptual symptoms experienced after removal of the spectacles during the main and control sessions, there was a trend toward greater lingering symptoms during the main session. It would be helpful for future work to investigate these persistent symptoms—the time course of symptoms that arise after spectacles are removed may be equally as important as the symptoms while spectacles are worn because both impact the patient's overall experience.

Predictors of Individual Differences in Symptom Severity

Individual differences in people's symptoms and tolerance of distortions can make it challenging to identify general best practices for improving comfort. Having metrics that can predict future comfort on an individual basis, however, could be quite valuable to aid spectacle prescribing. Thus we conducted exploratory analyses to examine whether the visual measurements taken from each participant at the start of the session—specifically fusional range and motion sickness susceptibility—might predict their later discomfort.

We anticipated that fusional range might be an important indicator of comfort related to eyestrain and double vision. Because our eight fusional range measures were correlated, we created a combined fusional range metric that took the mean across the eight fusional range measurements taken at baseline. We assessed the relationship between this fusional range metric and eyestrain or double vision. For both sessions, a weak trend was observed: lower fusional ranges were associated with larger eyestrain and double vision measured during the adaptation period. Specifically, this trend was significant for eyestrain in the control ($r^2 = 0.27$, $P = 0.019$), but not the main session ($r^2 = 0.14$, $P = 0.107$). Weak trends for double vision were not statistically significant (main session: $r^2 = 0.18$, $P = 0.062$; control session: $r^2 = 0.10$, $P = 0.171$). These data suggest that fusional range may be an indicator of future symptoms for patients receiving new prescription spectacles for anisometropia, but the predictive power may be limited. These trends may be stronger if people with atypical stereoacuity are considered; however, our screening procedures excluded such individuals. We also expected that the MSSQ might predict levels of nausea and dizziness. However, we found no correlation between the MSSQ and either of these symptoms reported during the adaptation task for the control or main sessions. The MSSQ is a coarse measure of motion sickness sensitivity based on self-report, so it is possible that more nuanced measurement tools could identify a predictor for these symptoms.

Future Directions

The results of this study are preliminary and will require future validation and follow-up studies. For example, here we focused on evaluating symptomology through subjective reports, specifically Likert scale responses to a customized questionnaire. However, these reports can be challenging for participants and have limited sensitivity. Objective measurements of how spectacles affect behavior—such as measures of changes in task performance or gaze patterns—would therefore also be valuable for understanding the factors that affect compliance with a new spectacle prescription. Gaze patterns in particular may prove to be a fruitful direction for future research. Aniseikonic spectacles produce changes in vergence demand that vary with gaze direction. We might therefore expect to observe greater vergence instability and potentially greater fixation disparity when people wear these spectacles during typical tasks. These gaze patterns could be linked to subjective eyestrain and double vision. Gaze patterns may also reflect adaptations to the visual disturbance of the lenses. For example, we might expect to see longer fixation times when people perform fine motor tasks while wearing aniseikonic spectacles if they struggle to perform depth judgements with disrupted stereopsis. The interplay between behavioral effects, adaptations, and subjective experience is likely a key driver of both typical adaptations and individual differences.

Indeed, the strength of both physical and perceptual adaptation could potentially be affected by increasing the adaptation duration and/or altering the activities being performed. Previous studies have suggested that sometimes days are needed for perceptual adaptation.[5,10] Thus it would be valuable to extend this paradigm to longer adaptation periods, potentially beyond a single day. It is also currently unknown whether certain activities or experiences support adaptation to optical distortions better than others, although some work suggests that intermittent breaks

could be helpful.[30] The activities in our adaptation period were selected to simulate a range of natural tasks and therefore may not have been the optimal activities to support physical and perceptual improvements. Similarly, prior work suggests that certain eye and head movements are most likely to elicit physical discomfort—perhaps limiting or ramping up these movements over time could reduce the escalation of physical symptoms.[4]

Last, we know that aniseikonic spectacles are not the only ones that can cause discomfort. Spectacles that produce equal or similar distortions in both eyes can also cause symptoms.[4] Here, we focused on a single example of aniseikonic distortions, but future work comparing adaptation between aniseikonic lenses of differing strengths, binocular minifying lenses, and even monocular viewing through a single minifier can help broaden our understanding of how a variety of new prescriptions can affect patients' comfort. Furthermore, optical distortions akin to those experienced in prescription spectacles can occur in emerging consumer technologies that use wearable optics, such as augmented and virtual reality systems. For users of these systems, there may be less incentive to tolerate even minor or moderate discomfort. By providing information about what types of discomfort people might experience when they initially put on wearable optics, we hope the results of our study can support future work and improve guidelines that mitigate discomfort across a range of contexts.

Conclusions

We systematically investigated how physical and perceptual symptoms change when people initially wear aniseikonic spectacles. Although one hour of adaptation did not prove long enough to see substantial adaptation effects, our results suggest interesting trends for persistence of symptoms after spectacle removal and distinctive differences in the development of physical and perceptual symptoms. These results are an important step to better understanding which symptoms people first experience with optical distortions, how these symptoms change, and how quickly they might be expected to resolve.

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