Perception of Coherent Motion in Infantile Nystagmus Syndrome

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PURPOSE. Research on infantile nystagmus syndrome (INS) and motion perception is limited. We investigated how individuals with INS perform coherent motion tasks. Particularly, we assessed how the null position affects their performance.

METHODS. Subjects with INS and controls identified the direction of coherent motion stimuli (22 subjects with INS and 13 controls) in a two-alternative forced-choice design. For subjects with INS, testing was done at the null position and 15 degrees away from it. If there was no null, testing was done at primary gaze position and 15 degrees away from primary. For controls, testing was done at primary gaze position and 20 degrees away from primary. Horizontal and vertical motion coherence thresholds were determined.

RESULTS. Subjects with INS showed significantly higher horizontal and vertical motion coherence thresholds compared with controls at both gaze positions ($P < 0.001$). Within the INS group, for 12 subjects with INS who had an identified null position, no differences in coherence thresholds were found between their null and 15 degrees away from it ($P > 0.05$).

CONCLUSIONS. Coherent motion perception was impaired in subjects with INS. The null position did not significantly influence motion coherence thresholds for either horizontal or vertical motion.

Keywords: infantile nystagmus syndrome, motion perception, coherent motion, null position

Infantile nystagmus syndrome (INS) is an involuntary, constant, rhythmic eye oscillation, which usually presents at or near birth and persists throughout life. Its waveform parameters can vary with gaze angle, leading many patients to the adoption of an abnormal head posture to enhance their vision.[1] The gaze position with minimal nystagmus intensity and better visual performance is known as the null position.[1–7] Nearly all the research on vision in INS has focused on static visual acuity and the time needed to get the eyes onto the desired target (i.e. target acquisition time).[8–13] Although these are important properties, they are not sufficient to reveal more complex visual functions entailed in real-life visual activities. Therefore, it is important to study how individuals with INS perform when they carry out a range of visual tasks and to examine how performance is influenced by the variability of INS at different gaze positions.[4,10,11,14]

In everyday life, we may be presented with objects in motion that we must identify and respond to, such as a flock of birds flying in the sky, or a large crowd of people walking in the street. This is known as coherent motion, which is the perception of the integrated direction of a group of objects moving in varying directions individually but with an overall trend for the group.

Research on INS and coherent motion perception is limited. Abadi et al.[15] investigated local and global motion detection using a focal target moving against a large textured background in five subjects with idiopathic INS. The authors reported that, compared with controls, subjects with idiopathic INS were approximately eight times less sensitive to the local and global motion of the target. A more recent study by Neveu et al.[16] sought to investigate coherent motion processing deficits in six subjects with nystagmus and albinism. In the Neveu et al.[16] study, an equivalent noise paradigm, which consisted of patches of drifting spatial frequency band-pass filtered noise in a circular aperture, was used to assess horizontal and vertical motion coherence thresholds for subjects with nystagmus and albinism, and controls. The equivalent noise paradigm allows for assessment both of the number of noise elements being integrated to form a percept as well as the precision with which each element's motion is processed. The motion coherence thresholds were defined as the percentage of drifting spatial frequency band-pass filtered noise required for subjects to correctly determine the motion direction at a 75% level. The authors reported that subjects with nystagmus and albinism showed much higher coherence thresholds (horizontal = 80% and vertical = 75%) than those of control subjects (horizontal = 45% and vertical = 46%). There was no significant difference in both groups between horizontal and vertical motion coherence thresholds. In addition, another three groups were recruited: one group had two subjects with albinism but without nystagmus, one group had three subjects with nystagmus and aniridia, and another group had

only one subject with idiopathic nystagmus. The subjects with albinism but without nystagmus showed normal coherence thresholds in both motion directions (horizontal = 46% and vertical = 53%). In contrast, the subjects with nystagmus and albinism (horizontal = 80% and vertical = 75%) or nystagmus and aniridia (horizontal = 74% and vertical = 65%) had grossly elevated coherence thresholds. The only subject with idiopathic nystagmus had very high coherence thresholds in both motion directions (horizontal = 100% and vertical = 100%). The authors concluded that individuals with nystagmus had elevated motion coherence thresholds. However, in their study, the investigators recruited only six subjects with nystagmus and albinism and did not clarify the exact types of their nystagmus, except to note that an unspecified number had congenital periodic alternating nystagmus. In addition, they did not evaluate the effect of gaze at subjects' null positions or elsewhere when evaluating coherent motion perception performance.

The null position in INS is of interest because it is possible to have different visual performance at the null position or at some specific distance away from it. A recent study by Fadardi et al.,[14] demonstrated that visual acuity of subjects with INS can be affected by increased cognitive demands, and these effects on acuity differed between null position and 15 degrees away from it. From low to high cognitive demand, the deterioration of acuity was greater for subjects with INS at the null position compared to 15 degrees away from it. The authors suggested that the larger effects at the null position might be due to the maximal foveation period duration there; this optimal foveation may be more vulnerable to cognitive load than would poorer foveation away from the null. Thus, the null position in INS allows better acuity than gaze elsewhere; other aspects of vision, such as motion processing, could also be better there.

In the present study, we investigated how individuals with INS perform coherent motion tasks. Particularly, we assessed how the null position affects their performance. To achieve this, we analyzed motion coherence thresholds at two different gaze positions for subjects with INS and controls. Two hypotheses were tested: (1) subjects with INS will perform poorly compared to controls in coherent motion tasks (i.e. subjects with INS will have higher motion coherence thresholds than controls because of the incessant horizontal retinal image motion they experience through life); and (2) the null position in subjects with INS will have a positive effect on coherent motion perception.

METHODS

Subjects

Twenty-two subjects with INS (aged 14–34 years, M = 23.95, SD = 5.88) and 13 healthy control subjects (aged 22–39 years, M = 27.00, SD = 5.29) were recruited from two testing sites (Melbourne, Australia, and Jinan, China). Twenty-one subjects were classified as idiopathic INS and one subject had an associated visual disorder (oculocutaneous albinism).

The diagnosis of INS was first made by the referring ophthalmologists and later confirmed by the investigators with a pre-testing clinical examination and analysis of eye movement recording analysis. Subjects with congenital periodic alternating nystagmus were identified by monitoring the nystagmus fast phase direction during their initial examination with extended primary gaze fixation for 4 minutes,[17] and they were excluded from the study as they generally do not have a fixed null position. The healthy control subjects had a corrected visual acuity of 0.0 logMAR or better, and their interocular acuity difference was no more than one logMAR line. They had no history of ophthalmic, neurological, or psychotic illness, and were not taking any medications that could affect their eye movements.

This study complied with the Declaration of Helsinki and was approved by the Human Research Ethics Committees of the Department of Optometry & Vision Sciences, The University of Melbourne, and Shandong Liangkang Eye Hospital, Jinan (Ethics ID: 1749588.5). Informed consent was obtained from the subjects after explanation of the nature and possible consequences of the study. For subjects aged under 18 years old, consent was sought from their parents/ guardians.

Clinical Demographic Record

For all subjects, basic demographic information was collected before testing. This included age, gender, occupation, and medical history. A basic ophthalmic examination was performed to assess their visual functions. Distance visual acuity was measured at 3 m with a logMAR chart. Near visual acuity was determined at 40 cm using a reading chart. Stereopsis was measured by a Randot Stereotest. A cover test was performed to detect the presence of strabismus. Abnormal head postures and the approximate null positions were also documented. Clinical characteristics of subjects with INS are presented in Table 1.

Apparatus

Subjects were seated at 75 cm from a computer monitor in a normally lighted room. The computer screen subtended a visual angle of 44 degrees × 25 degrees with a resolution of 2048 × 1152 pixels and a refresh rate of 60 Hz. Two eye trackers were used to record eye movements at different sites. In Melbourne, the Eyelink 1000 eye tracker (SR Research, Ontario, Canada) at a sampling frequency of 500 Hz was used, and in Jinan, a head mounted video eye tracker (SmoothEye, New York, NY, USA) was used at a sampling frequency of 1000 Hz. The experimental protocol was designed and built using PsychoPy version 1.85.4[18] and Experiment Builder (SR Research, Ontario, Canada) for coherent motion and biological motion tasks, respectively. Two metal arcs were made by the investigators to measure the gaze position of the subjects in both Melbourne and Jinan. It was mounted to the top edge of the monitor with targets at ± 30 degrees from the center in 5-degree steps, as shown in Figure 1. When subjects were asked to perform the task at 0 degrees gaze position, they were required to put their chin on the chinrest with their eyes looking straight toward the 0 degrees target at the center of the metal arc. When subjects were asked to perform the task at an eccentric gaze position, they were required to put their chin on the chinrest and then turn their head either leftward or rightward with their eyes looking straight toward the designated eccentric target on the metal arc to ensure they performed the task at the required eccentric gaze position.

Stimuli

The stimuli used were random dot kinematograms (RDKs) generated by PsychoPy version 1.85.4.[18] A single frame of the stimuli is shown in Figure 2 (see Supplementary

Table 1. Clinical Characteristics of Subjects With INS

No.	Age/Sex	Diagnosis	Distance VA (logMAR)	Near VA	Stereopsis	AHP
1	21/M	Idiopathic INS	0.6	N8	(-)	(-)
2	16/F	Idiopathic INS, XT	0.1	N6	200"	(-)
3	24/M	Idiopathic INS, XT	0.6	N14	400"	(-)
4	22/M	Idiopathic INS	0.4	N8	400"	(-)
5	21/M	Idiopathic INS, ET	0.7	N14	(-)	(-)
6	15/M	Idiopathic INS	0.6	N14	(-)	Face turn L
7	31/M	INS, OCA	0.6	N14	400"	(-)
8	25/F	Idiopathic INS	0.9	N14	400"	(-)
9	15/M	Idiopathic INS	0.7	N18	(-)	(-)
10	14/M	Idiopathic INS	0.4	N18	(-)	(-)
11	28/M	Idiopathic INS	0.0	N4	(-)	(-)
12	29/F	Idiopathic INS	0.0	N5	40"	Face turn L
13	26/F	Idiopathic INS	0.4	N6	(-)	(-)
14	33/M	Idiopathic INS, XT	0.7	N18	800"	(-)
15	26/M	Idiopathic INS, XT	0.2	N5	(-)	(-)
16	19/M	Idiopathic INS, XT	0.0	N4	(-)	(-)
17	27/M	Idiopathic INS, XT	0.2	N8	40"	(-)
18	30/M	Idiopathic INS	0.0	N4	(-)	Face turn L
19	22/M	Idiopathic INS	0.8	N14	(-)	(-)
20	21/F	Idiopathic INS	0.0	N4	25"	Face turn L
21	34/F	Idiopathic INS, XT	0.2	N4	(-)	Face turn R
22	28/F	Idiopathic INS, XT	0.7	N12	(-)	Face turn L

M and F refer to male and female. Ages are of years. R and L refer to right and left direction. XT and ET refer to exotropia and esotropia respectively. OCA refers to oculocutaneous albinism. AHP refers to anomalous head posture. (-) refers to no stereopsis or AHP in subjects with INS. N4-N24, "N" referring to near; "4-24" corresponding to Times New Roman characters, font size 4 to 24; font size is measured in points; 1 point is equal to 1/72 of an inch.

Figure 1. A metal arc mounted to the top edge of the monitor with targets at ± 30 degrees from the center in 5-degree steps. It was used to measure the gaze position of the subject.
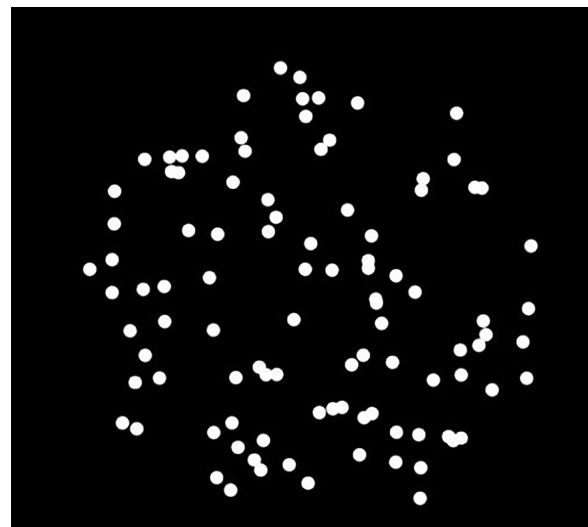

Figure 2. A single frame of the RDK stimuli used in the coherent motion task.

Video S1 for a moving RDK stimulus). The RDK stimuli consisted of 100 white dots (dot diameter 0.3 degrees and dot density 1.27 dot/deg^2) presented within a circular aperture (10 degrees diameter) at the center of a black screen. The dot diameter subtended 0.3 degrees of visual angle, which equated to approximately double the size of a visual acuity target of 1.0 logMAR. This would ensure all subjects with INS could see the stimuli because none of the subjects with INS had a visual acuity worse than 1.0 logMAR in the present study. Dots were displaced by 0.167 deg/frame resulting in a dot velocity of 10 deg/sec. To eliminate the possibility of detecting the direction of one single dot, all dots had a limited lifetime of six frames (approximately 100 msec), after which they disappeared and were regenerated at random locations within the aperture. The stimuli were presented for 39 frames (650.13 msec).

Procedure

At the beginning of the coherent motion task, a five-point pop-up calibration sequence (4 around the periphery and

TABLE 2. Characteristics of INS Waveform

No.	Null Position	Waveform	
		Primary Gaze Position/Null Position	15 Degrees Away From Primary Gaze Position/Null Position
1	(-)	0 degrees/ jerk, mixed direction	15 degrees R/ jerk, mixed direction
2	0 degrees	0 degrees/ jerk R	15 degreesR/ jerk R
3	(-)	0 degrees/ jerk R	15 degrees R/ jerk R
4	(-)	0 degrees/jerk, mixed direction	15 degrees L/ jerk L
5	0 degrees	0 degrees / jerk L	15 degrees R/ jerk R
6	20 degrees R	20 degrees R/no detectable nystagmus	5 degrees R/ jerk R
7	(-)	0 degrees / jerk, mixed direction	15 degrees R/ jerk, mixed direction
8	(-)	0 degrees / jerk, mixed direction	15 degrees L/ jerk, mixed direction
9	(-)	0 degrees / jerk L	15 degrees L/ jerk L
10	0 degrees	0 degrees / jerk L	15 degrees R/ jerk R
11	(-)	0 degrees / jerk, mixed direction	15 degrees L/ jerk, mixed direction
12	15 degrees R	15 degrees R/ jerk R	0 degrees / jerk R
13	(-)	0 degrees / jerk, mixed direction	15 degrees R/ jerk R
14	(-)	0 degrees / dual jerk	15 degrees R/ dual jerk
15	0 degrees	0 degrees / jerk L	15 degrees R/ jerk L
16	(-)	0 degrees / jerk R	15 degrees L/ jerk R
17	(-)	0 degrees / jerk R	15 degrees L/ jerk R
18	20 degrees R	20 degrees R/ no detectable nystagmus	5 degrees R/ jerk L
19	0 degrees	0 degrees / jerk, mixed direction	15 degrees R/ jerk, mixed direction
20	25 degrees R	25 degrees R/ jerk R	10 degrees R/ jerk R
21	15 degrees L	15 degrees L/ jerk R	0 degrees / jerk R
22	15 degrees R	15 degrees R/ jerk R	0 degrees / mixed jerk

(-) refers to no identified null position. R and L refer to right and left direction.

1 at the center of the screen) was performed binocularly. No validation procedure was performed. For subjects with INS, it is not always possible to have their calibrations validated because they are unable to fixate the targets stably for a sufficient period of time. In this case, the calibration was performed by a normally sighted calibrator. This has been reported to be a simple and easily applicable way to get relatively more accurate results compared with other alternative calibration methods.[19] The calibration performed is sufficient for this study because the eye movement recordings were mainly used to confirm the diagnosis of INS, and to identify the presence and location of the null position. Once calibration was completed, the INS subject was required to fixate on a dot presented horizontally across ± 20 degrees from the center in 5-degree steps on the computer screen. Each gaze position was tested twice from right to left and then vice versa, with each presentation lasting for 5 seconds. Characteristics of INS waveform at the null position and 15 degrees away from it are shown in Table 2. The gaze position with the least nystagmus intensity during this test was determined as the null position.[20,21] Following this, all subjects were required to perform the coherent motion tasks. The order of the tasks was randomized. A chinrest and forehead rest were used to stabilize the head of subjects. Investigators monitored the participants during the whole testing procedure to ensure that their heads were stabilized.

Motion coherence thresholds were measured with two tasks: (1) horizontal (when the coherent motion direction was either leftward or rightward); and (2) vertical (when the coherent motion direction was either upward or downward). Within each task, the thresholds were measured at two gaze positions. For subjects with INS with identified null positions, these were at their null position and 15 degrees away from it (either toward left or right). If the null position was in lateral gaze (± 10 degrees, ± 15 degrees, or ± 20 degrees), the 15 degrees away position was in the opposite direction to it. If the null position was at or near primary gaze (0 degrees or ± 5 degrees), the 15 degrees away from null position was either toward left or right. For subjects with INS without identified null positions, they performed at primary (straight-ahead) gaze position and 15 degrees eccentric position (either toward left or right). For control subjects, testing was done at primary (straight-ahead) gaze position and a 20-degree eccentric position (either toward the left or right). The order of the two tasks was randomized, and within each task, the gaze positions were randomized.

For both tasks, each trial began when subjects were asked to fixate on a black fixation dot (1.44 degrees × 1.44 degrees of visual angle). Following the fixation dot, subjects viewed the stimulus at the center of the screen for 39 frames (650.13 msec). After the stimulus presentation, the subjects were required to identify the direction of the coherent motion by pressing one of the two arrow keys on the keyboard indicating either leftward or rightward for the horizontal motion coherence detection task, or upward or downward for vertical motion coherence detection task. Each response elicited an audio tone from the program. A correct response generated a high tone and an incorrect response generated a low tone. Subjects were instructed about these tones so that they could be encouraged to be accurate and alert. The threshold of each subject's motion perception was measured by a three-down/one-up two-alternative forced-choice staircase procedure to estimate the 79.4% correct detection of the direction of coherent motion.[22] The staircase started at 100% coherence (100 dots) and had a step size of 10 dots until the first reversal and half of the current step size thereafter, until the fourth reversal reached 1 dot step size and thereafter. The criterion for a staircase reversal downward was three consecutive correct responses, and the criterion for a staircase reversal upward was a single incorrect response. The staircase terminated after six reversals. Staircases for two signal directions were interleaved within

either the horizontal (leftward and rightward) or the vertical task (upward or downward). Thresholds were determined separately for each of the two motion directions of each task by calculating the average of the last four of six reversal point values of each staircase. Each task was repeated three times to get the overall mean motion coherence thresholds of the subjects.

Before formal testing began, each subject received several practice trials to ensure they understood the task procedure. The practice trials started from 100% coherence threshold, for which the motion direction was easy to detect. Subjects were also informed that the task would become harder, and that it was important that they try their utmost to identify the direction and press the key as accurately as possible. However, if some of the trials were too hard for them to identify the motion direction, they were instructed to guess.

Statistical Analysis

Motion coherence thresholds, which were determined by the percentage of signal dots moving in the same direction, were recorded during the task. Data were analyzed utilizing SPSS version 21 (IBM Corporation, Armonk, NY, USA) and GraphPad Prism version 8 for Windows (GraphPad Software, San Diego, CA, USA). An outlier analysis (ROUT [Q = 1%]) was used to detect the outliers, and outlier values were removed for subsequent analyses.[23] Two-way mixed ANOVAs were used to measure the effect of INS on coherent motion task performance. Two-way repeated-measures ANOVAs were used to measure the effect of the null position and stimulus motion direction on coherent motion performance. Eye movements at different gaze positions were recorded, and the direction of the slow phase of jerk waveform was noted along with the direction of horizontal stimulus motion (leftward or rightward) during the task. Motion coherence thresholds when these directions were concordant or discordant were compared using a two-tailed paired *t*-test.

Results

Horizontal and vertical motion coherence thresholds tasks were analyzed for control subjects (primary gaze position and 20 degrees eccentricity), and subjects with INS (null or primary gaze position if no null present, and 15 degrees eccentric from it). No outliers were identified from subjects with INS and control subjects.

When comparing the motion coherence thresholds between subjects with INS and control subjects, a two-way mixed ANOVA showed that the subjects with INS had significantly higher horizontal (right and left) and vertical (up and down) thresholds than the control subjects at both primary and eccentric gaze positions (Figs. 3, 4; primary: F [1, 33] = 21.56, $P < 0.0001$ and eccentric: F [1, 33] = 21.53, $P < 0.0001$).

As this study aimed to investigate the effect of the null position on coherent motion perception in subjects with INS, the INS group was further divided into 2 subgroups: (1) 11 subjects with INS with a null (subgroup A), and (2) 11 subjects with INS without a null (subgroup B). A 2-way repeated-measures ANOVA revealed that no differences were found in subgroup A between their null position and 15 degrees away from null position for both horizontal and vertical thresholds (Fig. 5) (horizontal: F [1, 10] =
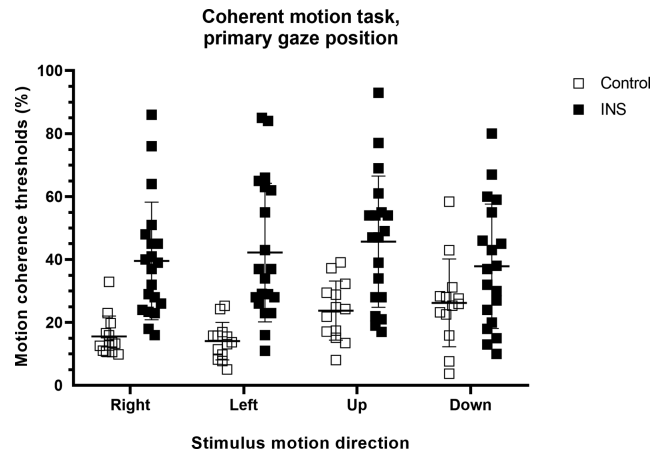

Figure 3. Horizontal (right and left) and vertical (up and down) motion coherence thresholds for control and subjects with INS at primary gaze position. Error bars indicate standard deviation, which holds for the following figures.
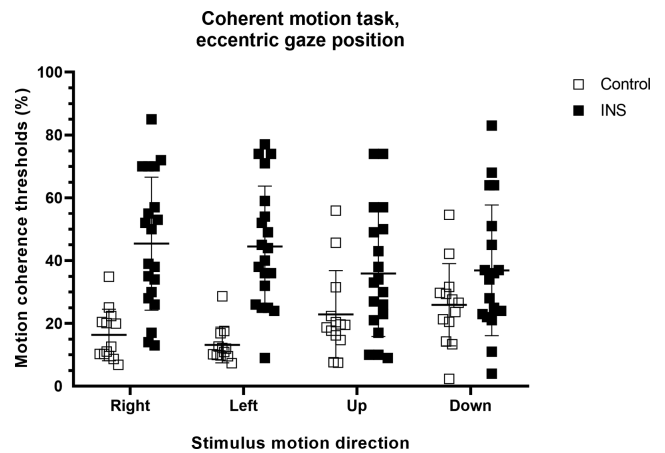

Figure 4. Horizontal (right and left) and vertical (up and down) motion coherence thresholds for control and subjects with INS at eccentric gaze position.
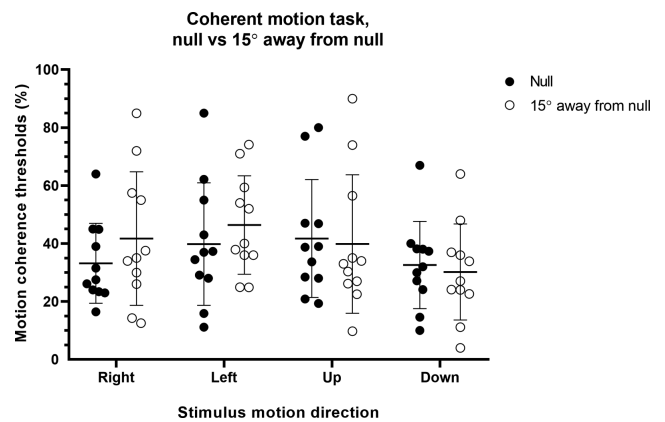

Figure 5. Horizontal and vertical motion coherence thresholds for the INS subgroup A (11 subjects with INS with null position) at their null position and 15 degrees away from null position.
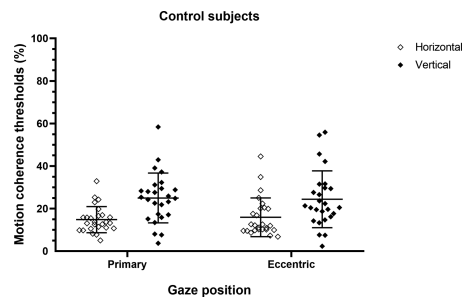
FIGURE 6. Horizontal and vertical motion coherence thresholds at primary and eccentric gaze positions for control subjects.
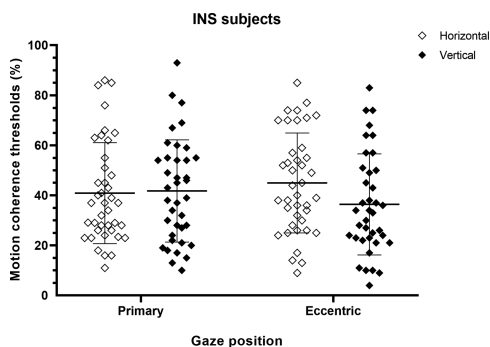

FIGURE 7. Horizontal and vertical motion coherence thresholds at primary and eccentric gaze positions for subjects with INS.

3.398, $P = 0.0951$ and vertical: F [1, 10] = 1.456, $P = 0.2553$), although there was a trend toward significantly lower horizontal thresholds at the null position than 15 degrees away from it. For subgroup B and the control group, 2-way repeated-measures ANOVAs showed no differences between different gaze positions (subgroup B: F [1, 10] = 2.530, $P = 0.1428$ and control group: F [1, 12] = 0.02666, $P = 0.8730$).

When comparing horizontal and vertical thresholds within the subjects with INS and the control groups, a 2-way repeated-measures ANOVA showed the control group had significantly lower horizontal thresholds compared to vertical thresholds at both primary and eccentric gaze positions (Fig. 6; F [1, 25] = 20.66, $P = 0.0001$). There were no differences for the INS group (Fig. 7; F [1, 41] = 1.139, $P = 0.2921$).
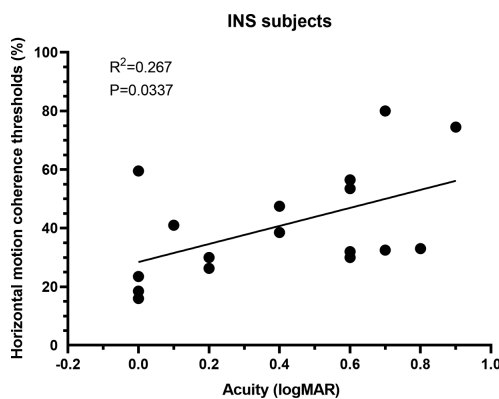
Because the subjects with INS had their nystagmus only in the horizontal plane, thresholds measured in the horizontal task (right and left) were compared with regard to the nystagmus slow phase direction for subjects with INS. Twelve subjects with INS at primary gaze and 15 subjects with INS at eccentric gaze had pure jerk left or right nystagmus that were analyzable (see Table 2 for data presentation). A 2-tailed paired *t*-test showed that when stimulus motion was in the same direction as the nystagmus slow phase, thresholds (42.74 ± 19.81%) were not significantly different from the thresholds of when stimulus motion direction was opposite to the nystagmus slow phase direction (43.22 ± 20.30%; t[26] = 0.1663, $P = 0.8692$).

Although the stimulus used in the present study was selected to be supra-threshold in acuity for INS subjects, the effect of visual acuity on motion coherence thresholds was investigated. Figure 8 presented the distribution of the horizontal and vertical motion coherence thresholds at primary/null position with respect to the visual acuity of subjects with INS. Pearson correlation and linear regression analyses showed a significant correlation between acuity and horizontal motion coherence thresholds in subjects with INS ($r = 0.5167$, $P = 0.0337$), but there was no correlation between acuity and vertical motion coherence thresholds ($r = 0.227$, $P = 0.3810$). This result demonstrated that visual acuity of subjects with INS only affects their motion coherence thresholds in the horizontal direction but not the vertical direction. If the visual acuity was considered to directly affect the thresholds, it should affect both directions, but not favor just the horizontal thresholds. The correlation between acuity and horizontal thresholds might be explained by the meridional amblyopia that has been reported in individuals with INS because motion coherence thresholds have been demonstrated to be elevated by amblyopia.[24–28]

DISCUSSION

Poorer Coherent Motion Detection Performance of Subjects With INS Compared With Controls

As hypothesized, subjects with INS showed poorer coherent motion detection performance (i.e. elevated motion coherence thresholds) compared with controls for both horizontal and vertical motion directions.

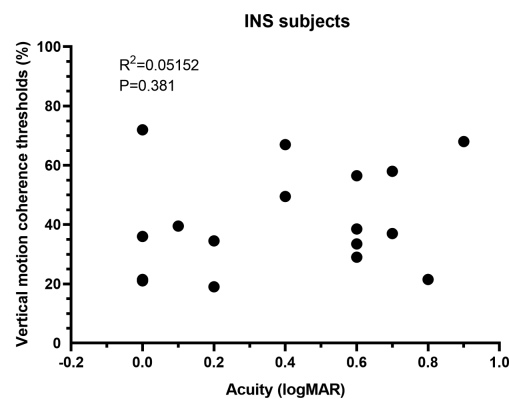The most relevant study pertaining to our findings was Neveu et al.[16] who evaluated local and global motion

FIGURE 8. Scatter plots showing the effect of visual acuity on horizontal and vertical motion coherence thresholds in subjects with INS.

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processing in subjects with nystagmus and albinism, and subjects with albinism only. As stated previously, nystagmus could be a contributing factor in elevating the motion coherence thresholds. In the present study, 21 (95%) of the 22 subjects with idiopathic INS showed elevated motion coherence thresholds, which is in agreement with Neveu et al.[16] Their stimuli were small, circular, drifting Gabor patches in fixed locations but with variably aligned drift directions. They thus could separately assess both local and global motion deficits. Our measurements were coarser, looking only at global motion in orthogonal vertical and horizontal directions. They also assessed contrast detection. Our study used drifting dots with 100% contrast and of a size within the resolution limits of all participants. However, we did not assess whether the detection these stimuli was of equal difficulty for all participants. A follow-up study could adjust the dot size for equal detectability as well as examine the effects of equating detection by varying contrast (i.e. lowering it for higher acuity subjects). The dependence of horizontal (but not vertical) thresholds upon acuity suggests that this might reduce variability of performance in the INS group.

Although it seems that the physical retinal image motion imposed by nystagmus may contribute to the deficits in coherent motion detection, a developmental component to these deficits cannot be ruled out. INS usually presents at or near birth, and early visual experience has been demonstrated to have a profound impact on visual areas of the brain.[29] One condition of interest is amblyopia, which has been well-reported in the literature as a result of binocular visual deprivation from early childhood due to INS.[30–32] Von Noorden[30] stated that individuals with congenital nystagmus could develop bilateral stimulation deprivation amblyopia, as the constant retinal motion could prevent the formation of well-defined images during the early critical visual developmental period. Felius et al.[31] found that children with idiopathic INS could have bilateral deprivation amblyopia due to pendular nystagmus with poor foveation characteristics during the early critical period of visual development. Similarly, Dunn et al.[9] assessed visual acuity in INS in the absence of retinal image motion and found that subjects with INS showed worse visual acuity than controls under tachistoscopic illumination conditions (i.e. flashed illumination) when the image motion blur was removed. Other studies have also noted that bilateral amblyopia might contribute in part to the poor vision in older children and adults with INS due to binocular visual deprivation from early childhood.[32,33] Overall, all these findings strongly suggest that eye oscillations in later life do not significantly impair visual acuity in individuals with INS; their visual acuity may have already been fundamentally limited by a stimulus deprivation amblyopia owing to motion blur during the early critical visual developmental period. Thus, it is possible that bilateral deprivation amblyopia could result from INS.

When assessing the coherent motion processing in individuals with amblyopia, several studies have reported elevated thresholds. Using RDK stimuli, Simmers et al.[27] investigated global motion processing in observers with unilateral strabismic and/or anisometropic amblyopia. They detected elevated motion coherence thresholds for both the amblyopic and the fellow eyes. The authors suggested that this coherent motion perception deficit consisted of both contrast- and signal-to-noise dependent components. The contrast-dependent deficit was related to the contrast sensitivity deficit in amblyopia, and the signal-to-noise dependent

deficit was likely associated with local motion integration in the second stage (dorsal pathway in extra-striate cortex) of global motion processing deficit. Aaen-Stockdale et al.[34] has also demonstrated that global motion deficit is independent of the low-level deficits to contrast sensitivity and spatial frequency in amblyopia, which suggest that global motion processing in amblyopia is broadband and high-level (extra-striate).

Apart from INS, congenital cataracts leading to deprivation amblyopia, and thus resulting in elevated motion coherence thresholds, have also been described in the literature.[26,28] Ellemberg et al.[26] assessed global motion sensitivity in subjects with unilateral or bilateral congenital cataracts using RDK stimuli, and found that subjects with unilateral deprivation amblyopia had elevated motion coherence thresholds for both eyes compared with controls; these findings are in agreement with Simmers et al.[27] Moreover, they also found that subjects with bilateral congenital cataracts exhibited more elevated motion coherence thresholds than those with unilateral congenital cataracts. These deficits imply an extra-striate cortex deficit of global motion processing in the dorsal pathway (middle temporal and medial superior temporal areas) in amblyopia.[26,28] In addition, the authors also found that individuals with bilateral developmental cataracts that occurred later in life showed normal motion coherence thresholds.[26] This suggests that clear visual input during the early critical period of visual development is essential for the development of global motion processing mechanisms. As most of the patients with bilateral/unilateral congenital cataract in Ellemberg et al.[26] showed either manifest or latent nystagmus, the authors discussed that the deficits in global motion perception are likely not attributed to nystagmus. They demonstrated that, for patients with bilateral congenital cataracts, the deficits in two patients who did not experience nystagmus (latent nystagmus but did not patch either eye) were as great as six patients with manifest nystagmus; for patients with unilateral congenital cataracts, five subjects who did not experience nystagmus (neither manifest nor latent nystagmus) performed no better than eight subjects with either manifest nystagmus or latent nystagmus while the good eye was patched. However, the authors did not examine the nystagmus of their participants with an eye tracker. It would be beneficial to further clarify the nystagmus types of the subjects with congenital cataract. An avenue for future research would be to assess the motion coherence thresholds in subjects with congenital cataracts with and without INS.

In this context, it is possible that the involuntary eye oscillations appearing from birth may directly affect the brain regions that are responsive to global motion, and that these brain regions fail to develop (or poorly develop) normal response properties to moving stimuli. MT is known to be the main brain area responsible for global motion.[35] Its removal or impairment results in impaired motion perception. Using functional magnetic resonance imaging (fMRI), Schmitz et al.[36] found that both MT and the superior colliculi brain regions in patients with INS and albinism remained active although there was no motion stimulation presented and no oscillopsia was reported by the subjects. The authors suggested that it was probably due to the continuous retinal image movement caused by INS in albino subjects.

In addition, a recent study by Yonehara et al.[37] reported reduced sensitivity for motion in the horizontal direction in mice with idiopathic INS and FRMD7 mutations due to

the loss of horizontal direction-selective responses in retinal ganglion cells. Although the visual systems of mice are very different to those of humans, the finding of the study raise the possibility that reduced coherent motion detection sensitivity in adults with INS may be result from hard-wired changes in the early visual system.

Overall, it appears that a developmental deficit in INS can affect global motion processing mechanisms located in the brain region MT resulting in impaired coherent motion detection. Hence, it can be proposed that a combination of physical retinal motion imposed by INS and developmental deficits from early childhood due to INS could account for the elevated motion coherence thresholds observed in the present study.

No Null Position Effect

It was hypothesized that the null position was expected to have a positive effect on coherent motion detection performance in INS. However, results of this study showed no statistically significant difference in motion coherence thresholds between the null position and 15 degrees away from it in subjects with INS, although there was a trend toward lower horizontal thresholds at the null position than 15 degrees away from it. The finding of no null effect raises the general question about why individuals with INS prefer to use their null position. A previous study by Dunn et al.[10] assessed the impact of the null position on visual acuity in subjects with idiopathic INS and reported that, although the improvement in visual acuity at the null position was statistically significant, its magnitude (0.08 logMAR) was much smaller than might be expected from the larger improvement in nystagmus parameters, like foveation duration. So why do individuals with INS adopt an abnormal head posture, if they gain only very small improvement in visual acuity at the null? This might be driven by improvements in multiple aspects of visual function, such as visual processing time or recognition time. Recently, Dai et al.[38] investigated the effect of null position on velocity discrimination in INS and found that subjects with INS had lower horizontal and vertical velocity discrimination thresholds at the null position than at 15 degrees away from it. The null might have had an effect on coherent motion perception in RDK stimuli if dot size or stimulus contrast were adjusted to be slightly above threshold for each subject. In doing that, the impact of the null position might be better evaluated. The presence of a trend toward improvement at the null for horizontal motion also supports the need for further investigation.

No Difference Between Horizontal and Vertical Motion Coherence Thresholds in Subjects With INS

Results of the present study showed no significant differences in subjects with INS for motion coherence thresholds between horizontal and vertical directions. This finding is partly consistent with the findings of Neveu et al.,[16] who reported no significant differences in both subjects with nystagmus and albinism and control subjects for motion coherence thresholds for the tested horizontal and vertical directions.

Nevertheless, in the present study, control subjects showed significantly lower motion coherence thresholds for horizontal direction than vertical direction. This is, in fact,

in agreement with previous studies reporting that healthy control groups showed significantly lower horizontal motion coherence thresholds than vertical thresholds.[39,40] Pilz et al.[40] assessed motion coherence thresholds for horizontal and vertical motion direction discrimination in younger and older participants using RDK stimuli. They reported that both groups of participants had lower motion coherence thresholds for horizontal than vertical motion (directional anisotropy), which supports similar research conducted in areas of attention and eye movements that reported asymmetries between cardinal directions.[41,42] Indeed, participants have shown better performance in horizontal than vertical direction,[41] and smooth pursuit has been reported to be more stable and accurate for motion along the horizontal than vertical axis.[42]

From an evolutionary perspective, there is a difference between horizontal and vertical performance, given that horizontal information is more relevant and important. For example, people, animals, or vehicles approaching are more likely to enter our visual field from the left or right rather than from up or down, resulting in a horizontal bias for contours in natural scenes.[43] From a neurophysiological viewpoint, there is also a larger quantity of neurons tuned to horizontal orientation compared to vertical orientation.[44]

In the current study, the difference of directional motion coherence thresholds between control and subjects with INS is proposed to be attributed to a dysfunction of area MT in the dorsal pathway for subjects with INS. Ellemberg et al.[26] reported that deficits in global motion processing after early binocular deprivation are most probably a result of damage to the directionally-selective neurons outside the primary visual cortex. An animal-based study by Spear et al.[45] investigated motion deprivation effects on the perception of motion in cats that were reared in an environment illuminated stroboscopically at 8 Hz that caused no retinal motion for both eyes. As a result, they found that cats showed profound deficits in direction discrimination of moving gratings, and such deficits were supposed to result from the loss of directionally selective neurons in both the striate cortex[46,47] and in the lateral suprasylvian cortex[45] – an area homologous to area MT.

Overall, the above-mentioned findings could suggest that the reduction of directionally selective neurons after binocular deprivation may contribute to the deficits in the ability of direction discrimination of motion. For subjects with INS, it is possible that binocular deprivation amblyopia and involuntary eye oscillations caused by the early onset nystagmus affected the directionally selective neurons within area MT, resulting in general deficits in both horizontal and vertical coherent motion processing, with impairments in horizontal coherent motion processing degrading the horizontal thresholds to the level of the normally poorer vertical thresholds. However, the exact underlying mechanisms are still not well understood. A proposed future study would be to assess coherent motion performance in subjects with INS with functional brain imaging (such as fMRI) to record the exact brain area that respond to the motion stimulus. By doing that, the mechanisms underlying deficits in global motion processing in INS would be better evaluated. Another future study could consider asymmetric step sizes when assessing the motion coherence thresholds. In the current study, the thresholds were measured using adaptive staircases with fixed step sizes, which has been shown to converge less reliably on the percent-correct values as opposed to using asymmetric step sizes.[48]

We also found that when stimulus motion was in the same direction as the nystagmus slow phase, thresholds were not significantly different from the thresholds of when stimulus motion direction was opposite to the nystagmus slow phase direction. However, for 19 of 22 subjects with INS in this study, concurrent eye movements while doing the motion tasks were not recorded because the eye tracker was not available during the task performance. It would be of benefit to further explore the relationships among slow phase velocities, foveation duration, and waveform types with performance (motion coherence thresholds) on the coherent motion tasks using stimulus with contrast scaling for each subject, when psychophysical testing and eye tracking could be done simultaneously, to better understand coherent motion perception in INS.

CONCLUSION

In summary, coherent motion perception was impaired in subjects with INS, with elevated thresholds seen for both horizontal and vertical motion and no difference was observed for thresholds between the two motion directions. The null position did not significantly improve motion coherence thresholds, although there was a trend toward significantly lower horizontal thresholds at the null position than 15 degrees away from it.

Together, the findings of the present study could help us to further understand how people with INS perform daily visual activities and assist us in developing new clinical visual function assessment tools for INS. Compared to static visual acuity, motion perception can be examined to assess the real-life visual function of INS more thoroughly. Questions related to visual motion perception can also be added to the current quality of life surveys[49–52] to better assess real-life related visual function in INS.

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