Eye (2021) 35:1758–1765
https://doi.org/10.1038/s41433-020-01160-y

The ROYAL COLLEGE of OPHTHALMOLOGISTS

ARTICLE

Block-building performance test using a virtual reality head-mounted display in children with intermittent exotropia

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Received: 26 September 2019 / Revised: 28 July 2020 / Accepted: 20 August 2020 / Published online: 1 September 2020

Abstract

Purpose To determine whether childhood intermittent exotropia (IXT) affects distance divergence and performance in block-building tasks within a virtual reality (VR) environment.

Methods Thirty-nine children with IXT, aged 6–12 years, who underwent muscle surgery and 37 normal controls were enrolled. Children were instructed to watch the target moving away and perform a block-building task while fitted with a VR head-mounted display equipped with eye- and hand-movement tracking systems. The change in inter-ocular distance with binocular distance viewing, time to stack five cube blocks of different sizes in order, and distance disparities between the largest and farthest cubes were assessed. All children were evaluated at baseline and 3-month time points.

Results The patients with IXT exhibited a larger distance divergence than did controls ($p = 0.024$), which was associated with greater distance angle of deviation and poorer distance control ($r = 0.350$, $p = 0.001$ and $r = 0.349$, $p = 0.004$). At baseline, the patients with IXT showed larger distance disparities in the block-building task than did controls in terms of the horizontal, vertical, and 3-dimensional (3-D) measurements (all $ps < 0.050$). Larger horizontal disparity was associated with greater distance angle of deviation ($r = 0.383$, $p = 0.037$). Three months after surgery, the horizontal and 3-D disparities in the patients with IXT improved significantly and were not comparably different compared with controls.

Conclusions These preliminary findings suggest that VR-based block-building task may be useful in testing possible deficits in visuo-motor skills associated with childhood IXT.

Introduction

Intermittent exotropia (IXT), which is inconstant, is the most common form of childhood-onset exotropia [1]. Nearly half of children with IXT exhibit variable control of their exodeviation, and IXT is mainly present when focusing at distance [2]. Therefore, patients with IXT are likely to spend their critical period of visual development with intermittent bifoveal fusion, usually demonstrating good visual acuity and normal near stereoacuity [3, 4]. A recent 3-year observational study of children with IXT showed that deterioration of stereoacuity or progression to constant exotropia was uncommon [5], whereas surgical treatment of childhood IXT is associated with high recurrence rates and long-term cure is likely to be difficult to achieve, casting doubt on the long-term efficacy of surgical intervention for IXT [6]. However, some functional problems and psychosocial concerns have been reported in children with IXT, with some reports showing lower health-related quality of life [7–10]. Children with IXT frequently experience symptoms including difficulty in focusing their eyes, eye pain, and photosensitivity to the sun [7]. Some patients with IXT complain of the occasional preference to close one eye even when diplopia is absent. Pineles et al. [9] suggested this could be related to decreased binocular summation, which was measured by a low contrast sensitivity test. One report showed a higher proportion of

Patient consent Informed consent was obtained from a parent or legal guardian and patients.

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monocular viewing and slower smartphone reading speed in adult patients with IXT compared to controls [10], but it is still not well known how IXT affects everyday tasks of the patients, particularly children.

Block-building is a typical activity requiring three-dimensional (3-D) spatial perception [11]. In brain science and rehabilitation medicine, block-building is commonly used as a measure of spatial ability and to train spatial assembly performance. Virtual reality (VR) systems typically offer a stereo image by presenting an image separately to each eye. Recently, VR-based treatment has been introduced as a potential therapeutic option for managing amblyopia by encouraging both eyes to work together to assimilate two separate images into a coherent whole [12]. We postulated that greater distance divergence would be exhibited in patients with IXT compared to controls in a 3-D virtual environment where a large dissociation between both eyes occurs, and that we would be able to evaluate an everyday task efficiently in patients with manifested exodeviation associated with IXT.

We developed a novel VR-based head-mounted display (HMD) system that facilitates an interactive 3-D block-building performance test. We assessed the magnitude of divergence during binocular distance viewing as well as block-building performance using this VR-based HMD in children with IXT, both preoperatively and postoperatively, and compared to age-matched normal subjects. In addition, we evaluated whether clinical factors are associated with this performance in children with IXT.

Materials and methods

Subjects

Children aged 6–12 years were recruited during 2017–2018, including 39 patients who underwent muscle surgery for basic-type IXT and 37 normal controls with no history of eye disease other than refractive error. Inclusion criteria included patients in the IXT group who had exodeviation of 20 prism dioptres (PD) or more at distance on the prism and alternate cover test, while control subjects exhibited orthotropia or exophoria within eight PD. Exclusion criteria included the presence or history of amblyopia, refractive error exceeding −5.00 D or +2.00 D, astigmatism >1.50 D, anisometropia >1.00 D, any structural lesion causing an inter-ocular difference, history of ocular surgery, and neurologic disease.

VR HMD with eye and hand movement tracking

We used a FOVE headset for VR display (FOVE, Inc., San Mateo, CA), which allows separate images to be presented to each eye, thus producing stereo images, and can display interactive games. The headset was equipped with an organic light-emitting diode display (5.8-in. diagonal, resolution of 2560 × 1440 pixels per eye), with a refresh rate of 90 Hz, 100° field of view, and mounted with eye tracking system of 120 frames per second. Eye movement data were obtained from an infrared video-based, pupil-tracking system mounted inside the VR headset. Hand movement data were obtained using a recording system linked to Leap Motion (Leap motion, Inc., San Francisco, CA) attached in front of the VR display. Recordings were considered acceptable for analyses if tracking reliability was more than 80%. Monocular calibration was achieved by presenting a small red dot (5 mm) on the display. The VR HMD headset was worn over any habitual refractive correction used by the patient. Results were displayed on a report screen of the laptop in real-time. A report file was generated and recorded on the laptop database containing the subject's identification, the executed time, and the measurements. All eye and hand movements were also video recorded.

Assessment of distance divergence and performance in the block-building task

All subjects underwent a complete ophthalmologic examination, including the Titmus Stereo Test (Stereo Optical Co., Inc., Chicago, IL), Worth 4-dot test, and the prism and alternate cover test. Control of exodeviation was assessed at distance using the Office Control Score for IXT, which ranges from 0 (phoria, best control) to 5 (constant exotropia, worst control) [13]. The examination using a VR HMD headset consisted of two sessions; one to measure the amount of divergence while viewing a car moving away and one to measure the performance in block-building. Two examiners were masked to the group allocation and clinical findings; they delivered all the VR tests and collected the data.

After successful calibration, subjects were instructed to watch a small car moving from the front to the back simulated by changes in the position and size, in the centre of the screen with binocular viewing (Fig. 1a). The amount of divergence was measured as change in the horizontal inter-ocular distance following distance viewing on the report screen (Fig. 1b). This session was repeated three times; the average angle was used to compare between IXT patients and controls.

Prior to performing the block-building test, alternate cover stimulation for 2 s was delivered three times to each eye to block binocular fusion in order to help patients manifest their exotropia in a VR environment (Fig. 1c). Subjects were instructed to vertically stack cubic blocks of 5 different sizes (2 × 2 × 2 cm, 3 × 3 × 3 cm, 4 × 4 × 4 cm, 5 × 5 × 5 cm, and 7 × 7 × 7 cm; similar to the font sizes of 60,

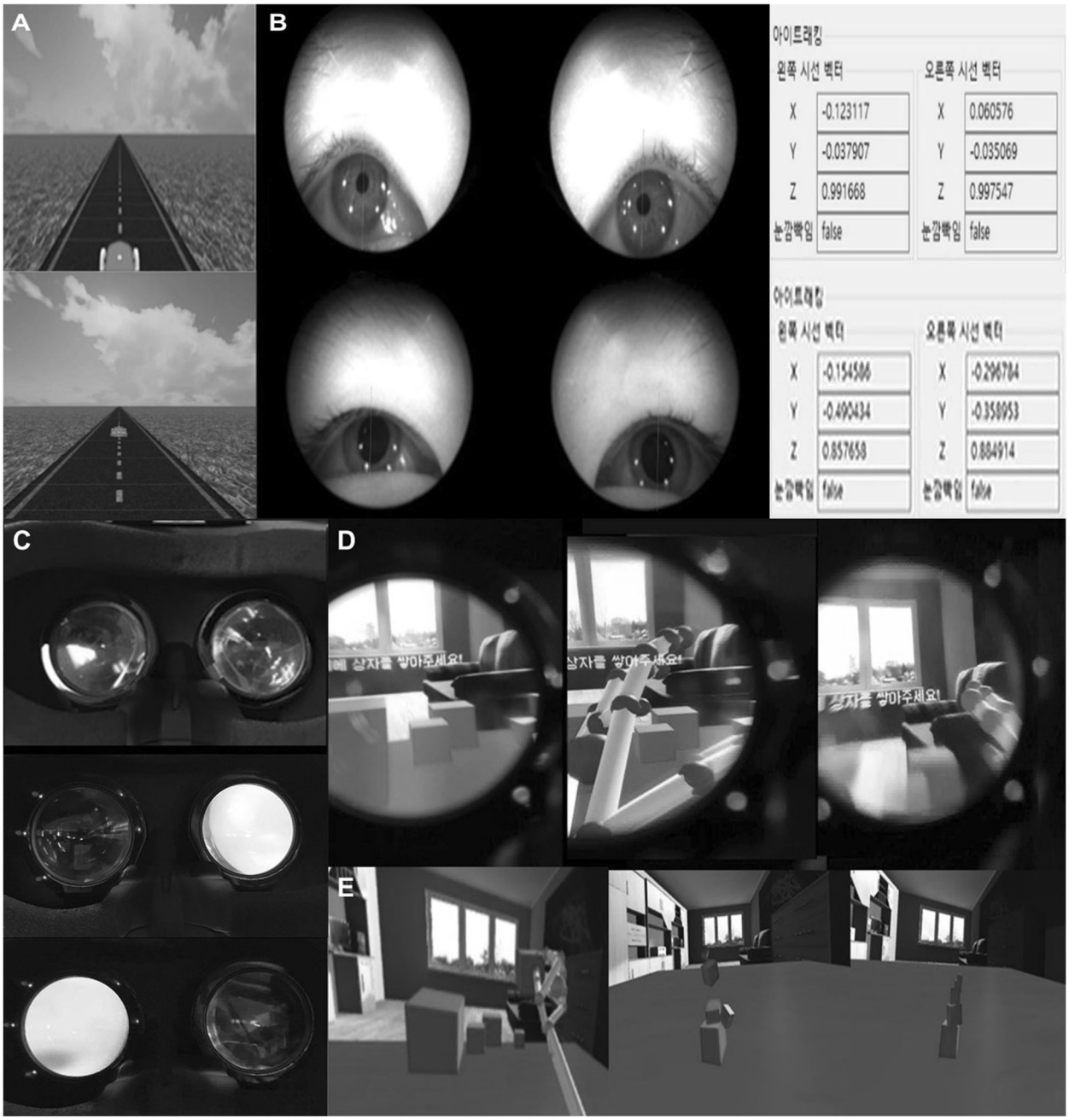

Fig. 1 Software programs developed to measure the magnitude of divergence during binocular distance viewing in a virtual reality environment (the first session) and block-building performance (the second session). Screenshots of the first session: **a** subject's view and **b** representative results on the report screen when subject is viewing the car moving from the front (top) to the back (bottom). The eyes are diverged and pupils are dilated during binocular distance viewing. Screenshots of the second session: **c** subject's view stimulating the alternate covering, **d** subject's view showing the block-building performance test, and **e** representative results on the report screen of a patient with intermittent exotropia (middle) and a normal subject (right).

90, 120, 150, and 210, respectively) in order from the biggest to the smallest one (Fig. 1d, e). The distance disparity between the centre of the biggest/closest one and the smallest/farthest one was measured horizontally, vertically, and three-dimensionally. Vertical and 3-D distance disparities were calculated by subtracting the innate block sizes from the total distance disparity. Execution time was also measured. All patients with IXT were evaluated at pre-operative and 3-month postoperative visits. The visually normal children also completed these tests at the same timepoints to allow calculation of the 95% confidence interval (CI) of changes to determine test–retest variability.

Statistical analysis

The first session results were compared using a t-test to determine the difference in magnitude of distance divergence in IXT patients compared to controls. The second session results were compared using a *t*-test to determine the difference in block-building performance within the 3-D VR environment in IXT patients compared to controls. Preoperative and 3-month postoperative results of the patients with IXT were compared using a paired t-test. In addition, the measured magnitude of distance divergence and the distance disparities in block-building were assessed using a regression analysis for correlation with severity of IXT (angle of deviation, distance control, and near stereoacuity), age, presence of suppression, and spherical equivalent. *P* values < 0.05 were deemed statistically significant.

Results

Thirty-nine children with 25.7 ± 7.1 PD of IXT undergoing surgery and 37 normal controls were enrolled. The mean age of the IXT patients was 7.6 ± 2.7 years and that of the normal controls was 9.5 ± 2.5 years, but the difference in age between groups was not significant. The clinical characteristics of the participants are shown in Table 1. All subjects completed the test without difficulty, dizziness, or diplopia, but two children in the normal control group complained of the heaviness of the HMD. 3 months after muscle surgery, 35 of the 39 IXT patients met the criteria for surgical success (orthotropia or exotropia within eight PD, or intermittent esotropia within four PD without diplopia), and the remaining four patients showed exodrift of 12–16 PD.

Table 1 Baseline demographic and clinical characteristics for the participants.

	Intermittent exotropia ($n = 39$)	Control ($n = 37$)	*P* value
Age (years)	7.6 ± 2.7	9.5 ± 2.5	0.853[a]
Sex (Male, %)	20 (51.3)	22 (59.5)	0.438[b]
Visual acuity (logMAR)	0.11 ± 0.16	0.09 ± 0.09	0.799[a]
Refractive error (D)	−0.67 ± 1.59	−0.25 ± 3.24	0.151[a]
Angle of deviation (PD)			
Distance	25.7 ± 7.1	0.2 ± 3.3	<0.001[a]
Near	24.9 ± 8.1	0.5 ± 3.0	<0.001[a]
Near stereoacuity (arcsec)	63.4 ± 32.5	48.5 ± 11.8	0.264[a]
Worth 4-dots test (FF: SF: SS, %)	8: 26: 5 (20.5:66.7:12.8)	NA	
Control score	3.3 ± 0.8	NA	

logMAR logarithm of the minimum angle of resolution, *D* dioptre, *PD* prism dioptre, *arcsec* seconds of arc, *FF* fusion at distance and near, *SF* suppression at distance and fusion at near, *SS* suppression at distance and near, *NA* not available.

[a]Independent *t*-test.

[b]Chi-square test.

Distance divergence in a VR environment

In a VR environment, the patients with IXT showed a larger amount of divergence during binocular distance viewing than did the normal controls (14.54° vs 8.77°, respectively, $p = 0.024$). The amount of divergence during distance viewing was positively correlated with distance angle of deviation and distance control ($r = 0.350$, $p = 0.001$, and $r = 0.349$, $p = 0.004$, respectively, linear regression, Fig. 2), but did not correlate with age, near stereoacuity, presence of suppression, or spherical equivalent.

Block-building performance in a VR environment

At baseline, the patients with IXT showed larger distance disparities in the block-building task than those of the controls in terms of the horizontal, vertical, and 3-D measurements (all *p*s < 0.050, Table 2). The patients with IXT tended to perform the block-building for a longer duration of time compared to normal controls, but the difference was not significant between groups ($p = 0.093$). Three months after surgery, the horizontal and 3-D distance disparities in the patients with IXT improved significantly, to a comparable level with the normal controls. The vertical distance disparity improved with a borderline significance ($p = 0.057$). However, the execution time did not differ between preoperative and postoperative timepoints in the patients with IXT (Table 2). For horizontal distance disparity in the block-building task, all patients with IXT showed improvements, and twenty patients (51.3%) showed improvement that exceeded the 95% CI for test–retest variability from the controls. For vertical distance disparity, 13 patients (33.3%) showed improvement over test–retest variability, while five patients (12.8%) showed deterioration. For the 3-D distance disparity, 15 patients (38.5%) showed improvement over test–retest variability and two (5.1%) showed deterioration (Fig. 3). At the 3-month time point, all distance disparities and execution time did not differ significantly between the IXT patients and normal controls, whether the patients with IXT who did not experience surgical success were included or not (Table 2). Four patients who showed unsatisfactory surgical results had improvement in the horizontal distance disparity; two of them showed improvement over test–retest variability.

Given that among measures of distance disparity, the most prominent difference between patients with IXT and normal controls, and between preoperative and postoperative timepoints, was observed in horizontal distance disparity, we analysed the correlation of the horizontal

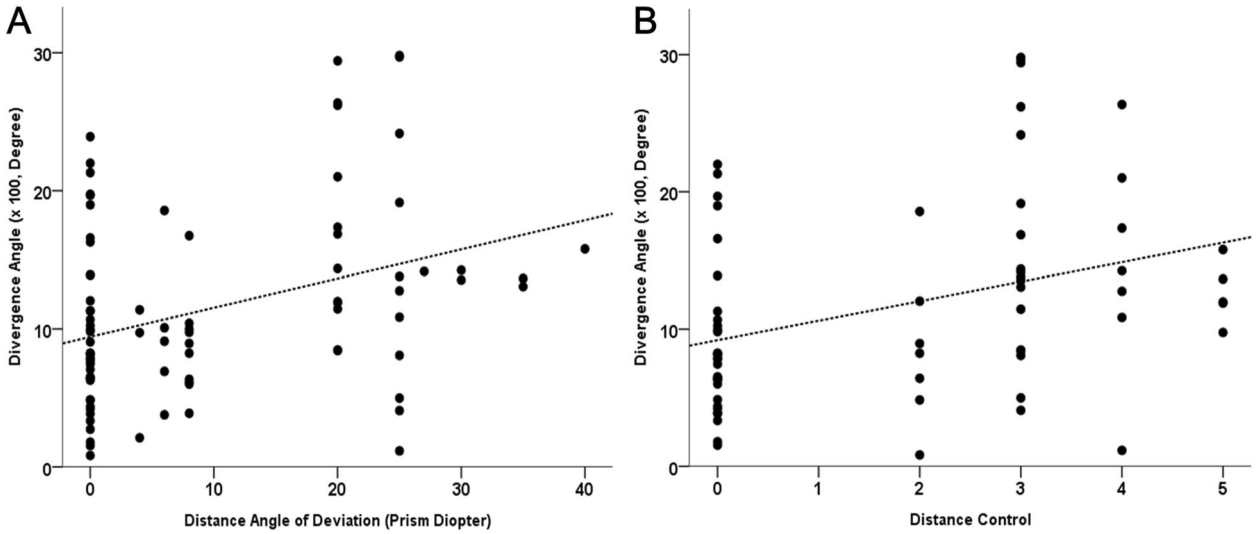

Fig. 2 The magnitude of divergence during binocular distance viewing in a virtual reality environment according to the distance angle of deviation and distance control. Scatterplots for the linear regression model showing a positive correlation between distance divergence angle measured in this system and **a** distant angle of deviation ($r = 0.350$, $p = 0.001$), and **b** distance control ($r = 0.349$, $p = 0.004$).

Table 2 Block-building performance in patients with intermittent exotropia and normal controls.

	Intermittent exotropia		*P* value[a]	Control ($n = 37$)	*P* value[b]	*P* value[c]
	Pre-op ($n = 39$)	Post-op ($n = 35$)				
Horizontal distance disparity (mm)	85.5 ± 8.7	42.8 ± 4.7	<0.001	40.8 ± 8.9	<0.001	0.984
Vertical distance disparity (mm)	85.7 ± 11.8	52.4 ± 4.8	0.057	59.4 ± 4.1	0.039	0.794
3-D distance disparity (mm)	131.5 ± 13.7	73.5 ± 5.5	0.004	79.3 ± 5.3	<0.001	0.786
Execution time (sec)	146.0 ± 12.5	134.9 ± 14.2	0.651	117.2 ± 4.8	0.093	0.381

3-D 3-dimensional.

[a]Paired *t*-test between preoperative and post-operative performances in the patients with intermittent exotropia.

[b]Independent *t*-test between preoperative performances in the patients with intermittent exotropia and at baseline performances in normal controls.

[c]Independent *t*-test between postoperative performances in the patients with intermittent exotropia and at baseline performances in normal controls.

disparity with the preoperative clinical characteristics. Regression analysis revealed that the preoperative horizontal distance disparity in the block-building task was significantly correlated with distance angle of deviation and near angle of deviation ($r = 0.383$, $p = 0.037$ for distance angle; $r = 0.410$, $p = 0.024$ for near angle), where the greater was the angle of exodeviation, the larger was the horizontal distance disparity. However, the preoperative horizontal distance disparity did not show significant correlation with age, distance control, near stereoacuity, presence of suppression, or spherical equivalent.

Discussion

In the present study, we found that children aged 6–12 years with IXT showed more divergence during binocular distance viewing and demonstrated poorer performance in the block-building task in a VR environment than did normal controls. In addition, we revealed a significant correlation between horizontal distance disparity in the block-building task and angle of deviation in the patients with IXT, and this disparity improved following a successful surgical intervention for IXT. This VR-based block-building performance test would be a useful means of evaluating visuomotor skills in children with IXT.

No published studies address eye movements of IXT under an immersive HMD, and no studies have determined whether or not IXT manifests in a VR environment. However, it is known that IXT is seen mainly during distance fixation, and manifestation of exotropia in IXT seems to occur through excessive divergence tone, a pathological eye movement that differs from normal fusional divergence [14]. In addition, some patients with IXT showed a reduced

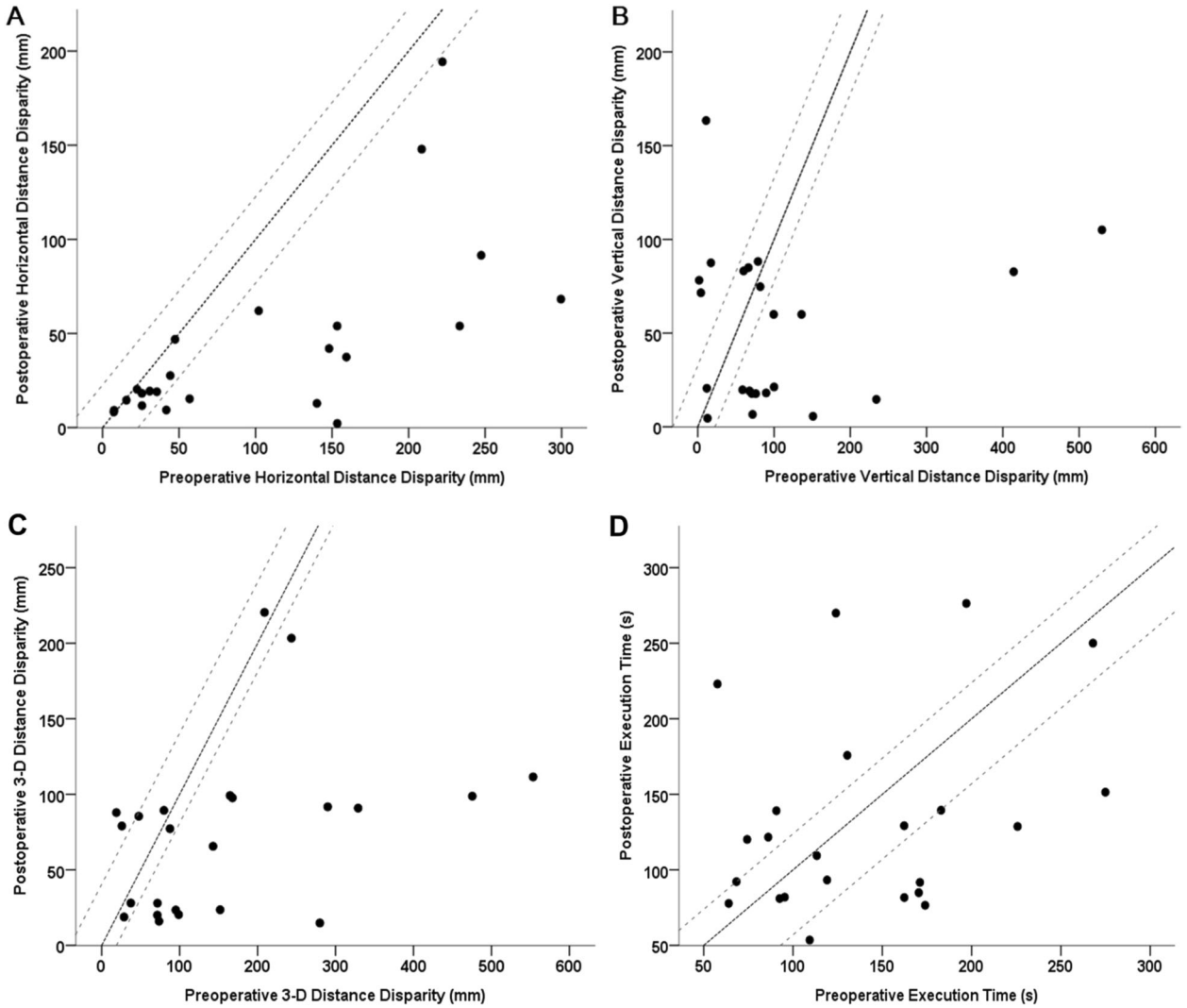

Fig. 3 Changes in the performance of block-building preoperatively vs post-operatively in the patients with intermittent exotropia. Scatterplot representations for **a** horizontal, **b** vertical, and **c** 3-dimensional (3-D) distance disparities, and **d** execution time. The dashed lines on either side of the unity line indicate 95% confidence intervals for change (test–retest variability) from the normal controls. Datapoints falling above the dashed line represent a change in the performance that exceeded test–retest variability. s second.

amplitude in distance fusional divergence [15]. Therefore, we evaluated eye movements in children with IXT when they were viewing targets moving away from them within a VR environment. We found more distance divergence in patients with IXT compared with normal children. This finding might not represent the exact manifestation of IXT, although it could be a demonstration of poor distance fusional divergence of IXT. It has also been reported that poor fusional divergence relates to a poor control score of exotropia [15]. In the present study, the magnitude of distance divergence in IXT was positively-correlated with angle of deviation and distance control, consistent with the previous report. In addition, it could be associated with some part of monocular viewing. It has been reported that monocular viewing and slower smartphone reading speed is more prominent in patients with IXT than in normal controls [10]. In the present study, no patient complained of diplopia or dizziness during the first test session despite the large distance divergence over the fusional divergence break point. Therefore, it is possible that some patients with IXT used only one eye to avoid diplopia. Immersive HMD, which we used in this study, may cause fatigue and asthenopia due to the limited field of view, low resolution, and mismatch between convergence and accommodation [16]. Based on this finding, it is possible that patients with IXT may feel more uncomfortable in the HMD using the pupil-tracking system. Further research is required to investigate the impacts of IXT on VR-related eye conditions.

We found that children with IXT showed larger distance disparities in a VR-based block-building performance task compared with the visually normal children. After surgery, all children with IXT showed improvement in horizontal

distance disparity, and more than half showed improvement above test–retest levels determined in normal controls. Our finding supports the detrimental influence of IXT on visuo-motor skills, hand-eye coordination skills, and the performance of fine motor skills. There are no published studies that evaluate visuo-motor skills or fine motor skills in children with IXT. However, some amblyopia studies demonstrated fine motor skill deficits in children with amblyopia compared with controls [17]; motor performance deficits were greatest in strabismic amblyopia. Furthermore, Webber et al. [18] reported that binocular amblyopia treatment improved fine motor skills in children with residual amblyopia. In their study, the improvement of visual acuity was not outside the test–retest levels, but there was a significant improvement in the fine motor skills score. They suggested the differences in improvement between visual acuity and fine motor skills may be due to different developmental periods; hand–eye coordination skills are normally developed until around 12 years of age, beyond the critical period for amblyopia (infancy) [19]. We included children aged 6–12 years who were usually considered to have passed the critical period of binocular vision development. The longer period to develop the visuo-motor skills may be a possible explanation for performance improvement in a VR-based block-building task in children who have reached a relatively old age for restoring binocular vision. It provides further evidence that there may be functional benefits to IXT surgery beyond improved binocular summation and psychosocial concerns in older children [3].

Block-building performance may improve with age or practice. However, it is unlikely that performance would improve spontaneously to the degree that we found over the short duration of the study; the improvement seen in the IXT group is unlikely to be due to practice effects because the performance abilities were stable between baseline and the 3-month time point in normal controls. It most probably reflects a real therapeutic effect.

Among measures of block-building performance, we found the most significant differences in horizontal distance disparity between IXT and control groups and between preoperative and postoperative timepoints. It could be related to the fact that the horizontal disparity of images is mainly required for stereopsis [20]. On the other hand, execution time did not significantly differ between groups. Some patients with amblyopia adopted slowed response times to allow for greater opportunity for visual feedback during the task [17]. However, we evaluated only five cubes in the performance test, so there was less opportunity for compensatory slowing of response times. Although horizontal distance disparity had a strong correlation with angle of distance, it did not show correlation with age, control of exotropia, near stereoacuity, or refractive errors. It could be attributed to the fact that control can vary considerably with time, and near stereoacuity is usually normal and stable in patients with IXT [2, 4, 21]. Therefore, we suggested that horizontal distance disparity in the block-building test may be a more sensitive clinical measure of visuo-motor skills and depth perception in the patients with IXT. Further assessment of the relationship between this horizontal disparity and other aspects of binocular function would be beneficial to fully explore the relationship between binocular vision and functional performance in the patients with IXT.

Our study has several limitations. Although we were able to monitor eye and hand movements in real time, which is a strength of the immersive VR HMD, hand movements displayed virtually may not match real-world hand movements in time and space due to the delay in delivery and perception of the virtual image [22]. Thus, the performance would be better in the real-world where there is less dissociation. Second, the eye movement tracking during block-building performance was too noisy to analyse. Despite alternate cover stimulation to break fusion prior to the test, we were not sure whether exodeviation was manifested or not. Third, an additional assessment of visuo-motor skills using alternative methods may be needed to verify this VR-based block-building performance test. Fourth, we did not measure distance stereoacuity, which may be more sensitive than near stereoacuity for evaluating sensory aspects of IXT [23]. In addition, our results are not generalisable to all IXT patients because we enrolled patients with only basic-type IXT with moderate angle and evaluated only 3 months after surgery. It is possible that by including convergence insufficiency-type IXT and long-term postoperative follow-up, different results would be obtained.

Despite the limitations, to our knowledge, this is the first attempt to test one of the everyday visuomotor tasks in a VR environment using HMD in children with IXT. Our preliminary findings, that is, poorer performance in the block-building task improved postoperatively and was positively correlated with angle of deviation, suggest that this VR-based block-building testing may be a useful method to assess visuomotor skills in children with IXT.

Summary

What was known before

- It is still not well known how intermittent exotropia affects everyday tasks of the patients, particularly children.
- Block-building is a typical activity requiring three-dimensional (3-D) spatial perception.
- Virtual reality systems typically offer a stereo image by presenting an image separately to each eye. No published

studies address visuo-motor skills of intermittent exotropia under a 3-D virtual environment where a large dissociation between both eyes occurs.

What this study adds

- In a virtual reality environment, children with intermittent exotropia displayed larger distance divergence and poorer performance in block building tasks compared with normal children.
- The poorer performance in the block-building task improved postoperatively and was positively correlated with angle of deviation, suggesting that this VR-based block-building testing may be a useful method to assess visuomotor skills in children with intermittent exotropia.

Funding This work was supported by the National Research Foundation of Korea grant funded by the Korea government (2017R1C1B5017453 and partially 2018R1C1B6003869).

Author contributions Design of the study: SAC, JC, and JK. Conduct of the study: SAC, JC, and SJ. Collection and management of data: SAC, JC, and SJ. Analysis and interpretation of data: SAC and JK. Preparation, review, or approval of the manuscript: SAC, JC, and JK.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval This study was conducted in accordance with the tenets of the Declaration of Helsinki; the research protocol was approved by the Institutional Review Board of Ajou University School of Medicine, Suwon, South Korea (AJIRB-MED-OBS-17–331).

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