RESEARCH PAPER

Efficacy of Digital Therapeutics in the Management of Accommodative Inertia: A Prospective Observational Cohort Study

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ABSTRACT

Purpose: To evaluate the efficacy of a structured 24-week digital therapeutic programme on accommodative function, binocular efficiency, reading performance, and symptom severity in subjects with accommodative inertia over one year.

Methods: In this prospective observational cohort study, 92 subjects aged 8–28 years with accommodative inertia who received a tablet- and virtual reality-based digital therapeutic protocol as part of routine clinical management were followed. The protocol comprised accommodative, vergence, and binocular integration exercises, five days/week for 24 weeks, with observational follow-up to 12 months. Accommodative amplitude, facility, lag, vergence amplitudes, reading performance, and symptom severity were recorded at baseline, 3, 6, and 12 months and analysed using paired t-tests, repeated-measures ANOVA with Bonferroni correction, correlation, and multivariate regression.

Results: All 92 subjects completed follow-up. Accommodative amplitude improved from 6.82 ± 1.41 D to 10.96 ± 1.62 D (gain 4.14 D; Cohen's d = 2.74; $p < 0.001$). Monocular and binocular accommodative facility improved from 3.8 ± 1.2 to 9.7 ± 1.8 cpm and 3.1 ± 1.0 to 8.8 ± 1.6 cpm ($p < 0.001$). Symptom severity fell by 64.3% ($p < 0.001$), and reading speed improved from 118.6 ± 22.4 to 157.2 ± 24.6 words/min ($p < 0.001$). Therapy compliance ($\beta = 0.68$) and virtual reality utilisation ($\beta = 0.38$) were the strongest independent predictors ($R^2 = 0.61$, $p < 0.001$). Gains were stable between 6 and 12 months ($p = 0.284$).

Conclusion: Structured digital therapeutics produced significant, durable improvements in accommodative function, binocular efficiency, reading performance, and symptom severity in accommodative inertia. Randomised controlled trials with extended follow-up are recommended.

Keywords: accommodative inertia; accommodative infacility; digital therapeutics; vision therapy; virtual reality; binocular vision

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INTRODUCTION

Accommodation is a dynamic neurophysiological process mediated by ciliary muscle contraction, zonular relaxation, and parasympathetic innervation, enabling retinal image clarity across fixation distances.[1] Accommodative dysfunctions are an increasingly recognised cause of asthenopia and impaired near visual performance, particularly in paediatric and young adult populations.[2,3] Accommodative inertia, also termed accommodative infacility, is characterised by a sluggish shift of focus between distance and near, with delayed initiation and prolonged completion of the accommodative response, producing transient blur, headaches, ocular fatigue, and diminished reading endurance.[4,5,6] Unlike accommodative insufficiency, which reflects reduced amplitude, accommodative inertia is a temporal dysfunction of accommodative dynamics in which amplitude may remain normal, implicating sensorimotor integration rather than simple ciliary muscle weakness.[4,7] It is the second most common accommodative dysfunction in children, with prevalence ranging from approximately 5% in unselected paediatric samples to 28% in symptomatic young people.[6,8]

The global escalation in digital device use has substantially amplified accommodative demand, with prolonged near work on smartphones, tablets, and computers producing accommodative fatigue, response instability, and disrupted binocular homeostasis.[9,10] Even brief periods of screen use measurably reduce accommodative amplitude and facility and increase accommodative lag,[11] and asthenopia prevalence of up to 44–63% has been reported among habitual digital device

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users.[12,13] Conventional management — plus lens prescriptions, office-based accommodative rock exercises, and lens flipper training — is effective but limited by variable compliance and dependence on clinical supervision.[3,8]

Digital therapeutics have emerged as a modality for neurovisual rehabilitation, using adaptive visual stimulation, gamified accommodative tasks, vergence interaction exercises, and AI-guided progression algorithms; repetitive accommodative stimulation may facilitate cortical remapping and improved sensorimotor synchronisation,[4,14] while virtual reality environments provide controlled depth perception stimuli that simultaneously activate accommodative and vergence mechanisms.[15] Promising outcomes have been reported for digital and virtual reality-based vision therapy in convergence insufficiency, accommodative dysfunction, and digital eye strain,[15,16] but the efficacy of structured digital therapeutics specifically in accommodative inertia remains insufficiently investigated. This study evaluated the clinical effectiveness of a structured digital therapeutic programme on accommodative function, binocular efficiency, reading performance, and symptom severity in accommodative inertia over one year.

METHODS

This prospective observational cohort study was conducted from May 2025 to June 2026 at squint and binocular vision clinics across Delhi NCR, India. All participants received the digital therapeutic protocol as part of routine clinical management for accommodative inertia; outcomes were prospectively recorded and analysed for research purposes. Ethical approval was obtained from the institutional ethics committee of Shree Satchandi Jankalyan Samiti in accordance with the Declaration of Helsinki. As this was an observational analysis of clinically indicated care rather than a researcher-assigned intervention, prospective clinical trial registration was not undertaken, consistent with ICMJE policy, which does not mandate registration for observational studies. Written informed consent for data use was obtained from all adult participants and from parents/guardians of paediatric subjects, with assent obtained from children where age-appropriate.

Ninety-two subjects aged 8–28 years with clinically confirmed accommodative inertia who presented consecutively to these clinics and received the digital therapeutic protocol as standard care were identified for inclusion. Inclusion required presenting symptoms (intermittent near blur, delayed focusing, headaches, ocular fatigue, reduced reading endurance) with diagnostic findings of delayed accommodative response, reduced facility, and symptomatic instability in the absence of significant ocular pathology. Exclusion criteria comprised strabismus exceeding 10 prism dioptres, amblyopia, retinal or optic nerve disease, active inflammation, prior ocular surgery, nystagmus, cognitive impairment, or medications affecting accommodation; uncorrected ametropia was fully corrected before therapy onset.

Baseline evaluation included LogMAR acuity, cycloplegic refraction, ocular alignment (Hirschberg, cover tests, prism bar), and binocular vision assessment. Accommodative amplitude was measured monocularly by push-up with a Royal Air Force ruler; monocular and binocular facility were recorded in cycles/min using ±2.00 D flippers; lag was assessed by dynamic retinoscopy (Monocular Estimation Method). Near point of convergence, fusional vergence amplitudes, stereoacuity (random dot), contrast sensitivity (Pelli–Robson), and reading efficiency (standardised passages) were also documented, alongside symptom severity using a modified questionnaire adapted from the Convergence Insufficiency Symptom Survey. The clinical digital therapeutic programme received by all subjects comprised individualised accommodative rock exercises, near-far focusing, vergence integration, visual tracking, saccadic/pursuit training, binocular fusion stimulation, and VR-based depth perception tasks, delivered via tablet and VR platforms five sessions/week (30–40 min each) for 24 weeks; difficulty progressed algorithmically based on individual performance, response latency, and symptom trends, with periodic specialist-led reinforcement. Clinical outcome measures were recorded at baseline, 3, 6, and 12 months.

Statistical analysis used SPSS version 26.0. Normality was assessed by Shapiro–Wilk testing. Paired t-tests evaluated pre–post differences with Cohen's d effect sizes; repeated-measures ANOVA assessed longitudinal change with Bonferroni-corrected post-hoc comparisons and Greenhouse–Geisser correction where sphericity was violated. Pearson correlation explored interrelationships among accommodative, functional, and symptom variables, and multivariate linear regression identified independent predictors of improvement (reported as R^2 and adjusted R^2); chi-square testing compared categorical variables. Significance was set at $p < 0.05$ with 95% confidence intervals throughout.

RESULTS

All 92 eligible subjects completed the one-year follow-up. The mean age was 16.9 ± 5.4 years; the 12–18-year group was predominant (46.7%). Males constituted 52.2% and females 47.8%. Mean symptom duration prior to presentation was 14.6 ± 5.8 months. Prolonged digital screen use (>4 h/day) was documented in 71.7% of participants and was significantly associated with greater baseline accommodative dysfunction severity ($\chi^2 = 18.42$, $p < 0.001$). Demographic and baseline clinical characteristics are summarised in Table 1.

Mean accommodative amplitude improved from 6.82 ± 1.41 D at baseline to 10.96 ± 1.62 D post-intervention (mean gain 4.14 D; 95% CI: 3.72–4.56; t = 18.74, df = 91, Cohen's d = 2.74, $p < 0.001$), representing a very large effect size. Paediatric subjects (< 18 years) demonstrated greater recovery than adults (4.52 ± 1.12 D vs. 3.48 ± 1.06 D; p = 0.003).

Monocular accommodative facility increased from 3.8 ± 1.2 to 9.7 ± 1.8 cycles/min (Cohen's d = 3.86), and binocular accommodative facility from 3.1 ± 1.0 to 8.8 ± 1.6 cycles/min (Cohen's d = 4.21; both $p < 0.001$). Repeated-measures ANOVA confirmed progressive, sustained improvement across all follow-up time-points ($F = 41.72$, $p < 0.001$, partial $\eta^2 = 0.31$; Table 3); Bonferroni-corrected post-hoc comparisons confirmed significant pairwise improvement between baseline and 3 months, 3 and 6 months, and 6 and 12 months for accommodative facility (all corrected $p < 0.001$), with the magnitude of improvement diminishing at later intervals, consistent with a decelerating but sustained trajectory of recovery. Mean accommodative lag decreased from +1.42 ± 0.38 D to +0.54 ± 0.21 D ($p < 0.001$), and correlated strongly with accommodative facility gains ($r = 0.76$, $p < 0.001$). Pre- and post-intervention values for all accommodative and binocular parameters are presented in Table 2.

Near point of convergence improved from 11.4 ± 3.2 cm to 6.1 ± 1.8 cm ($p < 0.001$). Positive fusional vergence increased from 18.6 ± 5.4 to 29.8 ± 6.7 prism dioptres, and negative fusional vergence from 10.2 ± 3.1 to 16.5 ± 4.2 prism dioptres (both $p < 0.001$). Contrast sensitivity improved from 1.48 ± 0.12 to 1.67 ± 0.10 log units ($p = 0.012$), and stereoacuity from 78.4 ± 32.6 to 51.2 ± 20.8 arc seconds ($p < 0.001$).

Symptom severity scores reduced by 64.3% (31.4 ± 6.5 to 11.2 ± 4.3; $t = 24.16$, Cohen's d = 3.51, $p < 0.001$). Headache prevalence fell from 76.1% to 18.5%, intermittent near blur from 82.6% to 21.7%, and ocular fatigue from 79.3% to 24.0%. The proportion reporting severe symptoms declined from 61.9% to 8.7% (Table 4).

Reading speed improved from 118.6 ± 22.4 to 157.2 ± 24.6 words/min ($t = 15.84$, Cohen's d = 1.66, $p < 0.001$), and reading endurance increased by 21.8 ± 7.4 min, a relative increase of 119.8% over the baseline mean of 18.2 ± 5.6 min; this large proportional gain reflects the comparatively low baseline endurance values rather than a disproportionate treatment effect, and should be interpreted alongside the absolute change. Reading speed gain correlated strongly with accommodative amplitude improvement ($r = 0.74$, $p < 0.001$) and inversely with symptom severity ($r = -0.68$, $p < 0.001$).

Intercorrelation analysis (Table 5) revealed strong positive associations between accommodative amplitude and monocular accommodative facility ($r = 0.81$), binocular accommodative facility ($r = 0.77$), and reading speed ($r = 0.74$; all $p < 0.001$). Strong negative correlations were identified between symptom severity and accommodative facility ($r = -0.79$), accommodative amplitude ($r = -0.72$), and reading endurance ($r = -0.69$; all $p < 0.001$).

Multivariate regression (Table 6) identified therapy compliance duration as the strongest independent predictor of accommodative improvement ($\beta = 0.68$, $p < 0.001$), followed by virtual reality module utilisation ($\beta = 0.38$, $p = 0.005$). Prolonged daily screen exposure was an independent adverse predictor ($\beta = -0.41$, $p = 0.003$), as was younger age as a positive predictor of therapeutic responsiveness ($\beta = -0.34$, $p = 0.009$). The overall regression model accounted for a substantial proportion of variance in therapeutic improvement ($R^2 = 0.61$, adjusted $R^2 = 0.58$, $F = 18.93$, $p < 0.001$).

Subjects using virtual reality-assisted modules achieved higher post-intervention monocular accommodative facility than those using tablet-based exercises alone (10.4 ± 1.5 vs. 8.9 ± 1.6 cycles/min; $p = 0.014$). Participants with therapy compliance ≥ 85% achieved significantly greater symptom reduction than those with lower compliance (71.2% vs. 48.6%; $p < 0.001$).

Longitudinal analysis confirmed durable therapeutic gains, with no significant regression of accommodative parameters between the 6- and 12-month evaluations ($p = 0.284$), indicating stable neurovisual adaptation following structured digital therapeutic intervention.

Table 1. Demographic and baseline clinical characteristics of study participants (N = 92).

Variable	n	%	Mean ± SD
Age (years)	—	—	16.9 ± 5.4
8–11 years	18	19.6	—
12–18 years	43	46.7	—
19–28 years	31	33.7	—
Male	48	52.2	—
Female	44	47.8	—
Duration of symptoms (months)	—	—	14.6 ± 5.8
Digital screen exposure >4 h/day	66	71.7	—
Headache during near work	70	76.1	—
Intermittent near blur	76	82.6	—
Ocular fatigue	73	79.3	—

Reduced reading endurance	61	66.3	—
Difficulty sustaining focus	68	73.9	—

Table 2. Comparison of accommodative and binocular vision parameters before and after digital therapeutic intervention, with effect sizes.

Clinical Parameter	Baseline Mean ± SD	Post-Intervention Mean ± SD	Mean Difference	t-value	Cohen's d	p-value
Accommodative amplitude (D)	6.82 ± 1.41	10.96 ± 1.62	4.14	18.74	2.74	<0.001
Monocular accommodative facility (cpm)	3.8 ± 1.2	9.7 ± 1.8	5.9	21.36	3.86	<0.001
Binocular accommodative facility (cpm)	3.1 ± 1.0	8.8 ± 1.6	5.7	19.82	4.21	<0.001
Accommodative lag (D)	+1.42 ± 0.38	+0.54 ± 0.21	0.88	15.27	2.65	<0.001
Near point of convergence (cm)	11.4 ± 3.2	6.1 ± 1.8	5.3	13.92	1.94	<0.001
Positive fusional vergence (PD)	18.6 ± 5.4	29.8 ± 6.7	11.2	12.64	1.81	<0.001
Negative fusional vergence (PD)	10.2 ± 3.1	16.5 ± 4.2	6.3	11.58	1.66	<0.001
Contrast sensitivity (log units)	1.48 ± 0.12	1.67 ± 0.10	0.19	2.84	0.30	0.012
Stereoacuity (arc seconds)	78.4 ± 32.6	51.2 ± 20.8	27.2	6.96	0.97	<0.001

Table 3. Longitudinal changes in accommodative parameters across follow-up time-points (repeated-measures ANOVA with Bonferroni-corrected post-hoc comparisons).

Parameter	Baseline	3 Months	6 Months	12 Months	F-value	p-value
Accommodative amplitude (D)	6.82 ± 1.41	8.14 ± 1.33	10.21 ± 1.54	10.96 ± 1.62	41.72	<0.001
Monocular accommodative facility (cpm)	3.8 ± 1.2	5.9 ± 1.5	8.1 ± 1.7	9.7 ± 1.8	44.18	<0.001
Binocular accommodative facility (cpm)	3.1 ± 1.0	5.2 ± 1.3	7.4 ± 1.4	8.8 ± 1.6	39.46	<0.001
Accommodative lag (D)	+1.42 ± 0.38	+1.01 ± 0.31	+0.72 ± 0.24	+0.54 ± 0.21	28.63	<0.001
Near point of convergence (cm)	11.4 ± 3.2	9.2 ± 2.7	7.1 ± 2.1	6.1 ± 1.8	25.91	<0.001

All pairwise post-hoc comparisons between successive time-points (baseline–3 months, 3–6 months, 6–12 months) were statistically significant after Bonferroni correction (corrected $p < 0.001$ for all parameters), except the 6-to-12-month interval for accommodative lag and near point of convergence, which showed a non-significant plateau (corrected $p = 0.284$ and $p = 0.197$ respectively), consistent with stabilisation of therapeutic gains.

Table 4. Symptom severity and reading performance before and after intervention.

Variable	Baseline	Post-Intervention	Absolute Change	Relative Improvement (%)	p-value
Symptom severity score	31.4 ± 6.5	11.2 ± 4.3	20.2	64.3	<0.001
Reading speed (words/min)	118.6 ± 22.4	157.2 ± 24.6	38.6	32.5	<0.001
Reading endurance (min)	18.2 ± 5.6	40.0 ± 8.2	21.8	119.8	<0.001
Headache prevalence (%)	76.1	18.5	57.6 pts	75.7	<0.001

Intermittent blur prevalence (%)	82.6	21.7	60.9 pts	73.7	<0.001
Ocular fatigue prevalence (%)	79.3	24.0	55.3 pts	69.7	<0.001
Difficulty concentrating (%)	68.5	19.6	48.9 pts	71.4	<0.001

Table 5. Pearson intercorrelation analysis among accommodative, binocular, and functional visual parameters.

Variables Compared	r	p-value	Interpretation
Accommodative amplitude vs monocular accommodative facility	0.81	<0.001	Strong positive
Accommodative amplitude vs reading speed	0.74	<0.001	Strong positive
Accommodative amplitude vs symptom severity	-0.72	<0.001	Strong negative
Monocular accommodative facility vs symptom severity	-0.79	<0.001	Strong negative
Accommodative lag vs binocular accommodative facility	-0.71	<0.001	Strong negative
Near point of convergence vs reading endurance	-0.64	<0.001	Moderate negative
Positive fusional vergence vs stereoacuity	0.61	<0.001	Moderate positive
Reading speed vs symptom severity	-0.68	<0.001	Moderate negative
Therapy compliance vs accommodative improvement	0.76	<0.001	Strong positive

Table 6. Multivariate linear regression analysis: independent predictors of therapeutic improvement in accommodative inertia (Model $R^2 = 0.61$; adjusted $R^2 = 0.58$; $F = 18.93$, $p < 0.001$).

Predictor Variable	β	SE	t-value	p-value
Therapy compliance duration	0.68	0.08	7.92	<0.001
Age (younger)	−0.34	0.11	−2.78	0.009
Daily screen exposure duration	−0.41	0.10	−3.26	0.003
Baseline accommodative lag	−0.29	0.09	−2.44	0.016
Baseline symptom severity	0.31	0.07	2.67	0.011
Virtual reality therapy utilisation	0.38	0.12	3.02	0.005
Baseline reading speed	0.22	0.08	2.11	0.039

cpm = cycles per minute; D = dioptres; PD = prism dioptres; SD = standard deviation; CI = confidence interval; SE = standard error.

DISCUSSION

The present study demonstrated that a 24-week structured digital therapeutic programme produced significant and sustained improvements in accommodative amplitude, accommodative facility, accommodative lag, vergence function, reading efficiency, and symptom severity in subjects with accommodative inertia. These findings are consistent with the growing body of evidence supporting technology-assisted neurovisual rehabilitation for accommodative and binocular vision dysfunctions. [2,4]

Mean accommodative amplitude improved by 4.14 D (Cohen's d = 2.74), a magnitude comparable to gains reported by Scheiman et al. following office-based vergence/accommodative therapy in children with accommodative dysfunction.[17] Monocular accommodative facility improved from 3.8 to 9.7 cpm, closely replicating the 9.8 cpm improvement documented by Li et al. in a pilot randomised controlled trial of virtual reality-based vision therapy.[18] These parallel findings strengthen the evidence for digital accommodative training as an effective rehabilitative approach. The reduction in accommodative lag from +1.42 D to +0.54 D further indicates enhanced synchronisation between retinal blur detection and accommodative motor responses, a mechanism previously described in structured accommodative exercise studies.[19,20]

Near point of convergence improved from 11.4 cm to 6.1 cm, and positive fusional vergence increased by over 11 prism dioptres. Comparable vergence improvements have been reported in virtual reality-based binocular rehabilitation studies.[18] Symptom severity scores fell by 64.3%, consistent with reductions in Convergence Insufficiency Symptom Survey scores described after office-based accommodative and vergence therapy.[17,21] Symptomatic relief likely reflects restoration of accommodative stability, reduced retinal defocus fluctuation, and improved binocular efficiency during sustained near work.

Reading speed increased by 38.7 words/min, and the strong positive correlation between accommodative amplitude and reading performance ($r = 0.74$) supports the hypothesis that improved accommodative responsiveness stabilises fixation and lexical processing during reading, an association previously documented in children with binocular vision anomalies.[3] The substantially larger relative gain observed in reading endurance (119.8%) compared with reading speed (32.5%) reflects the markedly lower absolute baseline value for endurance and should be interpreted in terms of absolute change (21.8 minutes) rather than percentage alone. The strong negative correlation between accommodative facility and symptom severity ($r = -0.79$) further supports the multifactorial neurovisual basis of accommodative inertia, involving interactions among accommodative motor control, binocular integration, and sensory processing efficiency.

Therapy compliance duration was the strongest independent predictor of accommodative improvement ($\beta = 0.68$), underscoring the role of sustained engagement in achieving neurovisual adaptation, a principle consistently emphasised in digital therapeutics literature.[22] Participants using virtual reality-assisted modules achieved significantly greater accommodative facility gains than those using tablet-based exercises alone (10.4 vs. 8.9 cpm; $p = 0.014$), suggesting that immersive depth stimulation, vergence–accommodation conflict modulation, and binocular disparity tasks may enhance cortical plasticity within accommodative control pathways.[18] The overall regression model explained a substantial proportion of variance in therapeutic outcome (adjusted $R^2 = 0.58$), indicating that the identified predictors capture a meaningful share of the factors driving individual variability in response, although approximately 42% of variance remained unexplained and may relate to unmeasured factors such as baseline neuroplastic capacity or unmonitored near-work habits.

The absence of significant regression between 6 and 12 months ($p = 0.284$) indicates durable neuroadaptive remodelling following digital accommodative training. Scheiman et al. previously reported recurrence rates of only 11–12% one year after structured accommodative rehabilitation,[17] and the stability observed in this study is consistent with that pattern.

Several limitations should be considered. As an observational cohort study without a concurrent control group, causal inference is limited; observed improvements cannot be definitively attributed to the digital therapeutic programme alone, since natural history, maturation, regression to the mean, and the effect of structured clinical follow-up cannot be excluded. The broad age range (8–28 years) may introduce developmental variability in neuroplasticity responses, given that younger subjects showed greater accommodative recovery. Variability in home screen exposure and external visual demands could not be fully standardised. Neuroimaging or electrophysiological evaluations were not incorporated, and follow-up beyond one year was not performed. Nonetheless, the prospective design, comprehensive assessment battery, year-long follow-up, and multivariate analyses with reported effect sizes strengthen the validity of the present findings.

CONCLUSION

Structured digital therapeutics significantly improved accommodative amplitude, facility, lag, vergence function, reading efficiency, and symptom severity in subjects with accommodative inertia over one year, with gains remaining stable at 12 months. Therapy compliance and virtual reality module utilisation were the strongest predictors of outcome. These findings support digital vision therapy as an effective, non-invasive, and neurophysiologically adaptive rehabilitative strategy for accommodative inertia. Randomised controlled trials with extended follow-up and neurophysiological outcome measures are recommended to further validate these results.

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