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Abstract

Aim: **Orthoptists are familiar with AC/A ratios and the concept that accommodation drives convergence, but the reverse relationship, that of the accommodation associated with convergence, is rarely considered.**
Methods: **This article reviews published evidence from our laboratory which has investigated the drives to both vergence and accommodation. All studies involved a method by which accommodation and vergence were measured concurrently and objectively to a range of visual stimuli which manipulate blur, disparity and proximal/looming cues in different combinations.**
Results: **Results are summarised for both typical and atypical participants, and over development between birth and adulthood.**
Conclusions: **For the majority of typical children and adults, as well as patients with most heterophorias and intermittent exotropia, disparity is the main cue to both vergence and accommodation. Thus the convergence→accommodation relationship is more influential than that of accommodative vergence. Differences in 'style' of near cue use may be a more useful way to think about responses to stimuli moving in depth, and their consequences for orthoptic patients, than either AC/A or CA/C *ratios.* The implications of a strong role for vergence accommodation in orthoptic practice are considered.**

Key words: AC/A, Accommodation, CA/C, Convergence

Introduction

Orthoptists are very familiar with the idea that accommodation (A) drives convergence (C). It has been a fundamental concept of orthoptics since the earliest classic texts on the theory of strabismus.[1] As we often very successfully manipulate the angle of strabismus with lenses, our clinical experience seems to confirm it as an important mechanism. But how often do clinicians think about the inverse relationship – the vergence that leads to accommodation (the 'CA/C' relationship)?

Our laboratory measures accommodation and convergence; in both eyes concurrently, objectively, and naturalistically using a remote haploscopic photorefractor. We have now tested over 800 participants of all ages and with a wide range of clinical conditions, so we have a very good overview of how people behave. We measure how vergence and accommodation relate to each other and how they relate to the three main cues (blur, disparity and proximal cues/looming) that drive them. This research has given us overwhelming evidence that, in most cases, accommodation does *not* drive much vergence, and it is usually the other way round.

In fact, neither phrase is precise: accommodation does not *drive* vergence, neither does vergence *drive* accommodation, but both *are driven by* a combination of cues from the outside world, of which disparity (usually considered by clinicians as only a vergence drive) predominates. This review paper gives an overview of research from our laboratory which has led us to re-think the fundamental mechanisms which influence orthoptic patients. Convergence accommodation may be much more important than most clinicians think. A discussion of the background and some theory will be followed by discussion of how this might change how we understand some clinical issues.

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Why the poor attention to convergence accommodation before?

There are three main reasons why convergence accommodation is rarely considered:

1. Firstly, our experience with a few special orthoptic patients has given us a false impression of how typical eyes behave. Lenses clearly change angles in accommodative strabismus, so we have 'evidence' that blur is always the stronger influence (i.e. blur drives accommodation which drives accommodative vergence: blur→A→AC).

But if we consider accuracy of cues, disparity detection is a much more precise system than blur detection. For example, typical depth of focus is approximately 0.5D, so an image at 50 cm could be seen as clear anywhere between 40 cm and 66 cm; and myopic and hypermetropic blur look subjectively very similar. In contrast, a fairly normal 55″ arc stereopsis using the Frisby test means we can spot 1.5 mm difference in depth, and can also easily tell whether the disparity is crossed or uncrossed. Why would anyone drive responses using a distance judgement made from blur, with a possible (and largely non-directional) error of 10–16 cm, when disparity provides almost 100 times more accuracy? Physiologists, for example Judge's

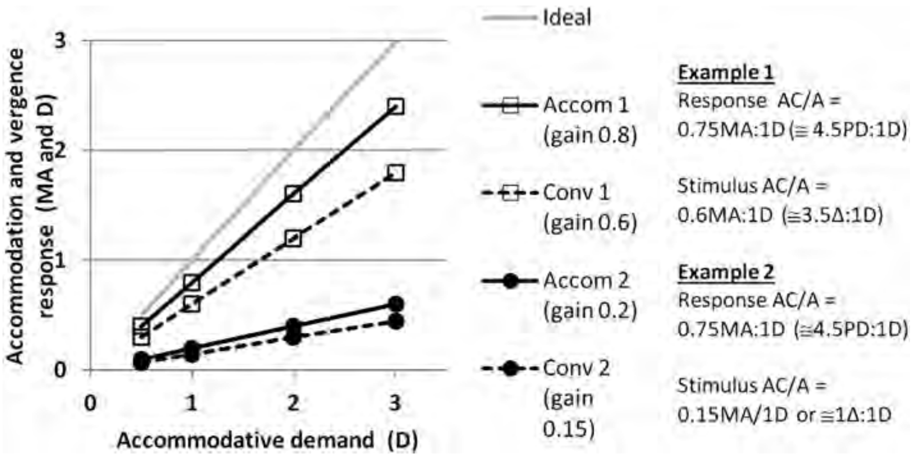

Fig. 1. Possible responses to a blur-only target, both of which we see in the laboratory. Example 1: Good vergence response and slightly lower accommodation response. Example 2: Poor vergence and accommodation responses to blur. Calculated AC/A ratios from these data are shown on the right. Response AC/A ratios can be identical with very different responses, while stimulus AC/A ratios differ from response ratios, and between examples. (Reproduced from Horwood and Riddell.[11])

group, found disparity to be the primary drive to near responses in primate studies from the 1980s and 1990s,[2,3] but many clinicians still consider accommodative vergence to be the primary drive to convergence.

If accommodation is primary, why don't all hypermetropes have accommodative esotropia? Why don't all uncorrected myopes have large near exodeviations because they can see for near without accommodating (and so do not produce accommodative convergence said to be the main contributor to the 18^{Δ} of vergence an adult with an interpupillary distance (IPD) of 60 mm needs to achieve to fix at 33 cm)? Current models explain these inconsistencies, which a 'strong A→AC theory' would predict, by claiming that slow tonic adaptation and positive and negative relative vergences work to counteract the angles driven by accommodative vergence. But an alternative explanation could be that blur-driven accommodative vergence is just less often induced than we think, so compensatory mechanisms are not required to counteract it. Although for a few of our patients A→AC linkages *do* seem to matter (the accommodative esotropias), perhaps they are a specific group who behave differently from most people? Could this be why they become patients?

2. Secondly, we can measure an AC/A ratio apparently easily. We put up a lens and the angle changes, therefore that must be how the system always works. But we usually only carry out this test in the types of squint where we predict we might find something abnormal, so are we getting a skewed impression? How often is the AC/A ratio tested when we would expect it to be normal? Despite literature stating that a normal ratio is around 4^{Δ}/1D we rarely question why lenses often change angles very little (a 'low' ratio). When clinical AC/A ratios are tested in typical groups, the ratios are often much lower than the 3^{Δ}:1D – 5^{Δ}:1D that textbooks tell us to expect[4–6] and ratios obtained using different methods, which should be the same, rarely correlate.[5,7,8]

Importantly, most laboratory research, which is often used to extrapolate to clinical situations, uses response AC/A ratios. These involve measuring both the vergence change and the accommodative *response* to a pure change in blur (usually induced by a lens). It is from this laboratory research that the 'about 4:1 is normal' belief stems. Response ratios are considered the most accurate, and do give a true ratio, but they are often very different from the 'stimulus' methods available to clinicians. When using stimulus methods we assume that because a patient has been given a 3D stimulus they will accommodate 3D, and we then work out the ratio based on that assumed response. Because of depth of focus of around 0.5D, most people only need to accommodate 2.5D anyway, even if they really clear the image subjectively. So response ratios are generally higher than even the most accurate stimulus ratios because the divisor is smaller. In our laboratory we find that very few people actually clear induced blur completely, even to a detailed target, and many seem very happy with what must be significant blur for detailed targets.[9] Even when given a demanding task such as to N5 text, accommodative responses may still be less than we would expect.[10]

Very different clinical response patterns can also produce identical response ratios.[11] Figure 1 (reproduced from Horwood and Riddell[11]) illustrates two different individuals with identical response AC/A ratios and very different actual responses to a blur-only stimulus (one 'good' (Example 1) and one poorer (Example 2; but a surprisingly common finding)). The figure shows how the different responses lead to very different stimulus and response ratios, especially if responses to blur cues are poor (Example 2). This shows how our clinical (stimulus) AC/A ratios can be little more than a rough guide to the true relationship between convergence and accommodation. Nevertheless, clinicians continue to measure and use stimulus AC/A ratios because they are readily available.

3. The third and main reason clinicians have ignored the disparity→C→CA relationship (disparity drives vergence and also convergence accommodation) is that it is extraordinarily difficult to measure. Accommodation needs to be measured objectively in at least one eye, while presenting a fusional vergence stimulus (with a prism or haploscopic device) to both eyes, all at the same time, without the refraction interfering with the stimulus.

Table 1. The inverse relationship between AC/A and CA/C relationships. Top row shows examples of calculations of response AC/A and CA/C ratios in a 'normal' relationship; lower rows show the 'High AC/A – Low CA/C' scenario (vergence exceeds accommodation) and the 'Low AC/A-High CA/C' scenario (accommodation exceeds vergence)

Target demand at 33 cm (IPD = 60 mm)			Actual responses to blur-only stimulus (e.g. lenses and dissociated)						Actual responses to disparity-only stimulus (e.g. prisms but open-loop accommodation)					
MA	D	Δ		D	Δ	MA	AC/A (Δ:D)	AC/A (MA:D)		D	Δ	MA	CA/C (D:Δ)	CA/C (D:MA)
3	3	18	**Normal**	2.5	12	2	4.8:1	0.8:1	**Normal**	2.5	18	3	0.14:1	0.83:1
			High	2.5	24	4	9.6:1	1.6:1	**Low**	1	18	3	0.06:1	0.33:1
			Low	2.5	2	0.33	0.8:1	0.132:1	**High**	3.5	18	3	0.19:1	1.17:1
			N.B. Some accommodative lag is typical.						N.B. Fusion is typically accurate.					

Until recently, this has only been possible in highly controlled laboratory setups, and so children and patients have rarely been tested. But just because it is difficult to measure does not mean it is not important.

How do the AC/A and CA/C ratios relate to each other?

Although it is generally accepted that, in an individual, CA/C and AC/A ratios exist in broadly inverse or reciprocal relationships (with a high AC/A accompanying a low CA/C, and vice versa[12–17]), this concept does not convey much meaning. It may be slightly easier if it is re-phrased as 'if someone drives their vergence from blur, they don't drive accommodation as much from disparity'.[11]

How does this work? Table 1 illustrates responses we could typically find in the laboratory or on clinical tests. An 'ideal' response to a target at 33 cm (in an adult with a 60 mm IPD) would be 3D of accommodation and 3 metre angles (MA*) or 18^{Δ}, of vergence). In fact, because accommodative lag is typical, few people accommodate completely to a blur target, so while vergence is usually almost perfect at 18^{Δ} (or 3MA) to a disparity-only target, 2.5D of accommodation (or often much less) is common. So a typical normal AC/A ratio would be 4.8^{Δ}:1D (0.8MA:1D) and a typical normal CA/C ratio would be 0.14D:1^{Δ} or 0.83D:1MA. If the D and MA responses of the 'Normal' example in Table 1 are compared, they show that it is normal to converge a little more than to accommodate to disparity stimuli (prisms), and to accommodate a bit more than convergence to blur stimuli (lenses).

But if these ratios are not typical there is usually a roughly inverse or reciprocal relationship between them. This means that a person with a high AC/A ratio might well have a low CA/C ratio (which just means that convergence is always proportionally greater than accommodation), while a person with a low AC/A ratio would have a higher CA/C (i.e. accommodation always exceeds convergence).

*Why do we use metre angles instead of dioptres or degrees of vergence? Metre angles give a direct vergence equivalent to dioptres of accommodation, and are independent of IPD, so we can compare the *appropriateness* of convergence for a target demand. For example, a baby with an IPD of 40 mm needs to converge only 12^{Δ} at 33 cm, while a large adult with a 70 mm IPD needs to achieve 21^{Δ}, but to respond perfectly both need to achieve 3MA of vergence to the 3D of accommodation the target demands.

Ratios or cues?

Both accommodation and convergence are necessary to look at a near object, and the brain makes a calculation of where that object is in space based on different cues which are mostly visual (blur, disparity, motion parallax, overlay of contours, perspective, looming, colour, etc.) but which can also be non-visual (awareness of nearness, touch, proprioception). This global calculation is then used to drive both accommodation and convergence. This is the main reason we try to refer to cues and their relationship, rather than A/C 'ratios' *per se*. The cues drive both vergence *and* accommodation responses; the ratios are only a consequence, not a cause of, differences between groups determined by the weighting placed on each cue.

Because techniques to measure the disparity→C→CA and blur→A→AC relationships usually differ, the relative weighting of blur compared with disparity has been difficult to assess under similar conditions of testing, lighting and recording. Most laboratory studies use unnatural or demanding tasks, sometimes only possible after training or practice, and participants are often opportunistically recruited from optometry or orthoptics students and staff who may unconsciously behave differently from naïve observers.[18] Our laboratory can assess the relative influence of each cue to drive uninstructed responses under otherwise standard conditions. We can measure accommodation and convergence simultaneously and naturalistically, and we can manipulate blur, disparity and proximal/looming cues independently to show how each drives responses when presented in isolation, and also how removing the same cue degrades responses when the other two remain.[9] We have also looked at the development of cue use across the lifespan, from prematurity to middle age.

Typical development

AC/A linkages are said to be innate, and indeed we have published that mean AC/A ratios do not change significantly in typical development.[19] But what does change is the weighting of the cues we use to drive our eyes. In adults and children over 5 years of age, disparity is by far the strongest cue, with blur and proximal cues being much weaker, so disparity→C→CA linkages are more influential than blur→A→AC.[9]

Infants and young children are very different. We studied 45 infants over their first year to explore developmental changes in cue use.[20] In very early infancy, proximal and looming cues (especially to approaching targets) are by far the best driver of responses. Visual acuity is poor and stereopsis does not emerge until 12–16 weeks of age,[21] making both blur and disparity unreliable cues under 12 weeks of age. Therefore proximity/looming is probably the most reliable cue for neonates to use. We have found that responding to proximal cues also seems to account for neonatal misalignments,[22] and may persist to drive infantile esotropia if stereopsis does not develop normally.[23]

In 'middle infancy' between 16 weeks and 1 year, visual acuity improves and stereopsis develops in typical infants, so all three cues become available. We found that responses to all three cues are more evenly balanced at this stage, but by 5–9 years of age the adult-like pattern has emerged as blur and proximal cues become less influential and disparity begins to predominate.[20] The disparity→C→CA linkage becomes more important, while the blur→A→AC and proximity→C & A drives lose weighting.

Infants' responses are also frequently erratic, and in infancy it is common for accommodation and vergence to appear to act much more independently. Although *mean* AC/A ratios for groups tested at different ages do not change during development, for individuals the development of a 'fixed ratio' actually only arises as individual children appear to learn that it is a good idea to converge and accommodate more or less in parallel.

Much of children's more general development involves similar shifts in emphasis and strategy: for example, a whole-hand grasp is abandoned in favour of a pincer grip; reading starts with children decoding individual letter sounds but ends with whole-word recognition. While practising any new skill, it is useful to be able to compare many different strategies, so early flexibility is advantageous. In many developmental spheres, mature control mechanisms and motor efficiency are often a result of a 'parsimonious' developmental process, with reliance on superfluous cues being pared down in favour of the most efficient and effective. Little-used neural connections in the cortex are pruned in favour of those which are reinforced. The same seems to occur for disparity cues superseding blur (and particularly proximal cues) to drive vergence and accommodation.

Typical responses beyond early childhood

For most older children and adults with normal binocular vision, adding or taking away modest blur makes little difference to either vergence or accommodation, especially if disparity is still available. So however much convergence is associated with each dioptre of blur-induced change in accommodation (the AC/A ratio), blur does not induce much change in the first place, so AC/A ratios are not very important for everyday behaviour. However, disparity generally drives the majority of both vergence *and* accommodation, so if disparity cues are available, vergence and accommodation are accurate, but if disparity is excluded (by occlusion, for example) both convergence and accommodation usually fail. This is why we should be paying more attention to not only the fusional vergence that disparity drives, but also the resulting vergence accommodation (the disparity→C→CA linkage).

Style

While for most people the blur→A→AC linkage (and the role of blur cues) is of little importance and the role of disparity→C→CA linkage is strong, this is not always the case. And it may be one reason why orthoptists, ophthalmologists and optometrists may ascribe more importance to accommodative vergence than is true for the general population. A major factor which has emerged from our research is that there are many different 'styles' by which people can drive their near responses. Although most people use disparity as their main cue, there are others who *do* use blur, and this blur response can lead to a strabismus. For them, the blur→A→AC linkage is more highly weighted. Children with accommodative esotropias seem to be such 'blur people'. We have evidence that there are different blur- and disparity-biased styles which we can detect in our laboratory and which correlate with a wide range of specific clinical diagnoses in heterophoria, intermittent strabismus, refractive error and accommodation/convergence anomalies.[11] We hypothesise that there may also be 'proximity people', for example in non-binocular strabismus where proximal cues could remain influential beyond early infancy. It appears that it may be just as, or more, important to know an individual's (or clinical group's) style as to measure any 'ratios', and our model goes much further to explain clinical characteristics that we meet. For a detailed discussion of this see Horwood and Riddell.[11]

We suggest that the more even weighting of cue use in middle infancy may provide a mechanism for the development of these differences in style between individuals and between clinical diagnoses.[11] It would allow different styles to emerge during the critical periods of visual development, based on the best cues an infant has available at the time. If stereopsis emerges normally, the most accurate and efficient disparity→C→CA 'normal' pattern develops. But if stereopsis does not emerge normally, perhaps due to minor brain insults as are common in prematurity, or a family history of binocular vision defects, or if stereopsis is degraded by anisometropia or suppression, then the 'next-best' cue may be adopted, leading to a child developing stronger weighting to blur or proximal cues, and weaker fusional vergence. Refractive error, especially superable hypermetropia, would aggravate this because it provides a greater-than-normal blur cue. This might explain why plus lenses change angles in some strabismus patients but not those of non-strabismic people.

How could thinking 'convergence accommodation' rather than 'accommodative convergence' affect clinical issues?

If it is accepted that disparity drives both vergence and accommodation more than blur does, many clinical findings can be explained in a very different way from conventional clinical thinking. Our research is all pointing in this alternative direction. In some diagnoses we only have predictions, while in others we have stronger evidence.

1. Dissociation reduces accommodation

(a) In our laboratory, for the majority of people, binocular accommodation is much better than monocular accommodation, so dissociation makes accommodation much worse or harder. We should encourage people to be binocular if we want to help them accommodate.

We studied a large group of young adults given a range of different orthoptic exercises.[24,25] Convergence exercises (even to a non-accommodative target) helped convergence *and* accommodation much more than accommodation exercises.

So should we pay much attention to monocular accommodation in our patients? Monocular accommodation exercises (e.g. flipper lenses) may help someone learn to pay more attention to blur, or help in situations when someone needs to be, or is forced to be, monocular, or when vergence and accommodation need to be used independently. In our study of normal young adults, monocular accommodation facility was particularly prone to pure short-term practice effects.[24] Many people have poor monocular accommodation at first, but rapidly get better just by repeated testing. It appears that monocular accommodation can often be not truly weak, just rarely practised.

Surprisingly, we also found that the 'relative vergence/accommodation' methods, usually considered the optimal way to improve accurate fusional vergences, were less effective in changing responses than exercising disparity and blur separately, so we have some evidence to suggest that responses to blur and disparity exercises may act in an additive fashion, but with vergence exercises producing the most objective change.

(b) Clinicians may ask about diplopia when convergence fails, but what is also clear from our research is that when control or convergence in intermittent exotropia fails for near, so does the accommodation.[26] If specifically asked, many children notice *blur* as they decompensate, not diplopia. So not only are they losing binocular vision on decompensation, it is also going blurred. This means that loss of control for near may be more significant for children's lives and education than previously thought. Alerting them to blur as a possible cue to loss of control might give us an additional technique to help them learn subjective awareness of their exotropia.

(c) Could poor accommodation on occlusion be why detailed close-work tasks are said to hasten response to amblyopia treatment? Evidence for this common advice has not been found by a PEDIG[27] study of a group of mixed types of amblyopia, but the full binocular status of their patients was not reported or analysed in detail. Accommodation would only be expected to be at risk on occlusion (and need to be encouraged) if disparity was usually used to drive it, so only those with relatively good motor fusion would be predicted to benefit from any additional attention to close work. Concentrating on detail will at least ensure that we encourage children to accommodate in a situation when they may naturally not do so much.

2. Lenses help an angle if you are a 'blur person'; surgery or prisms might change accommodation if you are a 'disparity person'

We often expect lenses to change angles, but our research explains why often lenses do *not* change angles for many people: they may just not be 'blur people'. They may, however, be 'disparity people', so changing blur with lenses will not affect the angle much, but changing an angle with prisms or surgery might have adverse accommodative consequences. This remains to be investigated.

3. Intermittent exotropes do not 'use accommodation to control'

Some children with distance exotropia are said to be using accommodation to control for near if the angle increases with plus lenses. Instead, and perhaps more logically, our research has found that all the intermittent exotropes we studied *converge* to control.[28] Most intermittent exotropes appear to be 'disparity people' and are no more reliant on blur cues than the general population. They appear to converge to overcome their primary large exodeviation, which then may *bring along* additional accommodation, so they actually accommodate a bit more than typical children and some may even over-accommodate. Minus lenses seem to work not by 'making them accommodate' but by *allowing* them to do as much convergence as they need; the lenses just correct any resultant over-accommodation.[29–31] The lenses mean that these children do not have to choose between a distance situation of straight eyes but resultant over-accommodative myopic blur, or normal accommodation but divergence. This would explain why minus lenses are only generally a temporary aid to control because the basic divergent angle, and the excessive convergence demand, remain the same.

4. Exotropia surgery might cause hypo-accommodation and risk convergence excess

A child with intermittent exotropia is likely to learn that a large amount of convergence is necessary to control their deviation, but they still only need to accommodate normally, so they learn to drive appropriate accommodation along with this excessive convergence. They still use disparity as the main cue, but have a low CA/C ratio as many dioptres of convergence are associated with each dioptre of accommodation. A good post-operative result and a smaller angle makes control easier and the vergence demand less, but they also suddenly lose a primary drive to accommodation, so risk under-accommodation. The only way they have ever accommodated is also with a large amount of convergence, so this could explain why a few children produce the hypo-accommodative convergence excess esotropias that can occur post-operatively, especially in the 'high AC/A ratio' types described by Kushner[32] who show a large increase in angle with plus lenses for near after diagnostic occlusion (but see point 5 below).

Fortunately for most, the A-C linkages are fairly flexible and so post-operatively patients quickly learn to re-calibrate how much accommodation comes along with the new vergence demand of a reduced angle. A near plus lens addition (or possibly monocular accommodation practice pre- or post-operatively) may help them in the short term while this re-calibration of their vergence and accommodation relationship occurs. Monocular accommodation exercises (showing them how to accommodate to blur or proximal cues) might be a useful pre-operative strategy for these children.

5. The near gradient 'AC/A ratio' may actually tell us something about the CA/C relationship

The near (plus lenses) and distance (minus lenses) methods of measuring a clinical AC/A ratio are often used interchangeably. In our laboratory, we regularly calculate objective response AC/A and CA/C ratios, as well as carrying out both clinical methods. So we were able to look at the correlations between the objective CA/C and AC/A ratios we measure compared with the near (+3.0DS) and distance (−3.00DS) clinical gradient AC/A ratios. While we found only very weak correlations between the two clinical ratios, the best correlation of all was between the near clinical AC/A and the laboratory CA/C ratio ($p = 0.004$).[5] We suggest that the poor correlation between the near and distance clinical ratios is because they could actually be assessing different relationships. Our alternative, but equally plausible, explanation is that the near +3.0D responses reflect the disparity→C→CA linkage (CA/C) thus:

The occlusion of the prism cover test dissociates the eyes, stops convergence and so also stops a major accommodation drive, so accommodation naturally relaxes. But the orthoptist is telling the patient they must make the image clear, and the only way that many intermittent exotropes know how to accommodate is by converging too: so the full divergent angle cannot be allowed to relax. The plus lenses used for the second part of the test give automatic clear near vision without accommodation being necessary, so convergence can be allowed relax fully and the full angle is revealed.

Thus a 'high near gradient AC/A ratio' may actually be telling us more about how much convergence is needed to drive accommodation, rather than vice versa. This is why it predicts the risk of post-operative hypo-accommodative convergence excess (as in point 4 above). Comparing angles with and without plus lenses for near (and making sure the target is fully cleared throughout) might provide us with a practical way of estimating the disparity→CA→C relationship in the clinic, which is currently impossible.

6. Poor convergence or binocular vision may have refractive error consequences

If good convergence is necessary for good accommodation then this might be an additional reason why children with strabismus often fail to emmetropise.[33–35] Clear retinal images are implicated in normal emmetropisation, but if poor binocular vision causes sub-normal accommodation (as is also common in refractive error[33,36-42]), then it may impair emmetropisation due to increased blur for near, even when refractive error is corrected for distance. This is a possible direction for further study.

So should we abandon measuring AC/A ratios?

No. But we should not place too much reliance on one measurement or any specific number, and we should be aware of what we are assessing. A 'high' stimulus gradient AC/A ratio tells us that blur is a significant cue to drive vergence, so lenses will change angles, and is still clinically useful to predict and guide management; but it is *not* the true AC/A ratio. The near gradient 'AC/A' could actually instead be telling us something about the CA/C linkage, and currently is the only clinical method available to tell us anything about this relationship.

So, in conclusion, we should consider convergence accommodation in many aspects of orthoptic practice. It is important that we think about what we are doing when we carry out these tests, and acknowledge their limitations. Most people converge to accommodate, so even if we cannot measure it, convergence accommodation probably affects more aspects of our everyday practice than commonly believed. Accommodative esotropias and possibly constant heterotropias are probably the only groups where blur-driven vergence seems to be a major consideration.

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