

Effects of a 12-Week Home-Based Eye Movement Training Program on Visual Function in School-Aged Children: A Randomized Controlled Trial

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Abstract

Evidence regarding the effects of home-based eye-movement training (ET) on visual function in children remains limited. This randomized controlled trial examined the effects of a 12-week ET program in 68 community-dwelling school-aged children assigned to intervention or control groups. Sixty-seven children were included in the analysis (intervention, $n = 34$; control, $n = 33$). The primary outcome was eye–hand coordination (EHC); secondary outcomes included horizontal moving digit identification (HDI), visuospatial working memory (VWM), and visual attention (VA). Changes were compared using analysis of covariance adjusted for baseline value, age, and gender. No significant intervention effect was observed for EHC ($\beta = 1.190$, $p = 0.117$). In contrast, improvement in VWM was significantly greater in the intervention group ($\beta = 1.673$, 95% CI 0.379–2.968, $p = 0.012$). No significant adjusted between-group differences were observed for HDI or VA. Older age was associated with greater improvements in all visual function measures, whereas lower baseline values were associated with greater improvements in HDI, VWM, and VA. These findings suggest that 12-week home-based ET may improve VWM but not EHC and that age and initial performance should be considered when evaluating visual function interventions in children. Trial registration: jRCT1032250379.

Introduction

Visual information plays an important role in daily life, learning, and sports activities. The ability to accurately and rapidly process visual information obtained from the external environment and translate it into appropriate motor responses is also crucial for childhood development. Studies involving children have reported associations between visual function and academic achievement, suggesting that the development of visual information-processing abilities may influence learning activities ¹. Furthermore, a systematic review of sports vision reported that visual function is an important component of athletic performance ². Eye movements are one of the components underlying visual function. They provide a fundamental mechanism for efficiently acquiring visual information and maintaining appropriate visual input and include saccadic and smooth-pursuit eye movements ³. Saccadic eye movements rapidly shift the gaze from one location to another, whereas smooth-pursuit eye movements enable the eyes to track a moving target smoothly (REF3). Recent studies have suggested that eye movements are not merely involved in gaze shifts but are also associated with cognitive functions such as visual attention and working memory ⁴.

Against this background, eye movement training (ET), which aims to improve oculomotor function, has attracted increasing attention. Regarding the trainability of oculomotor function, a study involving participants with poor saccadic performance reported that short-term ET improved saccadic accuracy ⁵. This finding suggests that oculomotor function can be improved through appropriate training. In recent years, visual training incorporating eye movement tasks has been used to enhance athletic performance and as a rehabilitation approach for patients with vestibular disorders ^{6,7}. However, most previous studies have focused on adults, competitive athletes, or patients with neurological or vestibular

disorders. To the best of our knowledge, no randomized controlled trial has examined the effects of ET in healthy, community-dwelling children. Clarifying the fundamental effects of ET in healthy children is important for understanding its influence on visual function during development and for evaluating its effectiveness in pediatric populations. Therefore, as a preliminary study, we conducted a single-group intervention study involving 24 weeks of home-based ET in community-dwelling children⁸. The study demonstrated high adherence and training frequency, supporting the feasibility of the program. Improvements in eye–hand coordination were also observed, and the magnitude of improvement was associated with training frequency. However, because the study employed a single-group design without a control group, the potential effects of natural development and learning could not be adequately excluded, precluding definitive conclusions regarding the effectiveness of ET.

Various measures have been used to assess visual functions associated with eye movements. Eye–hand coordination (EHC) involves the integration of visual perception with motor coordination⁹, whereas horizontal moving digit identification (HDI) measures the ability to identify moving visual stimuli. The ability to identify moving targets has traditionally been examined within the framework of dynamic visual acuity (DVA), which refers to the ability to identify targets moving horizontally or vertically while remaining at a constant distance from the observer¹⁰. In addition, visuospatial working memory (VWM) is a cognitive function that supports eye movements and visual search by maintaining and manipulating visual features and spatial locations¹¹, whereas visual attention (VA) reflects the ability to selectively process relevant visual stimuli¹². These four measures assess distinct aspects of visual information processing associated with eye movements. Therefore, combining these measures is important for comprehensively evaluating the effects of ET. Therefore, this randomized controlled trial aimed to examine the effects of a 12-week home-based ET program on EHC, HDI, VWM, and VA in community-dwelling school-aged children. Furthermore, because eye movements have been reported to be associated with postural control and motor performance¹³, balance ability and jumping performance—important indicators of physical fitness during childhood—were included as secondary outcomes in addition to the primary visual function outcomes, and the effects of ET on these measures were also examined.

Results

Participants were recruited through a local community newsletter between October 2025 and February 2026. Although the recruitment target was 70 participants, 68 eligible children were ultimately enrolled in the study. Following eligibility assessment, all 68 participants were randomly allocated in a 1:1 ratio to either the intervention group (IN group, n = 34) or the control group (CO group, n = 34). During the intervention period, one participant in the CO group did not attend the 12-week assessment and was therefore not included in the complete-case analysis. Consequently, 67 participants were included in the final analysis (IN group, n = 34; CO group, n = 33), corresponding to a follow-up rate of 98.5% (67/68) (Fig. 1).

No adverse events were reported during the intervention period. Participants in the IN group completed the 12-week ET program. The mean cumulative video viewing time was 6.4 ± 3.4 h, corresponding to a mean training frequency of 6.4 ± 3.1 sessions per week. A total of 34 automated alert emails were sent during the intervention period (Table 1).

Table 1

Adherence to the exercise program and distribution of exercise timing in the intervention group

Total video playback time (hour)	IN <i>n</i> = 34	P
	6.4 ± 3.4	-
Weekly Frequency (times / week)	6.4 ± 3.1	-
Alerts (total), n	34	-
Playback time slots		
Late night (0–3AM), (%)	0 (0, 0)	< 0.001
Early morning (3–6 AM), (%)	0 (0, 0)	
Morning (6–9 AM), (%)	6 (1, 27)	
Late morning (9 AM–12 PM), (%)	4 (2, 7)	
Early afternoon (12–3 PM), (%)	3 (0, 5)	
Late afternoon (3–6 PM), (%)	5 (1, 14)	
Evening (6–9 PM), (%)	34 (20, 49) ^a	
Night (9 PM-12 AM), (%)	25 (10, 47) ^b	
The overall difference among time periods was assessed using the Friedman test. Post hoc pairwise comparisons were performed using the Wilcoxon signed-rank test with Holm adjustment.		
⊠; Significantly higher than the late-night, early-morning, morning, late-morning, early-afternoon, and late-afternoon periods (all adjusted <i>p</i> < 0.01).		
⊠; Significantly higher than the late-night, early-morning, late-morning, early-afternoon, and late-afternoon periods (all adjusted <i>p</i> < 0.01).		
Data are presented as the mean ± SD or median (25th, 75th). IN, Intervention group; CO, Control group; SD, standard deviation		

The Friedman test revealed a significant difference in the proportion of total video playback time across time periods ($\chi^2 = 130.125$, $p < 0.001$). Holm-adjusted post hoc Wilcoxon signed-rank tests showed that the proportion recorded during the evening period (6–9 PM) was significantly higher than during all earlier periods (12 AM–6 PM; all adjusted $p < 0.01$), but did not differ from that recorded during the night period (9 PM–12 AM; adjusted $p = 0.417$). The proportion recorded during the night period was significantly higher than during all other periods except the morning (6–9 AM) and evening periods (all

adjusted $p < 0.01$ for significant comparisons). Overall, video playback time was concentrated primarily in the evening and night periods (6 PM–12 AM) (Table 1).

Table 2 presents the baseline characteristics of the participants. No significant differences were observed between the IN group ($n = 34$) and the CO group ($n = 33$) in age, gender, height, body weight, or body mass index (BMI). The distribution of sports participation was also broadly similar between the two groups. At baseline, no significant between-group differences were observed in any of the visual function measures, including EHC, HDI, VWM, and VA. Similarly, there were no significant between-group differences in balance ability, as assessed by the modified index of postural stability and one-leg standing time with eyes closed, or in grip strength or jumping performance.

Table 2
Participant characteristics

Age (year)	IN <i>n</i> = 34	CO <i>n</i> = 33	P
	10 (9, 12)	10 (9, 12)	0.438
Female gender, <i>n</i> (%)	14 (41.2)	15 (45.5)	0.731
Height (m)	1.41 ± 0.12	1.42 ± 0.13	0.593
Body weight (kg)	31.0 (25.3, 42.8)	35.8 (29.0, 45.0)	0.151
Body mass index (kg/m ²)	16.7 ± 2.6	17.9 ± 2.4	0.060
Exercise habits			
Swimming	13	14	-
Soccer	6	7	-
Gymnastics	5	6	-
Basketball	6	4	-
Tennis	2	5	-
Dance	4	2	-
Judo	4	0	-
Kendo	2	2	-
Karate	2	2	-
Volleyball	2	1	-
Boxing	2	0	-
Ballet	2	0	-
Rhythmic Gymnastics	0	2	-
Baseball	1	1	-
Track and Field	2	0	-
Other	5	3	-
Data are presented as the mean ± SD or median (25th, 75th). IN, Intervention group; CO, Control group; EHC, eye-hand coordination; HDI, horizontal moving digit identification; VWM, Visuospatial working memory; VA, Visual attention; OLS, One leg standing; SD, standard deviation			
Continuous variables were compared using an independent-samples t-test or Mann–Whitney U test, as appropriate according to data distribution. Gender was compared using the χ^2 test.			

Age (year)	IN <i>n</i> = 34	CO <i>n</i> = 33	P
	10 (9, 12)	10 (9, 12)	0.438
No sports participation	4	5	-
Visual function			
EHC (point)	34.8 ± 5.4	35.1 ± 5.4	0.790
HDI (point)	12.3 ± 4.2	12.9 ± 3.5	0.560
VWM (point)	16.2 ± 4.0	16.4 ± 3.2	0.990
VA (point)	6 (4, 8)	7 (5, 8)	0.416
Balance capability			
Modified index of postural stability	0.63 ± 0.28	0.70 ± 0.26	0.326
OLS with eyes closed (s)	20 (12, 50)	15 (9, 33)	0.093
Grip strength (kgf)	17.0 ± 6.1	18.2 ± 8.3	0.807
Jump strength (cm)	33.9 ± 7.9	36.0 ± 8.1	0.337
Data are presented as the mean ± SD or median (25th, 75th). IN, Intervention group; CO, Control group; EHC, eye-hand coordination; HDI, horizontal moving digit identification; VWM, Visuospatial working memory; VA, Visual attention; OLS, One leg standing; SD, standard deviation			
Continuous variables were compared using an independent-samples t-test or Mann–Whitney U test, as appropriate according to data distribution. Gender was compared using the χ^2 test.			

Table 3 presents the within-group pre–post comparisons for each outcome and the between-group comparisons of changes over the 12-week period. Regarding visual function, EHC improved significantly in both the IN and CO groups (both $p < 0.001$); however, the between-group difference assessed using analysis of covariance (ANCOVA) adjusted for baseline value, age, and gender was not significant ($\beta = 1.190$, 95% CI: -0.304 to 2.684 , $p = 0.117$). HDI also improved significantly in both groups (IN group: $p = 0.034$; CO group: $p = 0.004$), but no significant adjusted between-group difference was observed ($\beta = -0.383$, 95% CI: -1.929 to 1.163 , $p = 0.622$). Similarly, VA improved significantly in both groups (IN group: $p < 0.001$; CO group: $p = 0.019$), whereas the adjusted between-group difference was not significant ($\beta = 0.052$, 95% CI: -0.194 to 0.298 , $p = 0.675$). In contrast, VWM improved significantly from baseline in the IN group ($p = 0.002$), whereas no significant change was observed in the CO group ($p = 0.073$). The adjusted change in VWM was significantly greater in the IN group than in the CO group ($\beta = 1.673$, 95% CI: 0.379 to 2.968 , $p = 0.012$). Regarding basic physical function, no significant within-group pre–post changes or adjusted between-group differences were observed in mIPS, OLS, grip strength, or jumping performance.

Table 3

Changes in outcome measures from baseline to 12 weeks and adjusted between-group differences

Visual function	Group	Baseline	12 Weeks	P for time	Change between Baseline and 12 Weeks	Adjusted β (95% CI) *	P for ANCOVA*
EHC (point)	IN	34.8 $\pm$ 5.4	38.3 $\pm$ 6.7	< 0.001	3.6 $\pm$ 3.3	1.190	0.117
	CO	35.1 $\pm$ 5.4	37.7 $\pm$ 5.4	< 0.001	2.6 $\pm$ 2.8	(-0.304, 2.684)	
HDI (point)	IN	12.3 $\pm$ 4.2	13.8 $\pm$ 4.3	0.034	1.4 $\pm$ 4.0	-0.383	0.622
	CO	12.9 $\pm$ 3.5	14.6 $\pm$ 3.3	0.004	1.7 $\pm$ 3.1	(-1.929, 1.163)	
VWM (point)	IN	16.2 $\pm$ 4.0	18.2 $\pm$ 3.4	0.002	2.0 $\pm$ 3.3	1.673	0.012
	CO	16.4 $\pm$ 3.2	16.9 $\pm$ 3.3	0.073	0.6 $\pm$ 3.9	(0.379, 2.968)	
VA (point)	IN	6 (4, 8)	7 (5, 10)	< 0.001	1 (0, 2)	0.052	0.675
	CO	7 (5, 8)	7 (6, 10)	0.019	1 (-1, 3)	(-0.194, 0.298)	
Balance capability							
Modified index of postural stability	IN	0.63 $\pm$ 0.28	0.63 $\pm$ 0.27	0.860	0.02 $\pm$ 0.18	0.020	0.595
	CO	0.70 $\pm$ 0.26	0.70 $\pm$ 0.23	0.485	-0.02 $\pm$ 0.15	(-0.055, 0.095)	
OLS with eyes closed (s)	IN	20 (12, 50)	22 (15, 57)	0.473	0 (-3, 6)	-0.075	0.611
Data are presented as the mean $\pm$ SD or median (25th, 75th). IN, Intervention group; CO, Control group; EHC, eye-hand coordination; HDI, horizontal moving digit identification; VWM, Visuospatial working memory; VA, Visual attention; OLS, One leg standing; CI, confidence interval; ANCOVA, Analysis of covariance; SD, standard deviation							
*; Adjusted β coefficients (95% CI) and p-values were estimated using ANCOVA, with the change score as the dependent variable and group, baseline value, age, and gender as independent variables. For outcomes with non-normally distributed change scores, rank-transformed data were used in the ANCOVA.							

Visual function	Group	Baseline	12 Weeks	P for time	Change between Baseline and 12 Weeks	Adjusted β (95% CI) *	P for ANCOVA*
	CO	15 (9, 33)	18 (10, 43)	0.060	2 (-1, 10)		
Grip strength (kgf)	IN	17.0 $\pm$ 6.1	17.2 $\pm$ 6.2	0.961	0.2 $\pm$ 2.8	-0.804 (-2.116, 0.507)	0.225
	CO	18.2 $\pm$ 8.3	19.2 $\pm$ 8.5	0.119	1.0 $\pm$ 3.0		
Jump strength (cm)	IN	33.9 $\pm$ 7.9	34.0 $\pm$ 7.8	0.853	0.1 $\pm$ 4.7	1.213 (-1.000, 3.426)	0.278
	CO	36.0 $\pm$ 8.1	34.3 $\pm$ 7.8	0.103	-1.7 $\pm$ 5.5		
Data are presented as the mean $\pm$ SD or median (25th, 75th). IN, Intervention group; CO, Control group; EHC, eye-hand coordination; HDI, horizontal moving digit identification; VWM, Visuospatial working memory; VA, Visual attention; OLS, One leg standing; CI, confidence interval; ANCOVA, Analysis of covariance; SD, standard deviation							
*; Adjusted β coefficients (95% CI) and p-values were estimated using ANCOVA, with the change score as the dependent variable and group, baseline value, age, and gender as independent variables. For outcomes with non-normally distributed change scores, rank-transformed data were used in the ANCOVA.							

Supplementary Table 1 presents the results of the ANCOVA and interaction analyses for changes in visual function. In the primary ANCOVA models, age at baseline was significantly associated with changes in EHC ($\beta = 0.654$, $p = 0.016$), HDI ($\beta = 0.519$, $p = 0.024$), VWM ($\beta = 0.844$, $p < 0.001$), and VA ($\beta = 0.641$, $p < 0.001$), indicating that older children showed greater improvements. Baseline values were negatively associated with changes in HDI ($\beta = -0.574$, $p < 0.001$), VWM ($\beta = -0.749$, $p < 0.001$), and VA ($\beta = -0.721$, $p < 0.001$), indicating that children with lower baseline values showed greater improvements. In the exploratory interaction analyses, a significant group $\times$ gender interaction was observed for EHC ($\beta = 3.032$, 95% CI: 0.103 to 5.961, $p = 0.043$). In contrast, none of the group $\times$ baseline value, group $\times$ age, or group $\times$ gender interactions were significant for HDI, VWM, or VA.

Discussion

The effects of ET have previously been investigated in adults, competitive athletes, and patients with neurological or vestibular disorders⁵⁻⁷. In contrast, few medium- to long-term intervention studies have been conducted in children. One possible reason is the methodological difficulty of objectively recording and monitoring training participation during long-term home-based interventions, which makes it challenging to adequately assess intervention adherence. Therefore, the present study examined the

effects of a 12-week ET program in children using SUKUBARA®, a remotely monitored home-based exercise system capable of recording and managing training participation in real time. A key feature of this study was that the effectiveness of ET was evaluated in an environment that enabled objective monitoring and management of intervention adherence.

In the present study, recruitment through a local community newsletter enabled us to enroll nearly the target number of participants. We also achieved a high follow-up rate of 98.5% and high adherence throughout the 12-week intervention, with participants completing an average of 6.4 training sessions per week. Moreover, no adverse events were reported, supporting the safety of the program. These findings suggest that the remotely monitored home-based exercise system used in this study may provide a useful research platform for implementing and evaluating long-term home-based ET in children while maintaining high adherence. The participants in this study were community-dwelling children, and no significant between-group differences were observed at baseline in demographic characteristics, visual function, or physical performance. Moreover, most participants regularly engaged in sports activities; therefore, the present findings were obtained from community-dwelling children with established physical activity habits.

After accounting for age, gender, and baseline values, no significant intervention effects of ET were observed for EHC, HDI, or VA. In contrast, a significant intervention effect was observed for VWM, suggesting that ET may contribute to improvements in VWM during childhood. Furthermore, after adjustment for intervention group and other covariates, age at baseline was positively associated with changes in all visual function measures, indicating that older children showed greater improvements. In contrast, lower baseline values were associated with greater improvements in HDI, VWM, and VA. These findings suggest that changes in visual function may be associated with developmental stage and initial performance. In the exploratory analyses incorporating interaction terms with group, a significant group $\times$ gender interaction was observed for EHC, suggesting that the effect of ET may differ by gender, with girls potentially showing greater intervention-related improvement than boys.

The present study found no significant intervention effect on EHC, the primary outcome. Although a previous study reported improved EHC following a 24-week ET intervention⁸, EHC improved similarly in both the intervention and control groups in the present study, with no significant between-group difference. These findings suggest that the improvement in EHC observed in both groups may partly reflect natural development during childhood and familiarization with the assessment task. A longitudinal study of children aged 8–16 years showed that EHC improved from childhood to mid-adolescence and that its developmental trajectory varied according to task difficulty¹⁴. However, no clear intervention effect on EHC was observed in the present study. One possible explanation is that EHC is a complex ability involving not only eye movements but also visual information processing, response selection, upper-limb motor control, and the integration of these processes¹⁵. Therefore, the eye-movement-focused ET used in this study may not have provided sufficient stimulation to improve all components underlying EHC.

In contrast, the present study demonstrated a significant intervention effect on VWM. One possible explanation for the selective effect on VWM is that ET repeatedly engaged cognitive processes involved in VWM. Van der Stigchel and Hollingworth proposed that VWM is a fundamental component of the eye-movement system and is involved in target selection during gaze shifts, the retention of visual information, postsaccadic correspondence, and gaze correction¹¹. Therefore, the ET used in the present study, which included saccadic and smooth-pursuit eye movements, may have repeatedly activated cognitive processes related to the maintenance and updating of visuospatial information and gaze control, thereby contributing to the improvement in VWM. This interpretation is further supported by evidence that eye movements themselves require working-memory resources. Van Veen et al. reported that an eye-movement condition imposed a greater working-memory load than fixation and eyes-closed conditions, suggesting that eye movements are not merely shifts in gaze but cognitively demanding tasks involving the processing of changing visual input and continuous motor control¹⁶. Taken together, the 12-week ET program may have provided repeated opportunities to engage cognitive processes underlying VWM, thereby contributing to its improvement. Furthermore, exploratory analyses revealed no significant interactions of group with age, gender, or baseline value, suggesting that the beneficial effect of ET on VWM was relatively consistent across these participant characteristics.

No significant intervention effects were observed for HDI or VA. One possible explanation is a mismatch between the characteristics of the ET tasks used in this study and the functions required by these measures. HDI reflects the ability to perceive moving visual stimuli¹⁰, whereas VA reflects the ability to selectively process relevant visual stimuli¹². In contrast, the ET program implemented in this study primarily consisted of eye-movement exercises involving saccades, smooth pursuit, and the vestibulo-ocular reflex and did not repeatedly train the discrimination of moving stimuli or selective attention assessed by HDI and VA. Neuroplasticity is task-specific, and training-induced adaptations are considered to depend on the nature of the tasks experienced¹⁷. Therefore, improvements in HDI and VA may require more task-specific training that incorporates repeated practice of moving-stimulus discrimination and selective attention in addition to eye-movement exercises.

After adjustment for intervention group and other covariates, age at baseline was positively associated with changes in all visual function measures—EHC, HDI, VWM, and VA—with older children showing greater improvements over the 12-week period. This consistent pattern may reflect age-related differences in the developmental stage of visual function during childhood. Regarding EHC, Wicks et al. reported that its developmental trajectory varies according to task difficulty and that the period of greatest improvement may occur at an older age for more complex tasks¹⁴. The EHC task used in the present study was complex, requiring the integration of visual stimulus detection, decision-making, and hand motor responses. Thus, the association between age and changes in EHC may partly reflect developmental differences related to task complexity.

Kohmura et al. examined DVA in children aged 8–17 years and reported better performance in older children¹⁸. In the present study, age at baseline was positively associated with improvement in HDI over

the 12-week period after adjustment for baseline HDI and other covariates. Although the previous findings provide developmental context for this association, the cross-sectional study assessed age-related differences in performance rather than short-term changes. Moreover, DVA was assessed using Landolt rings in that study, whereas HDI in the present study required the identification of moving numbers. Therefore, caution is warranted when comparing the findings obtained using these different assessment tasks.

Isbell et al. reported that VWM capacity continues to develop throughout adolescence and does not reach adult levels even by the age of 16 years¹⁹. Vuontela et al. demonstrated that VWM accuracy and response speed improve with age in children aged 6–13 years and suggested that these improvements may be associated with the maturation of cognitive control functions, particularly those involving the prefrontal cortex²⁰. These findings provide developmental context for the positive association between age at baseline and changes in VWM observed in the present study. More mature cognitive control in older children may support the efficient maintenance and updating of visuospatial information and response inhibition, potentially facilitating improvement over the 12-week study period. However, the previous studies examined age-related differences in VWM performance rather than short-term changes; therefore, the mechanisms underlying the observed association between age and VWM improvement require further investigation.

Coetzee et al. followed children from approximately 7 to 10 years of age over a 3-year period and reported age-related improvements in visual perception, which is relevant to the processing of visual information required for VA²¹. However, that study did not assess VA itself or demonstrate that older children exhibit greater improvements over a short period. Therefore, the positive association between age at baseline and changes in VA observed in the present study may reflect differences in the developmental stage of visual-perceptual and attention-related functions, although the underlying mechanisms require further investigation. The absence of a significant group × age interaction suggests that this association represented a general pattern of change rather than an age-dependent effect of ET.

The exploratory group × gender interaction observed for EHC suggests that girls may have shown greater intervention-related improvement over the 12-week period than boys. EHC is a complex ability requiring the rapid detection of randomly presented visual targets, selection of an appropriate response, and quick and accurate execution of upper-limb movements. Thus, EHC performance depends not only on eye movements but also on visual information-processing speed, response selection, and motor control. Roivainen reported that female participants outperformed male participants on processing-speed and rapid-naming tasks involving numbers and letters and that performance on these tasks may become increasingly automatic through training and repetition²². Although these tasks differ from EHC, gender-related differences in processing speed and task automatization may have partly contributed to the greater improvement observed in girls. However, because the interaction analysis was exploratory and the underlying mechanism was not directly examined, this finding should be interpreted cautiously and confirmed in adequately powered studies.

For HDI, VWM, and VA, lower baseline values were consistently associated with greater improvements over the 12-week period after adjustment for intervention group, age, and gender. This pattern may indicate that children with lower initial performance had greater room for improvement. Previous studies have shown that VWM continues to develop throughout childhood and into adolescence²³, providing developmental context for the observed improvement among children with lower initial performance. However, these studies did not directly examine whether baseline performance predicts short-term changes. Moreover, regression to the mean²⁴ and the mathematical coupling between baseline values and change scores should be considered when interpreting these associations. No significant group × baseline value interactions were observed, providing no evidence that the effect of ET differed according to baseline performance.

In the present study, ET was performed predominantly from the late afternoon until bedtime. Because children generally spend weekday daytime hours at school or participating in extracurricular activities, home-based ET was likely to be performed after they returned home. This finding suggests that the video-based delivery system used in this study was acceptable as a home-based intervention compatible with the daily routines of both children and their parents. In addition, because the system automatically recorded video playback times, it enabled objective assessment not only of intervention adherence but also of the time of day at which training was performed. Such information may help optimize future intervention programs and reminder functions according to children's daily routines.

Limitations

This study has several limitations. First, the influence of potential confounding factors during the study period could not be completely excluded. Although participation in sports was recorded, the frequency, intensity, and duration of sports activities, as well as overall daily physical activity levels, were not assessed in detail. Therefore, these factors may have influenced changes in visual function over the 12-week period. Second, we were unable to directly verify whether the participants performed the training correctly while watching the videos. Although the system objectively records video playback duration, and a previous study in adults demonstrated a certain degree of validity as an indicator of training frequency²⁵, the participants in the present study were children. Therefore, the extent to which video playback duration reflects actual engagement in eye-movement exercises has not been sufficiently validated in this population. Future studies should examine the validity of video-viewing records as a measure of actual training participation in children. Third, the participants were limited to healthy children living in a single geographic area; therefore, the findings cannot be directly generalized to children from other regions or with different backgrounds. Future multicenter studies should examine more diverse populations, including children with neurological or vestibular disorders and those engaged in competitive sports. Fourth, the intervention period was limited to 12 weeks, and no follow-up assessment was conducted after the intervention. Because a previous pilot study⁸ reported improved EHC following a 24-week intervention, the possibility that longer-term training may produce effects on EHC and HDI, for which no significant intervention effects were observed in the present study, cannot be

excluded. Future studies should examine longer intervention periods and include post-intervention follow-up assessments. Fifth, the ET protocol used in this study may require further optimization. The program consisted of saccadic eye movements, smooth pursuit, and VOR $\times 2$ exercises (vestibulo-ocular reflex training in which the head and target move in opposite directions); however, it did not include VOR $\times 1$ exercises, which involve maintaining fixation on a stationary target while moving the head and are commonly used in vestibular rehabilitation. In addition, the VOR $\times 2$ exercises were performed at a relatively low head velocity of approximately $10^\circ/\text{s}$, and no progressive increase in training load was implemented throughout the intervention period. These protocol characteristics may partly explain the absence of significant intervention effects on EHC, HDI, and VA in the present study. Future studies should optimize the protocol by considering the composition and intensity of the exercises, as well as progressive increases in training load. Sixth, the neural mechanisms underlying the observed intervention effect on VWM were not evaluated. Because brain activity and changes in neural networks were not directly assessed, the underlying mechanisms remain unclear. Future studies should combine ET with neuroimaging and neurophysiological assessments, such as functional magnetic resonance imaging (fMRI) and electroencephalography (EEG), to elucidate the neural mechanisms through which ET affects VWM. Seventh, multiple secondary outcomes and exploratory interaction terms were examined without adjustment for multiple comparisons, and the study was not specifically powered to detect effect modification. Therefore, the intervention effect observed for VWM and the group $\times$ gender interaction observed for EHC should be interpreted as exploratory and confirmed in adequately powered studies.

Conclusions

In this randomized controlled trial involving community-dwelling school-aged children, the 12-week home-based ET program did not produce a significant intervention effect on EHC, the primary outcome. However, improvement in VWM, a secondary outcome, was significantly greater in the intervention group than in the control group after adjustment for baseline value, age, and gender. Older age was associated with greater improvements in all visual function measures, whereas lower baseline values were associated with greater improvements in HDI, VWM, and VA. These findings highlight the importance of considering age and initial performance when evaluating visual function interventions in children.

Methods

Target Children

Children aged 8–15 years living in Tsukuba City were eligible. Exclusion criteria were the need for assistance with ambulation or activities of daily living and physician-imposed restrictions on exercise. These criteria were identical to those used in our previous pilot study⁸. The study purpose and procedures were explained to the children and their parents or guardians, and written informed consent was obtained from the parents or guardians. Unlike the previous study, participants in the present study received a gift voucher worth JPY 2,000 at the initial assessment as compensation for their

participation. The study protocol was approved by the Ethics Committee of the Faculty of Systems and Information Science, University of Tsukuba (approval number: 2025R044; approval date: September 17, 2025). The study was prospectively registered with the Japan Registry of Clinical Trials (jRCT; ID: jRCT1032250379; registration date: September 19, 2025). The individual shown in Supplementary Videos 1A–1D was an adult demonstrator and not a study participant. Written informed consent for participation in the video recordings and for publication of the videos as supplementary material in an online open-access publication was obtained from the demonstrator.

This was a single-center, two-arm, parallel-group randomized controlled trial designed to assess the superiority of ET over usual lifestyle, with a 1:1 allocation ratio. All participating children visited the University of Tsukuba accompanied by a parent or guardian and underwent two assessments: one before and one after the intervention. Participants who did not attend the final assessment were considered dropouts, irrespective of their training participation. The primary outcome was EHC, a measure of visual function. The selection of the primary outcome and the study design were based on the findings of our previous pilot study.⁸ Using the estimated effect size from the pilot study (Cohen's $d = 0.7$), a two-sided significance level of 5%, and a statistical power of 80%, the required sample size was estimated to be 33 participants per group. To account for potential dropouts, the target sample size was set at 35 participants per group, for a total of 70 participants. Outcome assessors were not blinded to group allocation.

Randomization and Allocation Concealment

A computer-generated random allocation sequence was prepared using the RAND function in Microsoft Excel (Microsoft Corporation, Redmond, WA, USA). The allocation list consisted of 34 intervention-group assignments and 34 control-group assignments. A random number was assigned to each group assignment, and the list was sorted according to the generated numbers to produce a random sequence with a 1:1 allocation ratio. Participants were consecutively assigned to the next available group assignment in the sequence according to their order of enrollment. The allocation sequence was generated and implemented by the principal investigator (Y.S.). Because the principal investigator had access to the allocation list, no formal allocation concealment mechanism was used. Participants were not informed of their group assignment until the day of the baseline assessment.

Clinical Data and Laboratory Tests

The primary outcome of this study was the change in eye–hand coordination (EHC), one of the measures of visual function. Secondary outcomes included changes in three other measures of visual function—horizontal moving digit identification (HDI), visuospatial working memory (VWM), and visual attention (VA)—as well as changes in one-leg standing time with eyes closed (OLS), the modified index of postural stability (mIPS), grip strength, and jumping performance. The mIPS and OLS were included because they are considered sensitive quantitative measures of balance ability²⁶. In addition, grip

strength and jumping performance are widely used field-based measures of muscular strength and power in pediatric populations, and previous studies have reported acceptable test–retest reliability and construct validity for these measures^{27,28}. The mIPS was assessed under standing conditions with the eyes closed or on a soft surface. Measurements were performed once using a gravicorder (GP-6000; Anima Corporation, Tokyo, Japan) and a soft surface (rubber mat; AIREX Instruments, AIREX AG, Sarnen, Switzerland)²⁹. During each trial, participants stood barefoot in a standardized posture. The device measured postural sway based on center-of-pressure displacement and automatically calculated the mIPS score. OLS was assessed twice on each leg. The highest value obtained for each leg was averaged and used for analysis, with a maximum measurement time of 60 s under the eyes-closed condition. Grip strength was measured once for each hand using a handgrip dynamometer (ST100 T-1780; Toei Light Corporation, Tokyo, Japan), and the higher value was recorded in kilogram-force (kgf). Jumping performance was assessed using a digital vertical-jump measuring device (Jump-MD; Takei Scientific Instruments Co., Ltd., Tokyo, Japan). The device was attached to the participant's waist using a dedicated rubber belt, and jump height was calculated from the length of cord displacement during the jump. Two trials were performed, and the higher value, expressed in centimeters, was used for analysis. Detailed procedures for assessing balance ability, grip strength, and jumping performance have been reported previously⁸.

Visual Function

The assessment device used in this study was a digital interactive system (Supreme Vision L; Senoh Corporation, Ltd., Chiba, Japan). The device consisted of an elliptical panel measuring 906 mm in height and 1206 mm in width, with 39 LED light buttons arranged on its surface (Figure 2). The height of the panel was adjusted to one of five levels according to each participant's body size. Although the system included eight available programs, only four programs were used in the present study. These programs were originally designed as training tasks; however, they were used as assessment measures in this study. Prior to the formal assessment, each participant completed a brief practice trial under the supervision of a physical therapist to ensure understanding of the instructions and appropriate operation of the device.

EHC program (Eye-hand coordination; EHC)

This task was designed to assess eye–hand coordination by requiring participants to respond to randomly illuminated targets as quickly and accurately as possible (Supplementary Video1 A). When the program started, one of the buttons within Area C (Figure 2) lit up, and the buttons continued to illuminate one by one in a random order. Participants were instructed to press each illuminated button as quickly and accurately as possible using either their left or right hand. Each trial lasted 30 s, and the device recorded the number of correctly pressed buttons (points). Two trials were performed, and the higher score was used as the representative EHC value.

HDI program (Horizontal moving digit identification; HDI)

This task was designed to assess visual attention and information processing speed by requiring participants to identify and respond to horizontally moving digits (Supplementary Video1B). At the beginning of each trial, a target number was displayed at the top of the board. Subsequently, numbers were presented one by one within Area D (Figure 2), moving horizontally from left to right or from right to left at fixed intervals. Participants were instructed to press the button corresponding to the position at which the illuminated number matched the target number displayed at the top of the board. Thus, the task required participants to identify horizontally moving digits while keeping their head stationary. Ten stimuli were presented at each presentation rate, and the number of correct responses (0–10) was recorded. Three presentation rates (0.12, 0.09, and 0.06 s per light) were used, and one trial was performed at each rate. The total number of correct responses across the three rates (maximum score: 30) was used as the HDI score for analysis.

VWM program (Visuospatial working memory; VWM)

This test was designed to assess VWM through a task requiring participants to memorize and reproduce a sequence of illuminated stimuli (Supplementary Video 1C). At the beginning of the task, one location on the panel was randomly selected by the computer and illuminated for 0.7 s. After the light was extinguished, the participant was required to remember and press the corresponding location. Following a correct response, the next trial presented the previous location followed by one additional location, and the participant was required to press the buttons in the order presented. Thereafter, one new location was added in each successive trial, and the participant was required to reproduce the entire sequence in the correct order. The task was terminated immediately if the participant pressed an incorrect location. The test consisted of three patterns: Pattern 1 used Area A (9 locations), Pattern 2 used Area B (23 locations), and Pattern 3 used Area C (39 locations) (Figure 2). For each pattern, the stimuli were presented at 0.7-s intervals, and the maximum sequence length was set at 10 locations. Performance was scored as the number of illuminated locations reproduced in the correct order, with a maximum score of 10 points for each pattern. Participants completed Patterns 1–3 once each in sequence. The sum of the scores across the three patterns (maximum possible score: 30 points) was used as the representative value for analysis.

VA program (Visual attention; VA)

This test was designed to assess VA through a task requiring participants to identify and select numbers in a specified order (Supplementary Video 1D). Participants were required to press, within a specified time limit, the buttons corresponding to the numbers displayed on the panel in the designated numerical sequence. The test consisted of five patterns with different levels of difficulty, determined by the time limit, numerical sequence, whether correctly selected buttons were extinguished, and the illuminated area used—Area B or C (Figure 2). In Pattern 1, participants selected the numbers displayed in Area B in ascending order (1→2→3→...→9→0) within a time limit of 12 s. Correctly selected numbers were extinguished. Pattern 2 used Area C and required participants to complete the same ascending-order task within 10 s. Pattern 3 also used Area C and required completion of the same task within 8 s;

however, correctly selected numbers remained illuminated. Pattern 4 used Area C and required participants to select the numbers in descending order (0→9→8→...→2→1) within 8 s. Correctly selected numbers were extinguished. Pattern 5 used Area C and required completion of the same descending-order task within 7 s, with correctly selected numbers remaining illuminated. Each pattern was performed five times. Performance was scored as the number of trials correctly completed within the time limit for each pattern (0–5 points). The sum of the scores across the five patterns (maximum possible score: 25 points) was used as the representative value for analysis.

Interventions

Eye movement training (ET)

The eye movement training (ET) program was conducted according to the procedures described in our previous pilot study⁸. Briefly, the program consisted of three types of eye-movement exercises: saccadic eye movements, smooth-pursuit eye movements, and vestibulo-ocular reflex (VOR x 2) exercises. Participants performed the exercises while viewing a dedicated instructional video and were instructed to complete the training at least once daily. The only difference from the previous pilot study was the intervention duration. Whereas the pilot study implemented the ET program for 24 weeks, the present study employed a 12-week intervention period. This study adopted a randomized parallel-group design. Participants were randomly assigned to either an intervention group (IN), which performed the ET program, or a control group (CO), which did not receive the intervention. Participants in both groups were instructed to maintain their usual lifestyle habits throughout the study period and to refrain from initiating any new exercise or vision-training programs.

Remote monitoring at-home training system (SUKUBARA ®)

The remote monitoring at-home training system (SUKUBARA®; Advanced Research Initiative for Human High Performance, University of Tsukuba, Tsukuba, Japan) used in the present study was identical to that described in our previous pilot study⁸. Briefly, the system records and manages individual video-viewing status in real time, enabling administrators to remotely monitor training adherence through a dedicated management dashboard. Participants accessed the exercise videos through individually assigned streaming links, either by scanning their assigned QR codes or through a dedicated application using smartphones or tablets. Participants performed the eye movement training while viewing instructional videos using their smartphones or tablets, and video playback time was automatically recorded as training time. In addition, participants and their guardians received instructions regarding the use of the system during the baseline assessment. Detailed information regarding the system architecture, security features, training video delivery, adherence monitoring, and feedback procedures has been reported elsewhere³⁰.

Participants periodically received feedback regarding their training adherence (Figure 3), and an automated alert was generated when no video playback was detected for seven consecutive days, as described previously³⁰. To examine temporal patterns in training timing, the recorded video playback

time was categorized into eight 3-hour time slots: late night (12:00–2:59 AM), early morning (3:00–5:59 AM), morning (6:00–8:59 AM), late morning (9:00–11:59 AM), early afternoon (12:00–2:59 PM), late afternoon (3:00–5:59 PM), evening (6:00–8:59 PM), and night (9:00–11:59 PM)³⁰. For each participant, the cumulative video playback time within each time slot was expressed as a percentage of the total video playback time.

Statistical Analysis

Analyses were performed using complete cases. Participants with both baseline and 12-week outcome data were included in the analyses, and no missing data were imputed. The Shapiro–Wilk test was performed for all outcome measures to assess the normality of the data distributions and to select the appropriate statistical methods. Normally distributed variables are presented as the mean $\pm$ standard deviation, whereas non-normally distributed variables are presented as the median (interquartile range: 25th–75th percentiles). For baseline comparisons between the intervention (IN) and control (CO) groups, the independent-samples t-test was used for normally distributed variables, and the Mann–Whitney U test was used for non-normally distributed variables. Gender distributions were compared using the χ^2 test.

Within-group comparisons between pre- and post-intervention values were performed using the paired t-test for normally distributed variables and the Wilcoxon signed-rank test for non-normally distributed variables. To evaluate the intervention effects, ANCOVA was performed for each outcome, with the change score (12-week value minus baseline value) as the dependent variable and group (IN or CO), baseline value, age, and gender as independent variables. In addition, exploratory ANCOVA models were used to examine whether baseline value, age, or gender modified the intervention effect by including group $\times$ baseline value, group $\times$ age, and group $\times$ gender interaction terms. Results are presented as partial regression coefficients (β), 95% confidence intervals (95% CIs), and p-values. The coefficient of determination (R^2) and adjusted coefficient of determination (adjusted R^2) were also calculated. For outcomes with normally distributed change scores, the original data were used in both the primary and exploratory interaction ANCOVA models. For outcomes with non-normally distributed change scores, rank-transformed data were used in both models.

To examine the distribution of training times across different periods of the day in the intervention group, the Friedman test was performed. When the Friedman test indicated a significant difference, post hoc pairwise comparisons between time periods were conducted using the Wilcoxon signed-rank test, with Holm adjustment applied to control the type I error rate due to multiple comparisons.

All statistical tests were two-sided, and the significance level was set at 5%. Statistical analyses were performed using Python version 3.12 (Python Software Foundation, Wilmington, DE, USA).

Declarations

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Competing interests

Keisuke Hayashi and Yugo Setoguchi are employees of Senoh Corporation, the manufacturer of the Supreme Vision L device used in this study. Apart from the contributions of these authors, Senoh Corporation had no role in the study design, data analysis or interpretation, or the decision to submit the manuscript for publication. The remaining authors declare no competing interests.

Data availability

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request, subject to ethical, privacy, and institutional requirements.

Author contributions

Conceptualization, Ya.S., H.Ka., I.K., and Y.H.; methodology, Ya.S.; software, Ya.S.; validation, Ya.S.; formal analysis, Ya.S.; investigation, Ya.S., T.T., and S.H.; resources, Ya.S.; data curation, Ya.S., Yu.S., and K.H.; writing – original draft, Ya.S.; writing – review and editing, Ya.S., S.H., H.Kw., and Yu.S.; visualization, Ya.S.; supervision, Y.H. and K.S.; project administration, Ya.S.; funding acquisition, Y.H. All authors reviewed and approved the final manuscript.

Ethical Approval

All procedures followed were in accordance with the ethical standards of the responsible institutional committee and the Helsinki Declaration of 1964 and later versions. This study was approved by the Ethics Committee of the Faculty of Systems and Information Science, University of Tsukuba (approval number: 2025R044; approval date: September 17, 2025). The study was prospectively registered with the Japan Registry of Clinical Trials (jRCT; ID: jRCT1032250379; registration date: September 19, 2025 <https://jrct.mhlw.go.jp/latest-detail/jRCT1032250379>).

References

1. de Waal, E., Pienaar, A. E. & Coetzee, D. Influence of Different Visual Perceptual Constructs on Academic Achievement Among Learners in the NW-CHILD Study. *Percept Mot Skills* **125**, 966-988, doi:10.1177/0031512518786806 (2018).
2. Buscemi, A. et al. Role of Sport Vision in Performance: Systematic Review. *J Funct Morphol Kinesiol* **9**, doi:10.3390/jfmk9020092 (2024).

3. Kang, J.-J., Lee, S.-U., Kim, J.-M. & Oh, S.-Y. Recording and interpretation of ocular movements: saccades, smooth pursuit, and optokinetic nystagmus. *Annals of Clinical Neurophysiology* **25**, 55-65, doi:10.14253/acn.2023.25.2.55 (2023).
4. Hutton, S. B. Cognitive control of saccadic eye movements. *Brain Cogn* **68**, 327-340, doi:10.1016/j.bandc.2008.08.021 (2008).
5. Murray, N. P. et al. Oculomotor Training for Poor Saccades Improves Functional Vision Scores and Neurobehavioral Symptoms. *Arch Rehabil Res Clin Transl* **3**, 100126, doi:10.1016/j.arrct.2021.100126 (2021).
6. Lochhead, L., Feng, J., Laby, D. M. & Appelbaum, L. G. Training vision in athletes to improve sports performance: a systematic review of the literature. *International Review of Sport and Exercise Psychology*, 1-23, doi:10.1080/1750984x.2024.2437385 (2024).
7. Hall, C. D. et al. Vestibular Rehabilitation for Peripheral Vestibular Hypofunction: An Updated Clinical Practice Guideline From the Academy of Neurologic Physical Therapy of the American Physical Therapy Association. *J Neurol Phys Ther* **46**, 118-177, doi:10.1097/NPT.0000000000000382 (2022).
8. Suzuki, Y. et al. Effects of eye movement training on balance and vision in community-dwelling Japanese children: a pilot study using a single-group intervention. doi:10.21203/rs.3.rs-7440390/v1 (2025).
9. Coetzee, D., Pienaar, A. E. & van Wyk, Y. Relationship between academic achievement, visual-motor integration, gender and socio-economic status: North-West Child Health Integrated with Learning and Development study. *South African Journal of Childhood Education* **10**, doi:10.4102/sajce.v10i1.646 (2020).
10. Sawaki, K. et al. Sports and Kinetic Visual Acuity. *Juntendo Iji Zasshi* **68**, 387-392, doi:10.14789/jmj.JMJ22-0019-R (2022).
11. Van der Stigchel, S. & Hollingworth, A. Visuospatial Working Memory as a Fundamental Component of the Eye Movement System. *Curr Dir Psychol Sci* **27**, 136-143, doi:10.1177/0963721417741710 (2018).
12. Souto, D. & Kerzel, D. Visual selective attention and the control of tracking eye movements: a critical review. *J Neurophysiol* **125**, 1552-1576, doi:10.1152/jn.00145.2019 (2021).
13. Matsuura, Y., Sakairi, Y., Sato, H. & Takiura, K. Do Combined Oculomotor and Bimanual Coordination Exercises Instantly Stabilize Balance in Athletes? *Open Access J Sports Med* **15**, 77-89, doi:10.2147/OAJSM.S472125 (2024).
14. Wicks, L. J., Telford, R. M., Cunningham, R. B., Semple, S. J. & Telford, R. D. Longitudinal patterns of change in eye-hand coordination in children aged 8-16 years. *Hum Mov Sci* **43**, 61-66, doi:10.1016/j.humov.2015.07.002 (2015).
15. Rizzo, J. R. et al. The Intersection between Ocular and Manual Motor Control: Eye-Hand Coordination in Acquired Brain Injury. *Front Neurol* **8**, 227, doi:10.3389/fneur.2017.00227 (2017).
16. van Veen, S. C., Kang, S. & van Schie, K. On EMDR: Measuring the working memory taxation of various types of eye (non-)movement conditions. *J Behav Ther Exp Psychiatry* **65**, 101494,

- doi:10.1016/j.jbtep.2019.101494 (2019).
17. Kleim, J. A. & Jones, T. A. Principles of experience-dependent neural plasticity: implications for rehabilitation after brain damage. *J. Speech Lang. Hear. Res.* **51**, S225–S239; [https://doi.org/10.1044/1092-4388\(2008/018\)](https://doi.org/10.1044/1092-4388(2008/018)) (2008).
 18. Kohmura, Y., Yoshigi, H., Sakuraba, K., Aoki, K. & Totsuka, R. Development and gender differences in dynamic and kinetic visual acuities in children from 8 to 17 years of age. *Int. J. Sport Health Sci.* **6**, 128–134; <https://doi.org/10.5432/ijshs.IJSHS20080314> (2008).
 19. Isbell, E., Fukuda, K., Neville, H. J. & Vogel, E. K. Visual working memory continues to develop through adolescence. *Front Psychol* **6**, 696, doi:10.3389/fpsyg.2015.00696 (2015).
 20. Vuontela, V. *et al.* Audiospatial and visuospatial working memory in 6-13 year old school children. *Learn Mem* **10**, 74-81, doi:10.1101/lm.53503 (2003).
 21. Longitudinal influences of socio-economic status on visual-motor integration: The North-West Child Health, Integrated with Learning and Development study. doi:10.4102/sajce.
 22. Roivainen, E. Gender differences in processing speed: A review of recent research. *Learning and Individual Differences* **21**, 145-149, doi:10.1016/j.lindif.2010.11.021 (2011).
 23. Li, Y. & Geary, D. C. Developmental gains in visuospatial memory predict gains in mathematics achievement. *PLoS One* **8**, e70160, doi:10.1371/journal.pone.0070160 (2013).
 24. Barnett, A. G., van der Pols, J. C. & Dobson, A. J. Regression to the mean: what it is and how to deal with it. *Int J Epidemiol* **34**, 215-220, doi:10.1093/ije/dyh299 (2005).
 25. Suzuki, Y., Koda, M., Shimizu, Y., Tsubaki, T. & Hada, Y. Verification of the effects of a YouTube-based home-based (self-managed intervention) training system developed for frailty prevention: a pilot study. *J. Allied Health* **53**, 51–57 (2024).
 26. Suzuki, Y. *et al.* Balance Ability Characteristics and Related Factors in Athletes Across Different Sports: A Preliminary Study. *Healthcare (Basel)* **12**, doi:10.3390/healthcare12222240 (2024).
 27. Fernandez Santos, J. R., Ruiz, J. R., Gonzalez-Montesinos, J. L. & Castro-Pinero, J. Reliability and Validity of Field-Based Tests to Assess Upper-Body Muscular Strength in Children Aged 6-12 Years. *Pediatr Exerc Sci* **28**, 331-340, doi:10.1123/pes.2014-0196 (2016).
 28. Pate, R., Oria, M. & Pillsbury, L. (eds.) *Fitness Measures and Health Outcomes in Youth* (National Academies Press, 2012).
 29. Suzuki, Y. *et al.* Age-dependent changes in dynamic standing-balance ability evaluated quantitatively using a stabilometer. *J Phys Ther Sci* **30**, 86-91, doi:10.1589/jpts.30.86 (2018).
 30. Suzuki, Y. *et al.* Evaluation of the Effectiveness of Feedback in a Remote Monitoring Home-Based Training System for Workers: A Medium-Scale Randomized Parallel-Group Controlled Trial. *Healthcare (Basel)* **13**, doi:10.3390/healthcare13162069 (2025).

Figures

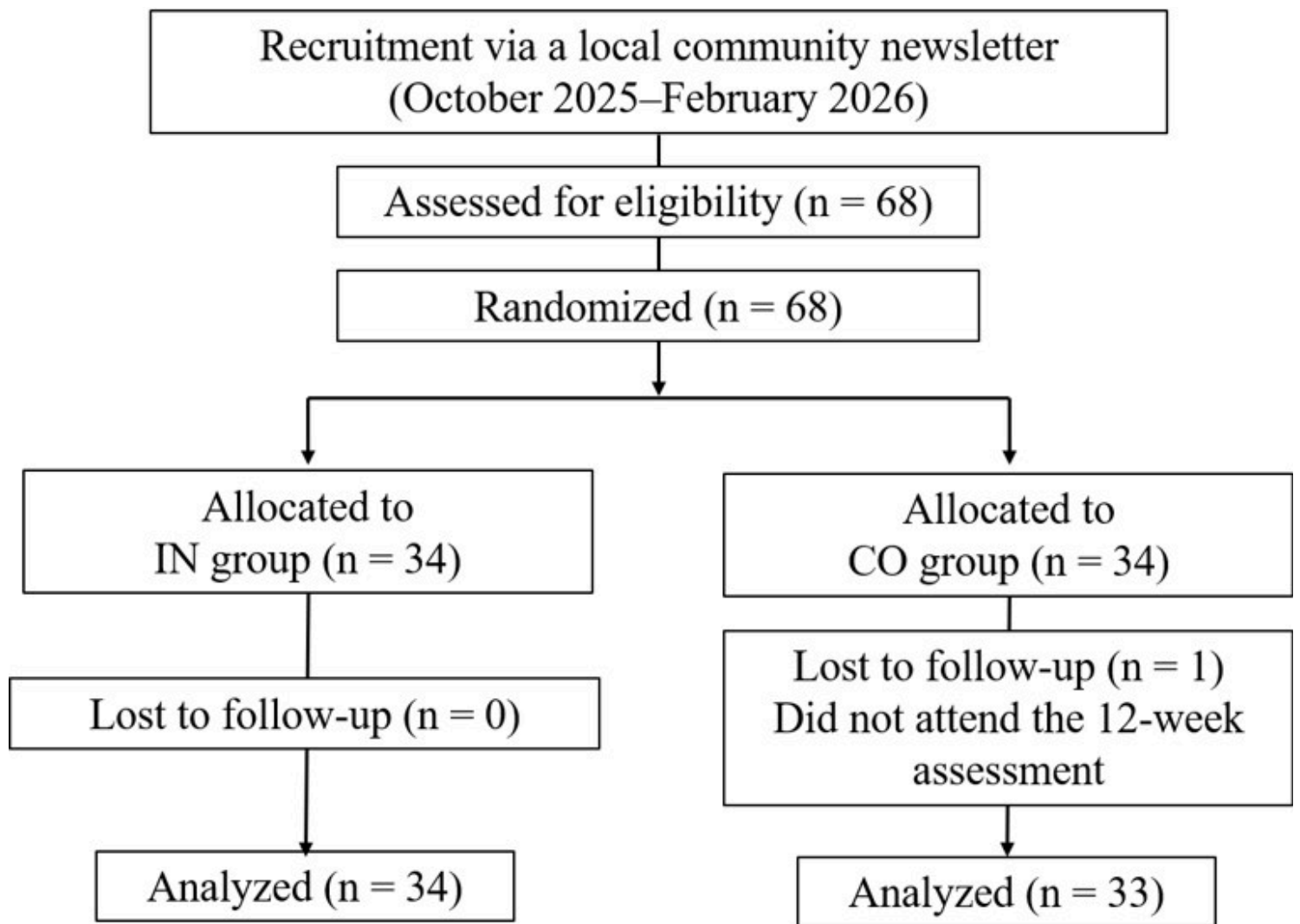


Figure 1

Study flow diagram.

One participant in the control group did not attend the 12-week assessment and was not included in the complete-case analysis. Consequently, 67 participants were analyzed (intervention group, $n = 34$; control group, $n = 33$).

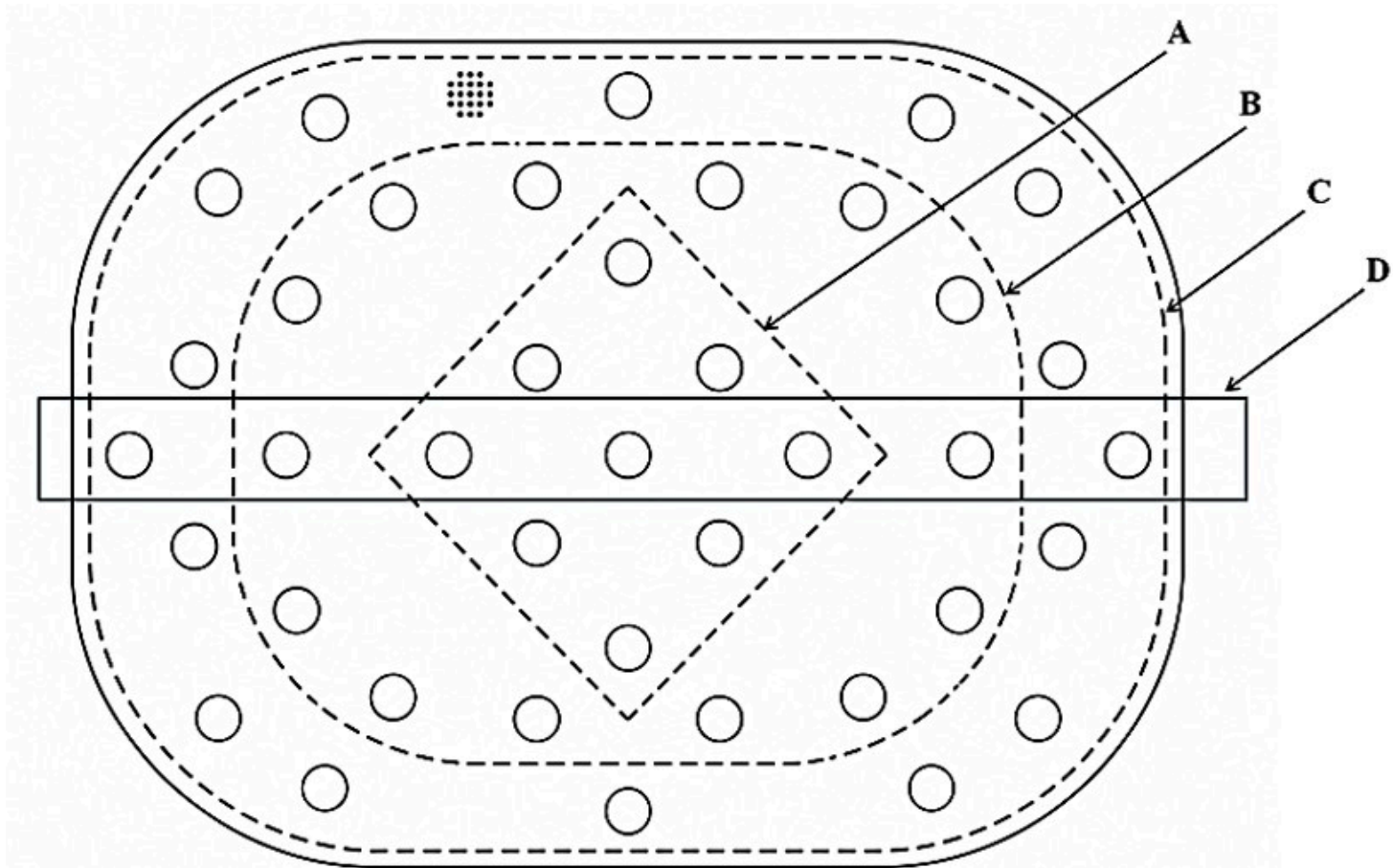


Figure 2

Configuration of the Supreme Vision L device

The device shows the arrangement of 39 LED buttons and the predefined task areas (A–D) used in the assessment programs.

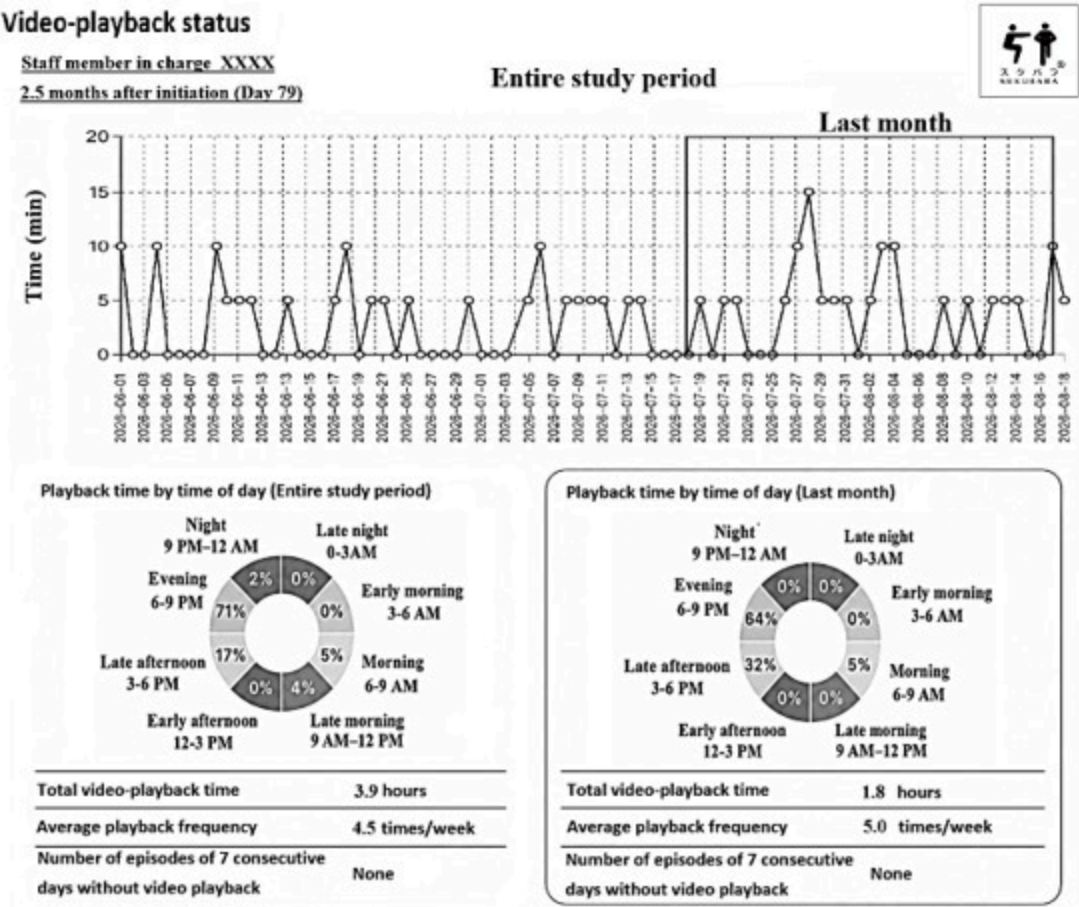


Figure 3

Example of a feedback sheet from the SUKUBARA® system.

Supplementary Files

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