The 13th Bielschowsky lecture: accommodation and convergence – ratios, linkages, styles and mental somersaults

The 13th Bielschowsky Lecture

Accommodation and Convergence – Ratios, Linkages, Styles and Mental Somersaults

A.M.Horwood
Infant Vision Laboratory, University of Reading, and Royal Berkshire Hospital, Reading UK

ABSTRACT:

A relatively fixed relationship between convergence and accommodation appears to be fundamental to binocular vision and its disorders. The accommodative convergence to accommodation ratio (AC/A) has traditionally been considered a major explanatory factor, but it fits only a small number of clinical diagnoses and fails to explain others. An alternative model, based on the different weights the visual system places on the main cues to target position in depth, fits concomitant strabismus, heterophoria and convergence and accommodation anomalies more comprehensively. Typical accommodation can be surprisingly variable and many intermittently-strabismic people still use binocular disparity as their primary visual cue, with blur and proximal/looming cues having less weight. The convergence-accommodation to accommodation (CA/C) linkage is therefore more important than the AC/A relationship in the majority of typical and atypical cases. Between-diagnosis style differences in the relative balance between these relationships can explain many clinical findings.
Instead of "accommodation drives convergence", or "convergence drives accommodation", we should instead think of the visual and non-visual cues which drive both systems more independently and flexibly.
Key Words: Accommodation; Convergence; Ratios; Model; Intermittent strabismus

1 INTRODUCTION

Alfred Bielschowksy was renowned for his work on motor aspects of strabismus, and also for how motor and sensory processes of binocular vision interact. In this tradition, the subject of my lecture is how our research into the motor processes of ocular vergence and accommodation responding to sensory input has led to us to re-think many traditional concepts of normal binocular vision and concomitant strabismus, many of which date from the time of Bielschowsky.

Many clinicians still work with the vergence model of Maddox in mind [1]. This model suggests that approximately two-thirds of the convergence produced when fixating a near target is driven by target blur (accommodative convergence). This is the theoretical basis of the widely quoted AC/A ratio of around 4Δ:1D. Within this early model, fusional and proximal cues play more minor or "fine tuning" roles.

When Professor Tricia Riddell set up our laboratory in 1997 to study the development of the AC/A ratio in infants, we largely expected to work within this model, but from the outset we found that it rarely fitted our results. Since then we have been working to develop a more nuanced model of how the visual world drives the processes of vergence and accommodation.

From the outset, it became clear that a major problem with interpretation of the literature was that convergence and accommodation in published studies were often measured in highly controlled laboratory experiments, using one paradigm to investigate one aspect of a process, and other very different paradigms to investigate others. The most highly controlled or technically precise experiments often required adult, knowledgeable, or experienced participants from within the vision science world, often given lengthy training.

The literature from laboratory studies may report that is possible to have good response to each of the different near stimuli e.g. disparity, blur and different proximal cues, but can ignore the fact that the reported response gains to the different individual stimuli would, if added, produce well over 100% of the response required. They must be weighted in some way, but this relative weighting is much more rarely considered.

Ophthalmology literature often quotes a “normal AC/A ratio” of 4:1 (or gain of 0.66) to a blur-only stimulus as being typical [2, 3] but the body of laboratory and clinical research is remarkable for the number of papers reporting how often, in practice, this is not the case [4-6]. Clinical studies [7, 8] acknowledge that clinical ratios are rarely repeatable between methods and may be well below 4:1. Unsurprisingly, AC/A ratios are not usually routinely tested, because they only seem to help clinical decision-making in specific conditions. We often only test an AC/A ratio when we expect it to be abnormal, to confirm a clinical impression we have already made. AC/A theory is insufficient to explain common clinical findings and conundrums; for example why manipulating accommodation with lenses will change one heterotropia angle significantly, and another not at all.

In particular, clinicians rarely consider the major differences that can exist between “stimulus” ratios, which are easy to test, and “response” ratios, which are not. A stimulus ratio presents a blur stimulus, measures the subsequent change in vergence and calculates the ratio assuming that the accommodative response has equalled the stimulus, but without measuring it. A response ratio measures both responses, so reflects what has actually happened.

We contend that there is much more to the accommodation-vergence linkage than the AC/A ratio.

2 METHODS

Remote Haploscopic Photorefraction

We have used photorefraction methods in most of our research. Early studies showed that in naturalistic conditions, using naïve or infant participants, accommodative lag was very common and accommodation dropped further and dramatically on monocular occlusion [9, 10]. Being binocular seemed a more important drive to both vergence *and* accommodation than the Maddox model suggested, supporting the views of Judge et al [11] based on animal studies.

We therefore developed a paradigm which could explore the relative weighting of the three major cues to the position of an object in depth[12], while all other conditions are identical. The cues are:- a) binocular disparity in its widest sense, encompassing both gross motor fusion of widely separated or diplopic images beyond the horopter, as well as fine disparity detection within Panum’s Area (necessary for stereopsis); b) blur; and c) “proximal” cues such as dynamic looming and size. Since 2002 we have used a Plusoptix Power Refractor to measure objective accommodation (in diopters (D)) and convergence (in metre angles (MA)) simultaneously in each eye, and continuously at 25Hz, while the participant watches simple targets moving backwards and forward in depth between five fixation distances between 25cm-2m from the eyes. Because the laboratory was set up to test uninstructable infants in naturalistic and short testing sessions, our control groups are generally also uninstructed. There are no specific instructions beyond “watch the picture”, so the participants are free to behave naturally, with their responses driven solely by the target characteristics.

The laboratory construction and targets allow us to present or minimise the three visual cues in turn. Disparity cues are available when the participant can see the target with both eyes, and can be excluded by preventing one eye seeing the target by remote occlusion at the level of the upper mirror (F in Fig 1). Blur cues are presented by using a complex, highly coloured, high contrast clown target with detail available down to 1 screen pixel, and can be minimised using a Gabor target which looks similar whatever the accommodative state.

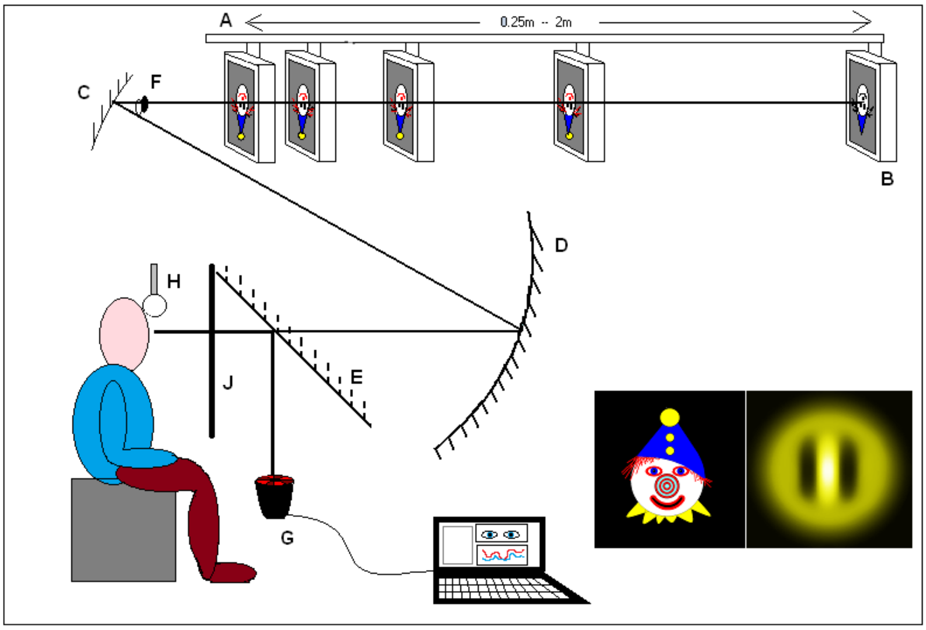

Figure 1. The remote haploscopic photorefractor. A/B:motorized monitor beam C/D mirrors E: transparent infra-red reflecting mirror F: occlusion of half the mirror here makes target invisible to one eye G: Plusoptix Power Refractor. Detailed and blur-available and minimal-blur cue targets bottom right.

Proximal cues are available if the participant watches the same size target loom and move between fixation distances, and can be minimised by scaling the target size for each distance and obscuring it while it moves, so that it subtends the same retinal angle at each distance. We can therefore present all eight possible combinations of these three cues while everything else about the testing is standardised. Over the years we have tested over 800 participants of all ages from birth to presbyopia, from a range of typical and atypical groups using the same paradigm. This standardised approach has enabled us to compare and contrast these groups under common test conditions.

3 RESULTS

First Impressions

Repeated studies of typically developing control groups show that, of the three cues, disparity is by far the most highly weighted, with much less weighting placed on blur and proximal cues. Any cue combination containing disparity drives much better vergence *and accommodation* responses than any combination without it. Vergence responses are usually closer to a gain of 1.00 (perfect response) than accommodation, with accommodative lag for most near targets [12]. More demanding targets produce the most accommodation [13, 14]. Within mean responses, however, there is much variability between targets, participants and cue combinations, so means often give a misleading impression of what is “normal”. Many visually normal and asymptomatic participants have linear vergence stimulus/response curves, but much more erratic, and often poor, accommodation for some or all targets. Even among visually typical participants, accommodation and vergence do not always behave in the “fixed linkage” suggested by the literature.

There are also large expert/naïve observer differences[15], with naïve, uninstructed observers responding very differently to those (similarly uninstructed) with visual experiment experience. Therefore comparisons between laboratory and clinical or infant literature must be made with caution.

AC/A and CA/C ratios

Among our cue combinations we are able to measure objective AC/A and CA/C ratios by calculating the vergence response in relation to the accommodation driven by a blur-only cue (AC/A) and the accommodation in relation to the vergence response driven by a disparity-only cue (CA/C). These "response" ratios use actual, not assumed, accommodation, so are much more accurate than most clinical methods. When correlated with clinical gradient AC/A ratios, measured as carefully as we could, we found no correlation (r=>0.88) between the "true" lab response AC/A ratio and the clinical near or distance ratios[16]. Most people find monocular accommodation more difficult, and many are not aware (and so will not report) when they are not accommodating during testing, even if asked to clear the image at each swap of an occluder. The majority of clinical "AC/A" ratios probably give a poor measure the "vergence driven by accommodation", because our research suggest that monocular blur cues may drive little accommodation in the first place.

In the same study, although the near and distance clinical ratios correlated weakly with each other (r = 0.29), the strongest correlation was between the clinical near ratio and the lab CA/C ratio (r = 0.38). We suggest that the near (plus lens) clinical "AC/A" ratio may instead be giving an indirect indication of how much disparity is used to drive accommodation. The possible explanation is that the initial occlusion/dissociation to measure the angle during "near gradient AC/A ratio" stops both convergence *and* accommodation by removing disparity cues. But a major requirement of the test is that the patient is instructed to clear an accommodative target at all times. Many people find accommodation impossible without some convergence so convergence cannot be allowed to relax fully if the target is to be cleared. Introducing plus lenses allows more convergence to relax because accommodation is now not necessary to clear the image. The "AC/A ratio" therefore may be giving us an idea of how much eliminating convergence on occlusion stops accommodation, and how strong the linkage between vergence and accommodation is when accommodation is forced, rather than measuring an AC/A ratio *per se*.

Our research suggests we need to consider the disparity drive to accommodation (the CA/C relationship) as much as, or more than, the blur drive to convergence (AC/A). The CA/C ratio is almost impossible to measure clinically because a good fusional target must be presented, while simultaneously and objectively measuring accommodation in at least one eye. But that does not mean it is not important.

Research generally agrees that while most people accommodate a little more than they converge to blur, and converge more than they accommodate to disparity (Figure 2a), the AC/A and CA/C ratios are inversely or reciprocally related (17) so if abnormal, a high AC/A accompanies a low CA/C and vice versa (Fig 2b) and c)).

.

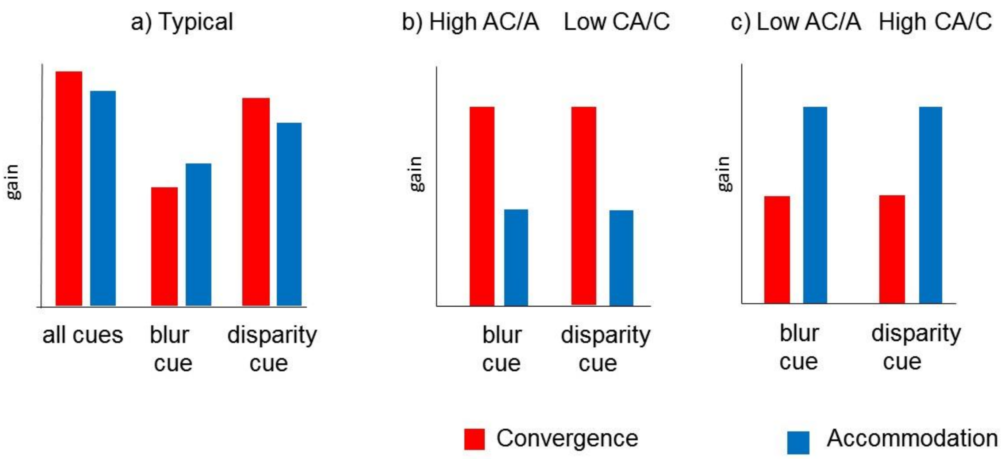

Figure 2. a) Typical response scenario to blur vs disparity cues in relation to all-cue naturalistic responses. b) high AC/A and low CA/C pattern c) low AC/A and high CA/C pattern.

In practice the high AC/A / low CA/C scenario simply means that these individuals always converge more than they accommodate, while the low AC/A / high CA/C combination means they accommodate more than they converge.

Variability and "style"

We have always been impressed by the variability and unpredictability of responses from even normal controls. Many asymptomatic and visually typical children and young adults appear to significantly and happily under-accommodate under naturalistic everyday conditions [12, 13, 18, 19] despite having normal accommodation near points and appropriate accommodation on dynamic retinoscopy. Although they *can* accommodate, some people *don't* unless they have been specifically asked to. Although means are broadly repeatable, they hide many different patterns and individual or between-sub-group differences to the different visual cues available. This could be the key to explaining why some patients "have not read the textbooks" and it chimes with a current trend the wider scientific literature, where individual differences are gaining more research attention [20].

In our dataset, some people respond well to any or all of the cues; others need multiple cues; or only respond to disparity; or respond to blur more than most. Similar mathematical response AC/A and CA/C ratios can exist in two very different patterns of response to blur vs. disparity for instance[21]. This led us to speculate that "style" of response to different cue combinations might correlate with different clinical patterns. Even if only the responses to blur and disparity are considered (so ignoring other, possibly influential, cues in this argument), there are different combinations which might help explain some common clinical questions. Clinicians are used to the fact that spectacles will alter one patient's strabismus or heterophoria angle, but not another's. It is quite possible that changing a blur cue with spectacles will only change an angle if the individual uses blur to drive their responses. Most typical individuals weight their responses towards disparity cues, and are relatively less responsive to blur, so a change in lens will not affect the angle as much.

We developed a new, more nuanced, model of vergence and accommodation control based around six different "styles" of being more sensitive to blur or disparity, but also whether the AC/A and CA/C relationships were typical, or a high AC/A / low CA/C, or low AC/A / high CA/C type. We then made predictions about how strabismic angles and accommodation would respond to changes in blur or disparity demand (such as would be provided by lenses, prisms or surgery)[21]. We have a very large database of many different clinical groups all tested under the same conditions, so we had the ideal dataset to test the predictions made by the model. We found that most common clinical diagnoses in intermittent strabismus, heterophoria and accommodation/convergence anomalies fitted well into one or other of the six categories. For example, near exophorias fitted well into the "disparity weighted low AC/A / high CA/C" category. Such patients respond well to disparity cues, but tend to under converge more than is typical; they do not respond much to blur cues, so spectacles make little difference to the angle. Convergence excess esotropias fitted well into the "blur weighted high AC/A / low CA/C category"; a change in blur cue (a change of spectacles) makes a big difference to the angle. If given a disparity-only target, they may remain aligned, but often under-accommodate.

These six categories are unlikely to be the only possible combinations of blur / disparity and proximity cue weightings, but serve to illustrate how weighting of the cues available in the visual world can predict clinical patterns and explain response to common treatments. The categories also may only apply to individuals with the potential for normal stereopsis i.e. without suppression. We predict that in the absence of the vastly superior precision afforded by normal disparity detection down to seconds of arc, other cues may be weighted more heavily. This might also explain why strabismic children are more likely to have a larger accommodative element to their deviation than non-strabismic children – without good binocularity they have learned to place more weight on blur cues.

The actual weightings an individual child places on the cues to drive vergence and accommodation may fall anywhere along the blur /disparity / proximal / or "other" continua. This is why children's eyes do not always respond as we would expect. Individual style might be influenced by early visual experience, genetic or anatomical factors, suppression, muscle tone or subtle cortical impairment. Modest refractive error seems a more equivocal causal candidate because childhood refractive error can be as much a consequence of poor binocularity or accommodation, as a cause.

4 DISCUSSION

Limitations of Language

It is extremely difficult to move away from many phrases we have used all our lives to convey some common and fundamental concepts, but some terms have major limitations.

Clinical AC/A "ratios" (particularly if tested on only one occasion, with one lens and one fixation distance) are rarely fixed, rarely repeatable, and the accommodation produced may not relate well to the amount of accommodation we have asked a patient to do. Even accurate (response) high ratios only tell us that they *can* change their angle in relation to a change of blur, but not that they usually *do*. The child might usually respond to disparity cues, so the AC/A ratio is less relevant, while for them the (clinically unmeasurable) CA/C ratio matters more. A "high AC/A ratio" may help us predict that spectacles will change an angle, but a single calculated number is unreliable.

A clinical "low AC/A ratio", may tell us nothing about the actual ratio (how much vergence is driven in relation to accommodation by blur) if the patient has not responded to the blur in the first place. If they were to accommodate, the ratio could be high or low. We are, however, unlikely to know if they have not accommodated, because they are unlikely to tell us. Firstly, depth of focus means that lag of <0.5D will not be noticed by the most observant patient. Secondly, inaccurate accommodation is part of normal life for many people in all but the most demanding situations, so they may not notice or promptly report changes in blur. Clinicians, therefore, may have little idea of the true AC/A ratio; "high-ish" and "low-ish ratios are probably the best we can say. In addition, even an accurately measured AC/A ratio may only make sense if it is considered alongside a CA/C ratio, which we rarely know.

Clinicians commonly say "accommodation drives convergence" or vice versa – but there is little evidence that one "drives" the other; the *cues* drive both. Our evidence suggests that they are both driven simultaneously by the same cues, and disparity is usually the primary cue for both systems.

There is a large literature to suggest that there is a "neural linkage" between convergence and accommodation, but no anatomical site had been identified to support this. Our data suggests that it is more likely that the two systems are more separate, but both are responding in parallel to the different visual characteristics of targets moving in depth. Infants learn that driving both responses together, to the same cues, is useful. Accommodation and convergence usually need to occur together, and the cues from a target moving in depth (blur, disparity, proximal) also usually co-vary, and so a "linkage" seems to exist.

The AC/A linkage is often described as "fixed and innate", with "positive and negative relative vergence and accommodation" compensating for any imbalances. Although mean responses support this, we find it is rarely supported at the individual level. Infants show appropriate mean accommodation and convergence to near targets by 8-9 weeks of age[22], and even we have reported infant "ratios" not significantly different from those of adults[10]; but these infant responses were erratic, with accommodation much more variable than vergence, so mean responses mask much more independent-looking systems in infancy. Even typical young adults can show occasional very erratic or apparently independent responses without reporting symptoms. In cases of accommodative spasm, we often demonstrate vergence and accommodation working totally independently. If this can occur in otherwise neurologically normal young adults, there must be a neural mechanism than can drive the systems independently in certain circumstances.

If the two systems have more independence, the terms "positive and negative vergence and accommodation" become superfluous – they are not necessarily "relative" to each other, with one being a reference value, but just two systems responding more independently to the same stimuli. So, for example, accommodation can remain appropriate despite a vergence change induced by a prism, or vergence can be linear to target demand while accommodation follows an "all or nothing" trajectory [22]. Poor "relative" ranges just mean that the two systems are strongly and inflexibly linked, which may cause some of the problems that present in our patients.

Instead of “teaching relative vergences”, orthoptic exercises probably just loosen problematical too-strong linkages and reinforce (or encourage tolerance to) more independent responses.

We are not the only lab to suggest that, especially in early infancy, that “gross motor fusion” or ocular alignment is, instead, two monocular adductions to fixate a near object. We even have evidence that in exceptional circumstances accommodation can be driven independently in each eye [23]. We still need clear evidence to prove that true consensual reflexes exist and are not just learned useful associations, working within different dead zones and broad envelopes of sensitivity.

Alternative language

We suggest we try to move away from some terms – although they do convey broad concepts we need to express, so it is very difficult. We would prefer “linkage” rather than “ratio”. Linkages can be strong or weak. A too-strong linkage may what gets a patient into trouble. Being unable to accommodate without converging, or vice versa, might be what turns someone with a heterophoria or refractive error into a “patient”, while someone with a more flexible linkage (who we often see in our lab as our asymptomatic, typical controls) may never seek advice, experience symptoms or present for investigation. “Linkage” also does not imply any causal direction between convergence and accommodation, both of which can be (commonly) disparity-driven or blur-driven (more rarely, but particularly in accommodative strabismus) in varying proportions. We should refer to the cues which drive the responses, not to one driving the other. Rather than “accommodation drives vergence”, blur or disparity can drive both, and one may be driven more than the other.

5 CONCLUSIONS

- Subjective accommodation responses are often very unreliable – especially monocularly – because many normal people seem very happy to tolerate habitual blur for many tasks.
- For people with the potential for normal binocularity (stereopsis) the disparity-accommodation (“CA/C”) linkage is generally more influential than the blur-convergence (“AC/A”) linkage. The strength of disparity cues to drive accommodation, means however, that we should consider whether surgery to reduce the angle (and thus remove some disparity drive) might also affect accommodation, at least in the short term (for example post-operatively in distance exotropia), until learned linkages are re-set.
- It is rare for pre-presbyopic individuals to think about, notice, or be bothered by what we might consider significant blur for some near tasks. We should probably discourage any impressions in a patient that people function with clear near vision all the time; it might make a susceptible or introspective person feel they have “a problem” when they are no different from normal.
- Variable (and often surprisingly poor) accommodation can be normal, so most people will not think it an issue - or tell you about it. As long as they *can* accommodate when necessary for extreme tasks such as needle threading or tiny text on small screens, it does not seem to be particularly important to many people’s lives that they *do,* if the task can be accomplished despite modest blur. Even adult close work usually demands near acuity well above threshold, so crystal clear vision is not necessary.
- Large expert /naïve observer differences mean that comparisons between laboratory and clinical or developmental literature can be difficult. We should be cautious when extrapolating laboratory studies into clinical contexts unless the laboratory participants, and particularly controls, were as naïve to the vision experiments as our patients are.
- Flexibility between vergence and accommodation is good. Inflexibility can be bad and indeed a too-strong linkage may be the problem. Orthoptic exercises probably just teach techniques to weaken the linkages and encourage independence and flexibility.
- Considering an individual’s style of response to blur, disparity (and probably other cues) may help determine our predictions about response to spectacles, prisms or surgery.
- Clinicians are used to patients who respond differently to standard treatments, but researchers have often considered individual differences “a nuisance factor to be ignored”[20]. Our work suggest that accommodation and convergence relationships are another area where differences between individuals seem crucial to our understanding.

Acknowledgement
None of this work would have been possible without my co-author Professor Patricia Riddell who set up the lab, started our research and continues with close involvement with the research.

REFERENCES

1. Maddox E. Investigations on the relationship between convergence and accommodation of the eyes. J Anat. 1893;20:475-505, 65-84.
2. Hoyt C, Taylor D. Pediatric Ophthalmology and Strabismus. 4th ed. Edinburgh: Elsevier Saunders; 2012.
3. Rainey BB, Goss DA, Kidwell M, Feng B. Reliability of the response AC/A ratio determined using nearpoint autorefraction and simultaneous heterophoria measurement. Clin Exp Optom. 1998;81(5):185-92.
4. Havertape SA, Cruz OA, Miyazaki EA. Comparison of methods for determining the AC/A ratio in accommodative esotropia. J Pediatr Ophthalmol Strabismus. 1999;36(4):178-83.
5. Murray C, Newsham D. Normative Values for the Accommodative Convergence to Accommodation Ratio (AC/A). Invest Ophthalmol Vis Sci. 2010;51(5):801.
6. Pankhania SR, Firth AY. The response AC/A ratio: differences between inducing and relaxing accommodation at different distances of fixation. Strabismus. 2011;19(2):52-6.
7. Gage J. A comparison of AC/A ratio measurement using the gradient method at near and distance fixation. Brit Orthoptic J. 1996;53:25.
8. Jackson JH, Arnoldi K. The Gradient AC/A Ratio: What's Really Normal? Am Orthopt J. 2004;54:125-32.
9. Horwood A, Riddell P, Turner JE, Houston SM, editors. Assessment of the AC/A ratio using a remote haploscopic photorefractor. IX International Orthoptic Congress; 1999; Stockholm, Sweden: Berufsverband der Orthoptisten.
10. Turner JE, Horwood AM, Houston SM, Riddell PM. Development of the response AC/A ratio over the first year of life. Vision Res. 2002;42(22):2521-32.
11. Judge SJ. Can current models of accommodation and vergence control account for the discrepancies between AC/A measurements made by the fixation disparity and phoria methods? Vision Res. 1985;25(12):1999-2001.
12. Horwood A, Riddell P. The use of cues to convergence and accommodation in naïve, uninstructed participants. Vision Research. 2008;48(15):1613-24.
13. Ludden SM, Horwood AM, Riddell PM. Children's Accommodation to a Variety of Targets – A Pilot Study. Strabismus. 2017;25(3):95-100.
14. Roberts TL, Manny RE, Benoit JS, Anderson HA. Impact of Cognitive Demand during Sustained Near Tasks in Children and Adults. Optom Vis Sci. 2018;95(3):223-33.
15. Horwood A, Riddell P. Differences between naïve and expert observers' vergence and accommodative responses to a range of targets. Ophthalmic & Physiol Optics. 2010;30:152-9.
16. Horwood A, Riddell P. The Clinical Near Gradient Stimulus AC/A ratio correlates better with the response CA/C ratio than with the response AC/A ratio. Strabismus. 2013;21(2):140-4.
17. Rosenfield M, Ciuffreda KJ, Chen HW. Effect of age on the interaction between the AC/A and CA/C ratios. Ophthalmic Physiol Opt. 1995;15(5):451-5.
18. Horwood A, Riddell P. Hypo-accommodation responses in hypermetropic infants and children. BJOphth 2011;95(2):231-7.
19. Horwood AM, Toor SS, Riddell PM. Change in convergence and accommodation after two weeks of eye exercises in typical young adults. J AAPOS. 2014;18(2):162-8.
20. Mollon JD, Bosten JM, Peterzell DH, Webster MA. Individual differences in visual science: What can be learned and what is good experimental practice? Vision Res. 2017;141:4-15.
21. Horwood AM, Riddell PM. Disparity-driven vs blur-driven models of accommodation and convergence in binocular vision and intermittent strabismus. Journal of American Association for Pediatric Ophthalmology and Strabismus {JAAPOS}. 2014;18(6):576-83.
22. Horwood A, Riddell P. Developmental changes in the balance of disparity, blur and looming/proximity cues to drive ocular alignment and focus. Perception. 2013;42:693-715.
23. Toor S, Horwood AM, Riddell P. Asymmetrical accommodation in hyperopic anisometropic amblyopia. British Journal of Ophthalmology. 2017; Oct 19. pii: bjophthalmol-2017-310282. doi: 10.1136/bjophthalmol-2017-310282. [Epub ahead of print].