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INVITED REVIEW

Aberrations and accommodation

Antonio J Del Águila-Carrasco* PhD
Philip B Kruger† PhD OD
Francisco Lara‡ PhD
Norberto López-Gil‡ PhD

*Eye and Vision Research Group, School of Health Professions, University of Plymouth, Plymouth, United Kingdom
†College of Optometry, State University of New York, New York, United States
‡Instituto Universitario de Investigación en Envejecimiento (IUIE), University of Murcia, Murcia, Spain

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[Corresponding author]

Norberto López-Gil

E-mail: norberto@um.es

[Abstract]

Modern methods of measuring the refractive state of the eye include wavefront sensors that make it possible to monitor both static and dynamic changes of the ocular wavefront while the eye observes a target positioned at different distances away from the eye. In addition to monitoring the ocular aberrations, wavefront refraction methods allow measurement of the accommodative response while viewing with the eye's habitual chromatic and monochromatic aberrations present, with these aberrations removed, and with specific aberrations added or removed. A large number of experiments describing the effects of accommodation on aberrations and vice-versa are reviewed, pointing out the implications for fundamental questions related to the mechanism of accommodation.

[Introduction]

Accommodation can be thought of as a natural adaptive optics mechanism to improve the retinal image quality of objects placed at different distances. It was Thomas Young who demonstrated at the beginning of the 19th century that the change in refractive power of the eye is due to the crystalline lens.[1,2] Currently, it is well known that there are no significant changes in corneal power during accommodation,[3,4] and only small changes have been observed in the sclera.[5] In addition to this, Young realised that the refractive power in the periphery of his pupil was greater than in the centre, and when he accommodated, the refractive power distribution was opposite.[1,2] This was the first observation that proved that the spherical aberration (SA) of the eye changed its sign with accommodation.

Two centuries after Young's discoveries, the measurement of spherical and other aberrations of the accommodated eye can be performed *in vivo* using wavefront sensors. As accommodation changes dynamically,[6,7] fast wavefront sensors, such as a Hartmann-Shack need to be used.[8,9] The experimental system should include the possibility of changing the vergence of the target (by changing the distance between the eye and the target, or by adding lenses), to stimulate subject's accommodation. There are several commercially available devices that can measure aberrations while stimulating accommodation (for example, irx3, COAS-HD, WASCA, iTrace) as well as custom-built systems.[10]

Figure 1 shows a schematic of the methodology typically used to measure ocular aberrations during accommodation in a static procedure. A Badal lens (not shown) is usually used so the target always subtends the same visual angle regardless of its optical vergence.[11] After each change in vergence the target remains static for some time before the wavefront is measured to allow time for the subject to accommodate. Step changes in vergence (0.5 D in Figure 1), far point (FP), maximum vergence, and target configuration (for example, monochromatic/polychromatic, spatial frequency content) vary depending on the study. For dynamic studies, the target vergence is usually modified continuously, following a predetermined vergence function such as a sinusoidal or a random step function.

Besides the changes of ocular aberrations due to the change in curvature of the external surfaces of the crystalline lens of the eye,[12] the ocular wavefront may also change due to:

- displacement and tilt of the lens[13]
- pupil changes (accommodative miosis)[13]
- torsions on the eye globe produced by binocular convergence[14]
- changes of the internal iso-indicial surfaces of the lens.[15]

The study of accommodation and its relationship with aberrations can be carried out through two time domains: static and dynamic. The term static accommodation refers to the steady state condition of accommodation while viewing a stationary target at a fixed distance from the eye. But accommodation is never really static, instead fluctuating continuously over a small range. These small microfluctuations[6,7] of accommodation are a dynamic characteristic of accommodation even under static steady state conditions. Dynamic accommodation refers to the change in ocular focus that occurs in response to changes in accommodative demand, including sudden step changes from one target distance to another, sinusoidal changes, and unpredictable sum-of-sines changes in target distance. Finally, dynamic accommodation also refers to the ongoing microfluctuations of accommodation.[6,7]

Knowledge of how aberrations vary with static accommodation provides information about the shape of the surface of the lens[12] as well as information about its internal structure.[15] Dynamic accommodation studies usually shed light on fundamental questions such as which cues trigger the accommodation system to accurately change the power of the lens and accommodate in the right direction,[10,16–19] which is of particular interest concerning myopia development.[20–22] From an applied science perspective, knowledge of how aberrations change with accommodation can lead to improved designs of multifocal and accommodative intraocular lenses, which imitate the profile of ocular aberrations during accommodation. Knowing the effect of aberrations on accommodation can also lead to new contact and intraocular lens designs with customised aberration profiles that extend the depth of field.[23–25]

This review examines the relationship between accommodation and ocular aberrations in detail. Given the differences in methodologies and the different types of aberrations considered by different authors, this manuscript treats static and dynamic accommodation, and the effect of monochromatic and chromatic aberrations separately.

The influence of aberrations on the subjective and objective amplitude of accommodation

The amplitude of accommodation (AA) can be measured objectively as the dioptric change between the FP and the near point (NP). However, the eye does not present a constant refractive power across the whole pupil due to astigmatism and other higher-order aberrations (HOAs), and theoretically numerous FPs and NPs exist depending on the region of interest examined within the pupil. Therefore, HOAs influence the AA. A number of objective methods (metrics) for determining accommodation or AA from wavefront analysis have been applied.[26,27] All of them show smaller objective AA values than the subjective AA obtained as the dioptric difference between the subjective far and near points. Three optical reasons have been proposed to explain such differences:

Typically, subjective AA is measured after correcting any distance ametropia and computed as the inverse of the distance to the NP with respect to the spectacle plane. However, using this reference plane without performing the corresponding mathematical correction overestimates subjective AA, especially in young myopic subjects.[28]

The metric chosen to calculate the subjective AA can cause a false accommodative error. For instance, positive SA (typical in an unaccommodated eye) can cause the objective measurement of the FP to be more myopic than the subjective one,[29,30] and as a consequence an accommodative lead will be observed (Figure 2). On the other hand, negative SA (typical in the accommodating eye), can result in a smaller objective maximum accommodation than observed with the subjective method, which translates to an apparent accommodative lag[12,29,31,32] (Figure 2).

It has been demonstrated that the eye uses its depth of field both in far and near vision in order to increase the subjective AA.[33] In addition to the limitation imposed by photoreceptor sampling and photonic noise, depth of field occurs because of the presence of HOAs when the pupil is larger during relaxed accommodation,[24] and as a consequence of the accommodative miosis.[34]

Monochromatic aberrations and static accommodation

During accommodation, not only is the defocus term modified, but other monochromatic aberrations vary too. The change in monochromatic aberrations during accommodation has been studied extensively.[29,35–38] In general, all monochromatic aberrations change with accommodation, however, this change is generally small and subject-dependant.[37]

The change in astigmatism is generally small,[39] although there are some exceptions where the magnitude and axis vary significantly with accommodation.[40,41] Changes in astigmatism with accommodation may be due to an increase in lens tilt caused by the combined effects of a slacker zonular tension and gravity.[42] Astigmatism can also change with accommodative miosis in the presence of HOA, although this potential explanation has not been verified to date.

Third-order aberrations (that is, coma and trefoil) may also vary during accommodation, but not systematically,[36,37] and in many eyes these aberrations remain relatively stable over the range of accommodation demands.[35,42,43]

In the case of fourth-order SA, there is agreement between numerous studies about its well-defined trend, becoming less positive (or more negative) with increasing accommodation.[29,35,36] As mentioned earlier, this was originally discovered by Young,[1,2] although he did not give it the name of SA. After Young, many others reported this change,[29,35,36] which has been proven to be generated because the hyperbolic shape of the surfaces of the crystalline lens.[12] Usually, in the relaxed eye corneal positive SA is larger than the absolute value of the crystalline lens SA (negative value), so the total eye has a slight positive SA. However, when the eye accommodates the crystalline lens increases its SA negative value, and the total SA of the eye becomes negative (see Figure 3). Therefore, generally speaking, the relaxed eye has positive SA and the accommodated eye has negative SA. However, there are exceptions to this rule. For instance, the eye may have negative SA when relaxed which becomes more negative during accommodation; or it may have a large positive value of SA which decreases during accommodation but never becomes negative. But in any case, SA decreases with accommodation for a fixed pupil size.

There are no other systematic changes in any HOA except sixth-order SA, which increases during accommodation.[12,44] However, the values of that aberration are usually very small, and in many cases fall below the experimental errors.

There are a few studies that have shown how some aberrations influence static accommodation. In particular, Khosravi[45] showed that the accommodation response to a grating stimulus in the presence of astigmatism depends on the orientation of the grating, but for multiple orientations, the accommodation response usually corresponds with the circle of least confusion. A different study used adaptive optics to study the effect of one micron of coma or fourth-order SA on the accommodation response, finding that those aberrations may increase the accommodation error, especially when positive SA was induced.[46] The effect of fourth- and six-order SA on the accommodation response has also been studied theoretically by other researchers[32] with the hypothesis that the change of SA during accommodation may play a role in myopia development. Their explanation is based on the fact that the combination of negative SA (typical in the accommodated eye) with negative defocus (hyperopic image, or lag of accommodation) increases visual detection of the letters although it reduces image contrast, which may promote growth of the eye.

Chromatic aberration and static accommodation

In a non-cyclopleged eye, even when the target vergence is kept constant, the level of accommodation fluctuates continuously over a small range of approximately ±0.50 D at temporal frequencies ranging up to a few cycles per second.[6,7] Chromatic dispersion of light by the optical components of the eye[47–49] results in retinal images of polychromatic objects with subtle colour fringes at the edges that reliably indicate whether the image is focused behind or in front of the retina.[47–49] These colour fringes change substantially when the eye changes focus (Figure 4). When red light is focused on the retina, blue light is focused in front of the retina, and a fuzzy blue colour fringe is formed at the image edge, so under-accommodation (hyperopic defocus) is characterized by a red colour fringe, while over-accommodation (myopic defocus) results in a blue colour fringe. These colour cues provide reliable directional signals for accommodation.[50–54]

Fincham[50] was the first investigator to remove the effects of chromatic aberration by using monochromatic light and by placing a specially designed achromatizing lens in front of the eye. He used a coincidence optometer to measure accommodation while trial lenses were placed in front of the subject's eye and found that accommodation was impaired in some subjects when chromatic aberration was removed. By the mid-1980's high-speed recording of accommodation was available[55] to test Fincham's hypothesis that chromatic aberration provides a cue for static accommodation. Subjects viewed stationary targets at 0 D, 2.5 D and 5 D in white and monochromatic light, and in white light with chromatic aberration reversed by a specially designed lens.[52] When chromatic aberration was removed, some subjects had difficulty accommodating and when chromatic aberration was reversed, so that blue light focused further back in the eye than red light, accommodation was severely impaired, and some subjects accommodated in the wrong direction when chromatic aberration was reversed.

Next, computer-generated images that simulated hyperopic and myopic defocus with and without the effects of longitudinal chromatic aberration (LCA)[53] or transverse chromatic aberration (TCA)[54] were used to drive accommodation for near and far distances. These simulated images were viewed through small pinhole pupils to eliminate the normal blur feedback from trial-and-error microfluctuations[6,7] of accommodation that were believed to be essential for effective accommodation. Accommodation responded readily to these static simulations of LCA, and accommodation was not adversely affected by simulations of LCA that included typical amounts of TCA.

Some authors have argued that chromatic aberration does not play a role in accommodation because when an isoluminant target is used (that is, a red target on a green background or vice-versa, both with the same luminance), accommodation is not induced.[56,57] However, this conclusion may not be valid[58] since colour and luminance signals are mixed in a single neural channel rather than separate channels.[59,60] Furthermore, it is well known that many other visual functions fail under isoluminant target conditions, including form, colour, motion, and depth perception.[59,61,62] Further investigations are required in this field.

The magnitude of longitudinal chromatic aberration depends on the refractive index and dispersive power of the ocular media. The crystalline lens of the eye has a gradient refractive index structure (GRIN) with maximum refractive index at the centre and a minimum at the periphery.[63–65] During accommodation it becomes more convex, especially the anterior lens surface, and there is also a change in the distribution of the gradient refractive index that produces a small increase in the equivalent refractive index of the whole lens. The increase in the equivalent refractive index is approximately 0.0013 per dioptre of accommodation.[63–65] This is accompanied by a small increase of the chromatic aberration of the eye amounting to approximately 3% per dioptre of accommodation.[49] Charman measured an increase of approximately 0.2 dioptres of chromatic aberration between 422 nm and 633 nm when accommodating six dioptres.[49]

In another study, Jaskulski et al[66] studied the accommodation response to three target vergences for three different wavelengths and white light, all having the same luminance. They found a shift in refractive error for each colour condition corresponding to the defocus shift created by the LCA, but the accommodation responses did not change significantly. However, Kruger et al. found that some subjects accommodated less accurately in monochromatic light when stationary targets were positioned significantly closer or further away than the subject's resting position of accommodation.[52]

Monochromatic aberrations and dynamic accommodation

How does the visual system know when to accommodate or disaccommodate and by how much? Researchers have been trying to answer to this fundamental question for a long time, and still there is not a completely satisfactory answer. It is well known that the visual system makes use of information from the outside world, such as the intensity and wavelength of light reflected from objects, as well as information about the interaction of light with the optics of the eye itself, such as the effects of inaccurate refraction and chromatic dispersion. This information that the visual system uses in order to change the accommodation state accordingly is typically referred to as "cues" for accommodation.[67] For example, from the disparity between the two signals, or images, formed by the two eyes, the visual system is able to interpret depth,[68] and depth perception guides accommodation.[50,69] Nonetheless, most people are able to accommodate correctly under monocular conditions. The reason for this is that the visual system can extract depth information from monocular cues. Some of these monocular cues are apparent distance,[70,71] changing size,[72–74] and interposition of objects.[71] But even when all these monocular cues that allow the visual system to interpret depth are removed, many people are still able to change their accommodation state appropriately. How is this possible with the lack of external cues? In this case, the visual system uses information extracted from the image formed on the retina, or from the way light rays reach the retina (optical cues for accommodation). It is known that an out-of-focus retinal image of a perfect eye without astigmatism and HOAs can trigger accommodation.[75] However, there are other optical cues that are based on the fact that images formed at the retina differ if they are focused in front (myopic defocus) or behind the retina (hyperopic defocus) (see upper part of Figure 5). Even-order monochromatic aberrations, which generate different images for different signs of defocus[16,76] may also play a role. Irregularly shaped pupils,[16,77] and the Stiles-Crawford effect,[78–80] can lead to different retinal images of the object depending upon if they are formed in front of or behind the retina.[16]

One aberration that has always been linked to accommodation has been spherical defocus. Phillips and Stark[75] demonstrated that blur alone could trigger accommodation with a remarkable experiment using a sophisticated system at the time. In their experiment, the only way in which the eye could accommodate was by trial and error, or how Phillips and Stark referred to it, the eye was constantly “hunting”, searching for the correct direction of accommodation. The recorded responses were at times in the wrong direction, and then changed rapidly towards the correct direction. Their main conclusion that blur alone drives accommodation, however, seems too far-fetched from their measurement in a single subject who usually responded in the wrong direction to a sudden change in target vergence. Recent work by Del Águila-Carrasco et al[10] suggests that accommodation responds to the actual changes in target vergence, and not changes in blur alone. A similar experiment[19] to that of Phillips and Stark agreed somewhat with their results, nevertheless, when target blur was changed quickly, some participants’ accommodation was worse or even absent. An interesting conclusion of this work is that accommodation works much better when changes in light vergence were present than when there were only changes in target blur.

The majority of studies about the effect of monochromatic aberrations on dynamic accommodation have been carried out recently, thanks to the development and implementation of adaptive optics (AO) in vision.[81,82] Using AO technology, some or all the aberrations of the eye can be corrected, or different amounts of them can be induced in real time. Since some of the ocular monochromatic aberrations change with accommodation,[29,35–37] it is essential that their correction is performed in real time. By correcting particular monochromatic aberrations and evaluating the accommodative response of the eye, it is possible to assess the effect of these aberrations on accommodation, if any. Recent studies manipulating the eye's natural aberrations suggest that the eye does not use monochromatic aberrations for accommodation,[17,83–85] since no significant differences were found between the response with natural aberrations present, or corrected. In a recent experiment,[17] the accommodative response of 2 out of 8 subjects seemed to increase slightly when astigmatism was present while other monochromatic aberrations were corrected. A different approach has been used to elucidate whether certain monochromatic aberrations do provide a cue for dynamic accommodation.[18] The approach consists of blurring the target computationally using different combinations of the subject's own monochromatic aberrations together with defocus, and measuring the accommodation response in open-loop conditions (without feedback). Results from these simulation experiments suggest that the eye does not use monochromatic aberrations to detect the sign of defocus, since a large number of participants did not respond to the simulations, and the few who showed some response, could not follow the changes in blur properly.[18] Nevertheless, these studies were carried out on relatively small populations, thus larger sample sizes need to be evaluated in order to draw firm conclusions.

Chromatic aberration and dynamic accommodation: the chromatic cue

Fincham's original findings[50] were confirmed in monkeys[86] and in a series of experiments in humans in which the longitudinal chromatic aberration of the eye was doubled, neutralized and reversed[58,73,74] while a Maltese cross target, viewed in a Badal optical system, moved sinusoidally towards and away from the eye at 0.2 Hz oscillating between 1 D and 3 D of accommodative demand (Figure 6). Doubling the amount of chromatic aberration had no adverse effect on accommodation, neutralising chromatic aberration reduced the response for most subjects, and reversing chromatic aberration so that red light focused further forward in the eye than blue light severely impaired the dynamic accommodative response (Figure 6). Subjects accommodated poorly to sinusoidally moving targets in narrowband monochromatic light, their response improved as the bandwidth of the light increased, and the response was best in broadband "white" light.[51,87,88]

Using sinusoidally moving sine-wave grating targets, accommodation responded to an intermediate band of spatial frequencies between 1 and 8 c/deg, with peak sensitivity to the effects of chromatic aberration between 3 and 5 c/deg.[89,90] Even very small amounts of normal chromatic aberration (for example, 0.25 D) improved dynamic accommodation gain, while small amounts of chromatic aberration in the reversed direction significantly impaired the dynamic response.[91] It was also established that both dynamic gain and the accuracy of static accommodation were improved by the presence of chromatic aberration.[52]

All of these dynamic accommodation experiments were performed under normal "closed-loop" conditions where blur feedback from small oscillations of accommodation was available. But the presence of blur feedback can mask the true nature of the stimulus cue, and it was important to repeat these experiments under "open-loop" conditions without blur feedback from oscillations of accommodation and without trial-and-error changes in focus. Effective dynamic accommodation responses with high dynamic gains in the absence of blur feedback confirmed that chromatic aberration provides a highly reliable directional signal for dynamic accommodation.[92]

This series of dynamic accommodation experiments established that ratios of the contrasts of the red, green and blue components of the retinal image provide the optical signals that drive accommodation. Calculations of the cone-contrasts measured by long- middle- and short-wavelength-sensitive cones[93] and empirical tests of this theory[94] proved that it was ratios of L-, M- and S-cone-contrasts that provide the directional signals that drive dynamic accommodation in two colour directions: red-green and blue-yellow.

Another series of experiments showed that isolated short-wavelength-sensitive-cones (S-cones) drive dynamic accommodation on their own, without any input from L-cones or M-cones.[95–97] In the first of these experiments, accommodation was monitored continuously to a sine-wave grating target (3 cpd; 0.53 contrast) moving with an unpredictable sum-of-sines motion in a Badal stimulus system under two experimental conditions: a "blue" condition (420 nm blue grating + 580 nm intense yellow homogeneous adapting field) and a "white" condition (broadband white grating). Mean dynamic gains for 8 subjects were reduced by 50% in the "blue" condition compared to the "white" condition.[95] Both S-cones and LM-cones mediate static and signed step accommodation responses to changes in accommodation demand.[96] S-cone contrast drives accommodation strongly for near, resulting in significant over-accommodation of more than 1 D, but the S-cone response is too slow to influence step dynamics when LM-cones participate. The latencies and time constants for the accommodation response mediated by S-cones alone to step changes in optical vergence are two to three times longer than the latencies and time-constants for accommodation mediated by LM-cones.[96] Thus the slow accommodation response from S-cones actually reduces dynamic gain to sinusoidal target motion at 0.2 Hz.[97] The directional signal from the chromatic mechanism that compares S- and LM-cone- contrasts (S - [L + M]) cannot assist accommodation to sinusoidally moving targets.[97]

Finally, L-cones on their own and M-cones on their own can mediate both static and dynamic accommodation: L-cone-contrast reduces the mean accommodation level, while M-cone-contrast increases the mean accommodation level.[98] Mean accommodation level is decreased when L-cone contrast is higher than M-cone contrast, and increased when M-cone contrast is higher than L-cone contrast.[98] In summary, L-cones reduce accommodation while both M-cones and S-cones increase accommodation.[98,99] The same chromatic cues, cone-contrasts and neural mechanisms that control everyday focusing of the human eye, also control long-term emmetropization and development of myopia in animals.[100]

Future directions

The interaction between aberrations and ocular accommodation has been studied extensively. Nevertheless, there are still a number of questions that need to be resolved and the possibilities for future research on the topic are almost countless. Some areas need further work. For instance, more detailed studies about the optics of the crystalline lens and its change during accommodation are needed. In particular, those corresponding to the changes in its internal structure (iso-indicial surfaces) during accommodation[15] and their effects on the accommodation response. More detail about the shape of the back surface of the lens and its change during accommodation are also needed since current data are not precise enough. New imaging technology devices based on OCT probably combined with other wavefront technologies will likely allow more accurate determination of these types of lenticular changes in the near future. Further investigation into the change in monochromatic aberrations during accommodation may lead to improved designs of intraocular and contact lenses to compensate for presbyopia.

Another interesting area of research is to determine how the visual system is able to detect the sign of defocus and thus, accommodate appropriately. There are still many fundamental research studies to perform in this regard. For example, it has not been investigated whether not having a perfectly circular pupil is used by the visual system as a directional cue for accommodation. Moreover, in the last 5 years theoretical studies have been carried out to determine if the sign of defocus can be detected by particular structures of the retinal anatomy.[101,102] In particular, Vohnsen et al have carried out computational simulations to show that there are different distributions of the electromagnetic field along the cone when light is focused either before or after the photoreceptor entrance plane, which may produce different cone signals.[101] Lopez-Gil et al have taken a different geometric optics approach based on different shadows that are cast by retinal vessels in the peripheral retina when light is focused in front, on, or behind the blood vessel plane.[102] Further experiments in humans should be conducted to test these theoretical hypotheses of optical vergence detection by the retina. The long-term goal of this fundamental research is to extend what we have learned about cues for everyday accommodation and the long-term focusing mechanism called emmetropization, which operates to avoid the development of refractive errors.

CONCLUSIONS

Accommodation not only changes the refractive power of the eye to improve the retinal image quality of objects located at different distances, but also modifies its aberrations. Reciprocally, aberrations may influence the accommodation response, increasing, for instance, the lag of accommodation. The most significant change in HOA during accommodation is that experienced by fourth-order SA, which decreases during accommodation, usually changing its value from positive to negative, while chromatic aberration changes very little during accommodation. Dynamic accommodation studies have shown that monochromatic aberrations do not seem to play a role in accommodation. On the contrary, longitudinal chromatic aberration provides a strong signed cue that guides accommodation reliably.

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FIGURE CAPTIONS

Figure 1. Schematic of the methodology for measuring aberrations during accommodation. In this example, the stimulus (S) is initially placed 0.50 D beyond the subjective far point, FP, (FP +0.50D), where a wavefront (A) is measured. Then, it can be moved to the FP, where wavefront B is now obtained. The same procedure is repeated until the stimulus vergence reaches the maximum vergence to be measured corresponding in this case to 10.00 D closer than the FP (FP -10.00 D), giving the wavefront D. To cover all the intervals of accommodation it is assumed that the largest vergence (10.00 D) is closer than the subject's near point.

Figure 2. Typical accommodative response. For an accommodative demand of 0 D, that is, when the stimulus is at the FP accommodation of the eye should be relaxed, but usually presents an accommodative lead. For vergences larger than 2.00 D, the eye typically presents an accommodative lag. Objective amplitude of accommodation is found as the dioptric range between the minimum and the maximum accommodation response.

Figure 3. Example of the change of 4th-order spherical aberration with accommodation in a young subject with an AA > 12.00 D. In the relaxed eye the value is positive decreasing with accommodation and becoming negative. For large values of accommodation demand, spherical aberration tends to zero because the subject's pupil becomes small.

Figure 4. Ray diagrams illustrate under-accommodation (hyperopic defocus) on the top left side of the figure and over-accommodation (myopic defocus) on the top right side. In the presence of chromatic aberration, under-accommodation produces blur spread-functions with a red colour fringe, whereas over-accommodation produces blur spread-functions with a blue colour fringe, as can be seen in the bottom row. *Adapted from Del Águila-Carrasco.*[66]

Figure 5. Ray diagrams illustrate under-accommodation (hyperopic defocus) on the top left side of the figure and over-accommodation (myopic defocus) on the top right side. In the presence of monochromatic aberrations, under-accommodation and over-accommodation produce different retinal images. Red arrows indicate some of the differences between the images. The bottom row shows dynamic accommodation response for one subject while viewing a Maltese cross target in a Badal optical system moving sinusoidally toward and away from the eye at 0.2 Hz, oscillating between 1.00 and 3.00 D (grey line) with natural aberrations present (blue line) and with all aberrations corrected except for defocus (red line). *Adapted from Del Águila-Carrasco.*[66]

Figure 6. Dynamic accommodation responses for two subjects while viewing a Maltese cross target in a Badal optical system moving sinusoidally toward and away from the eye at

0.2 Hz, oscillating between 1.00 and 3.00 D (red line) with chromatic aberration of the eye normal, neutralised, with monochromatic light and reversed chromatic aberration. Accommodation (blue line) responded well with normal chromatic aberration (first row), the response was reduced with chromatic aberration neutralized by an achromatizing lens (second row), and with monochromatic light (third row); and the response was severely impaired when chromatic aberration was reversed (fourth trace). *Adapted from Kruger et al.*[57]

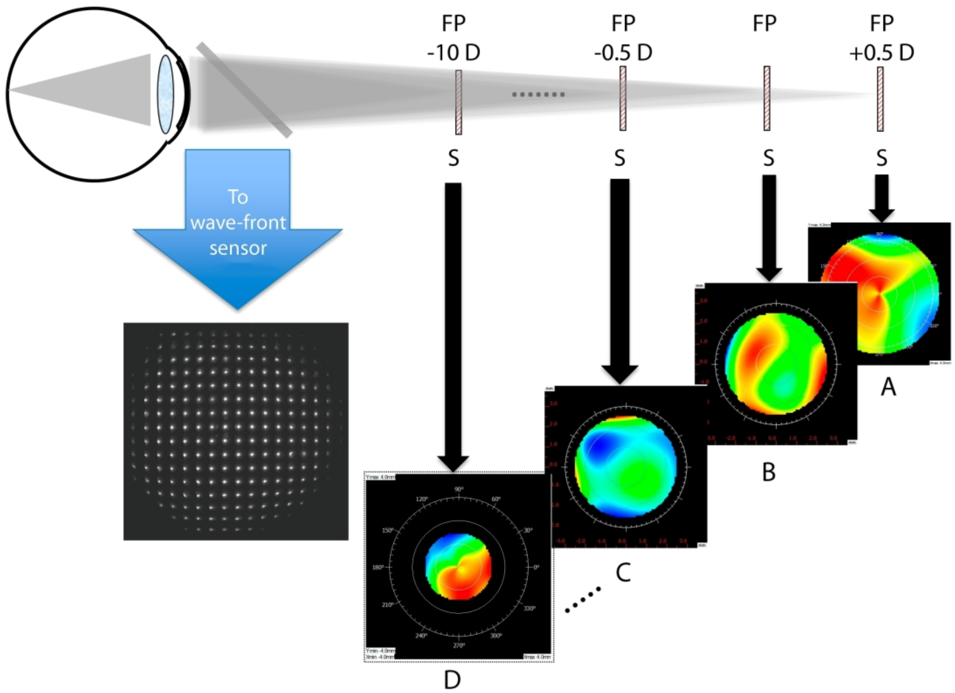

Figure 1. Schematic of the methodology for measuring aberrations during accommodation. In this example, the stimulus (S) is initially placed 0.5 D beyond the subjective far point, FP, (FP +0.5D), where a wavefront (A) is measured. Then, it can be moved to the FP, where wavefront B is now obtained. The same procedure is repeated until the stimulus vergence reaches the maximum vergence to be measured corresponding in this case to 10 D closer than the FP (FP -10 D), giving the wavefront D. To cover all the intervals of accommodation it is assumed that the largest vergence (10 D) is closer than the subject's near point.

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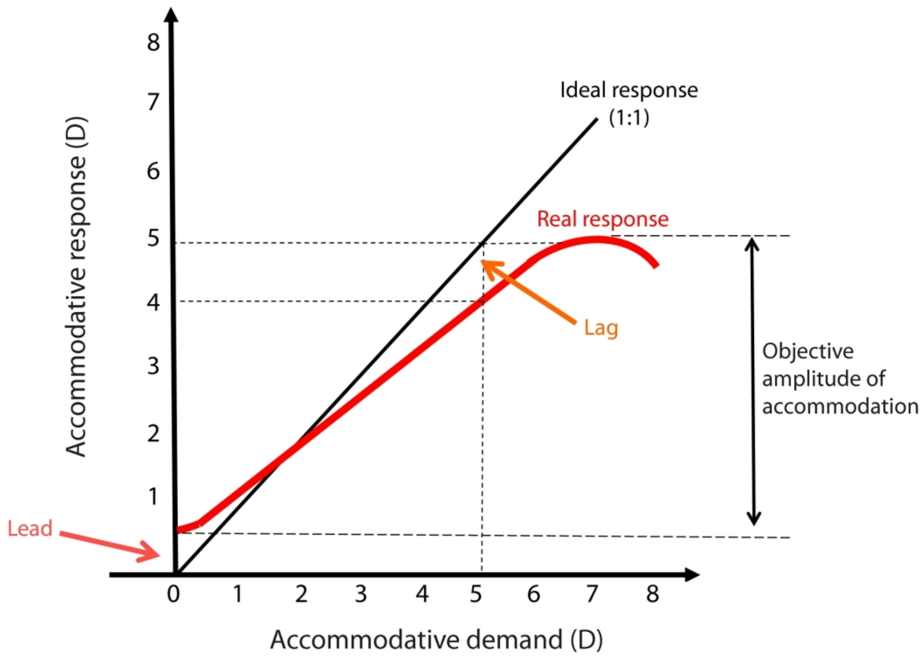

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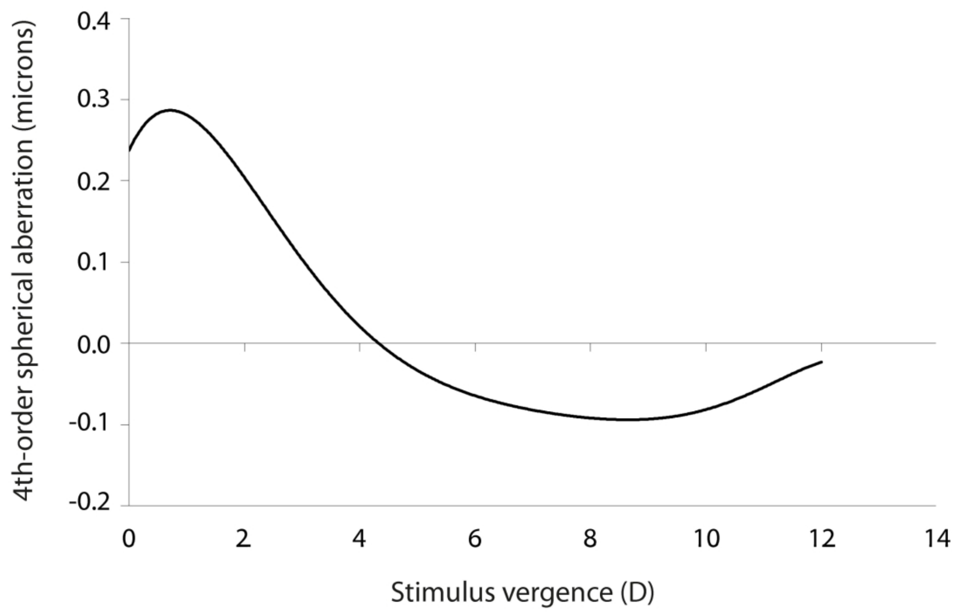

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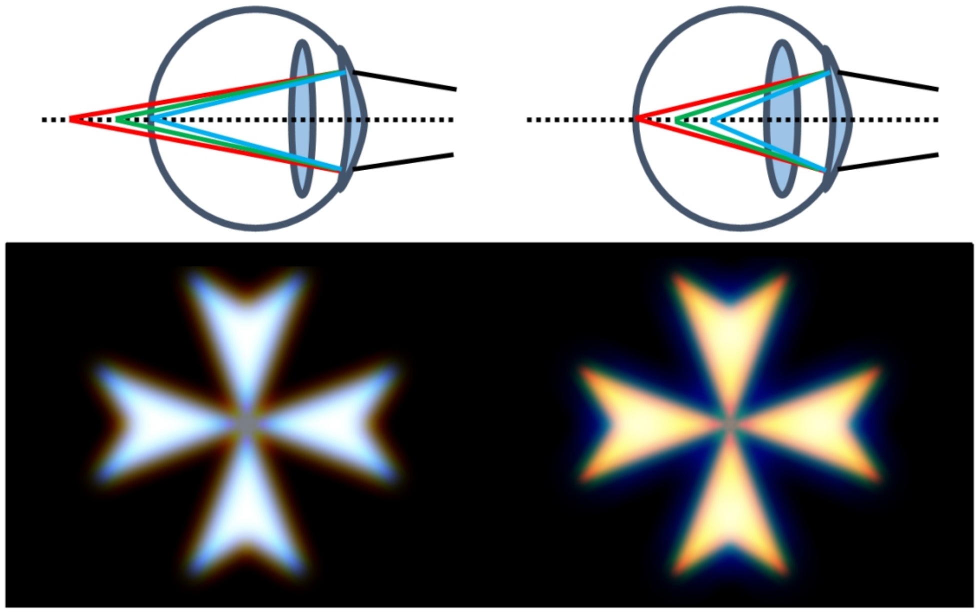

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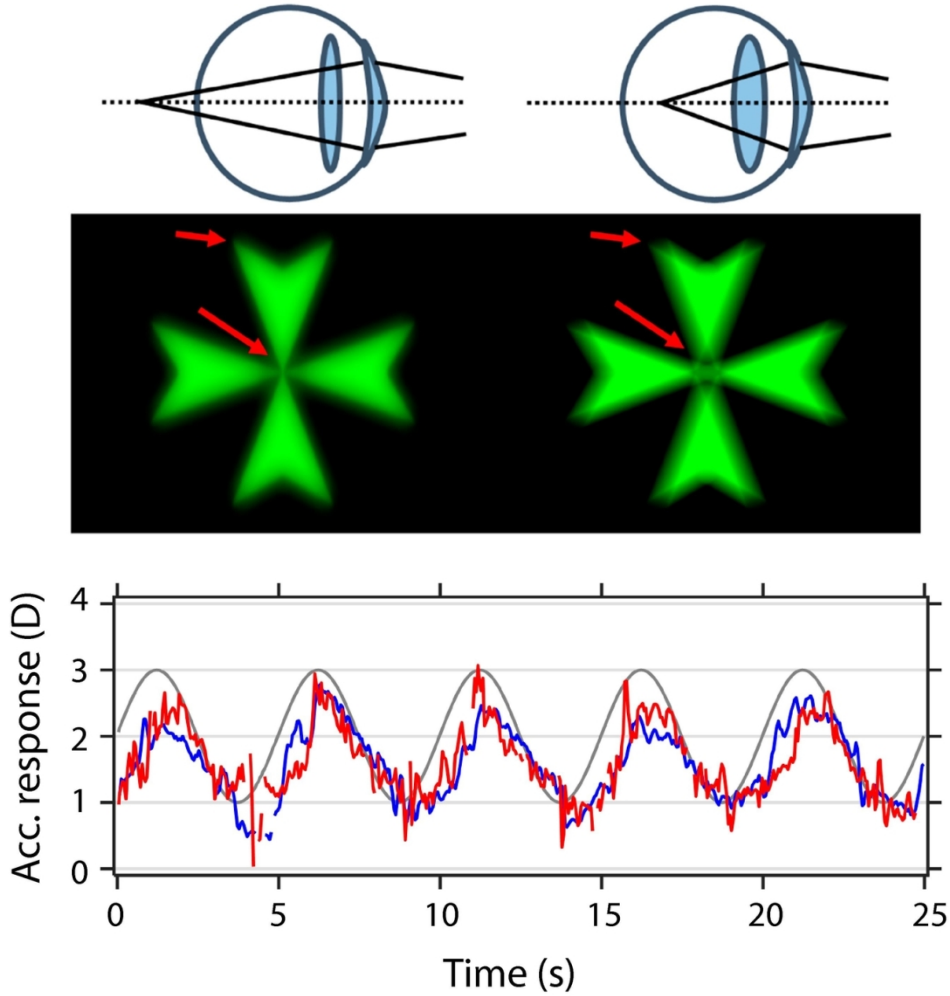

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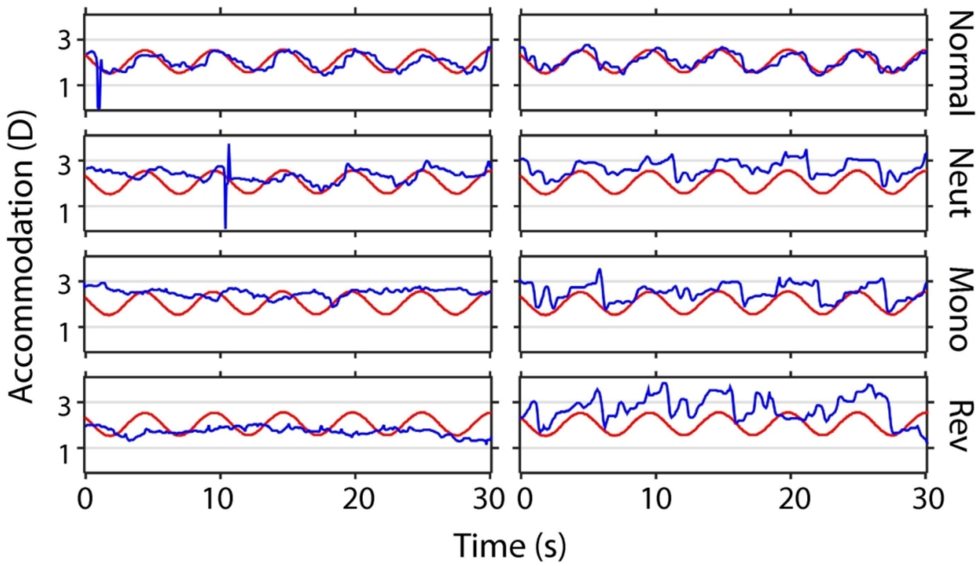
119x124mm (300 x 300 DPI)



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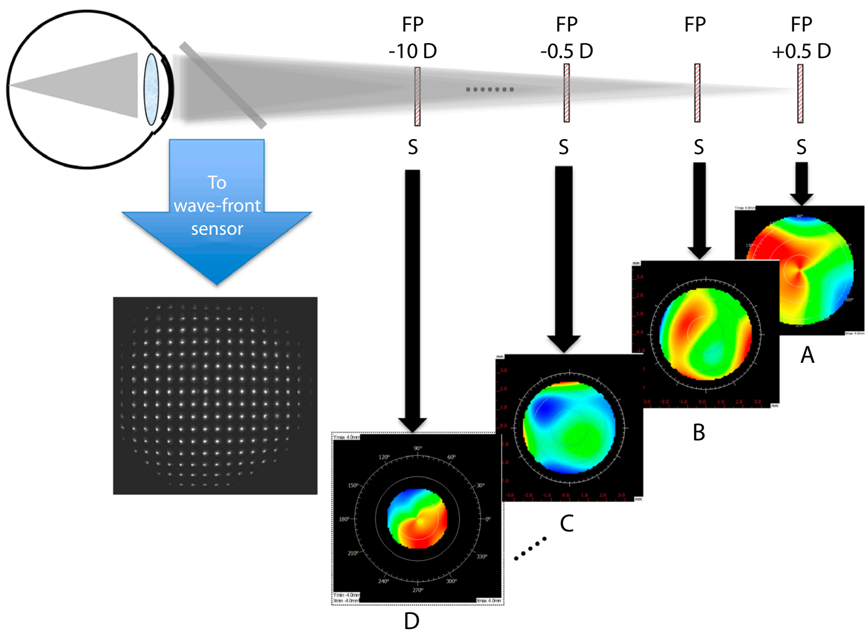
CXO 19-113
INVITED REVIEW
Aberrations and accommodation
Lopez-Gil



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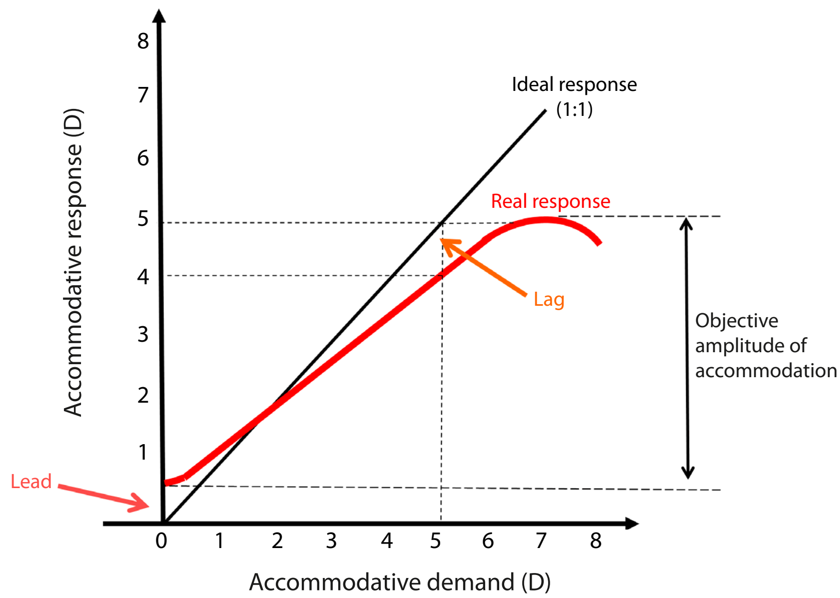

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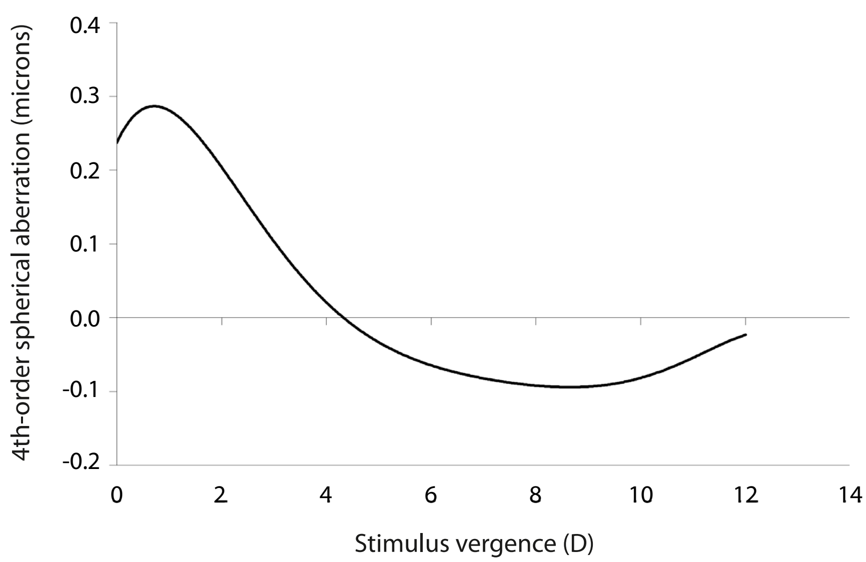

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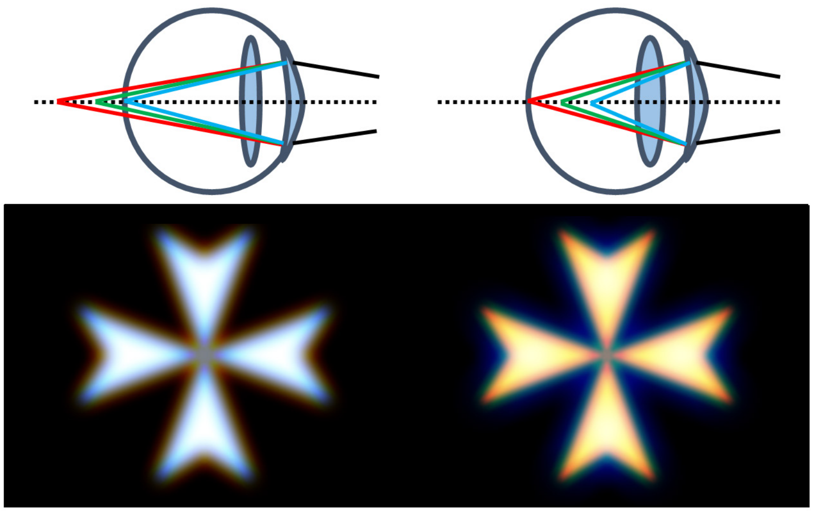

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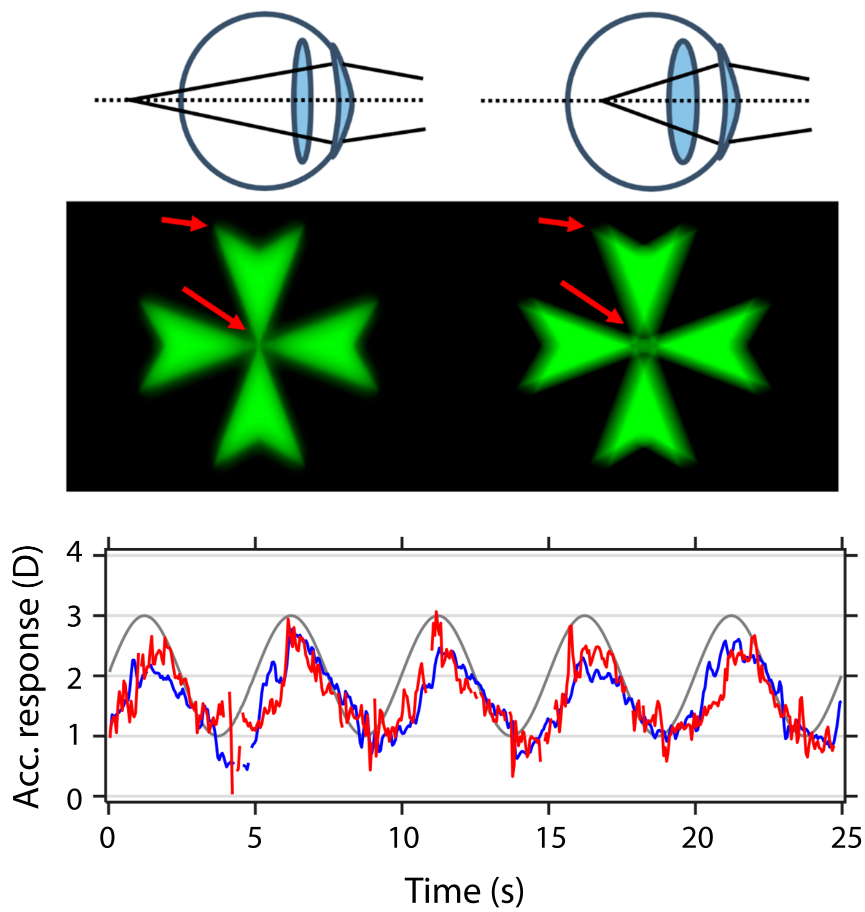

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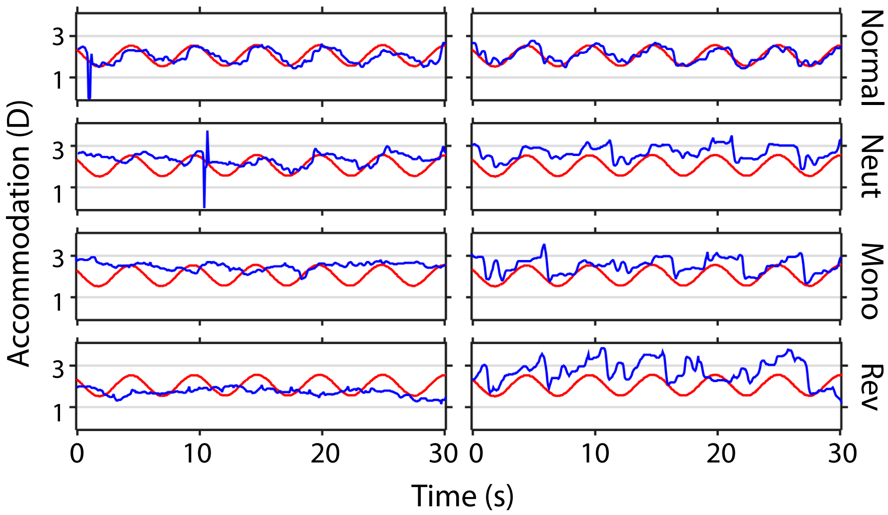

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