Voluntary Effort as a Stimulus to Accommodation and Vergence

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Voluntary effort can be used to elicit changes in accommodation and vergence. We investigated the potential cross-coupling interactions of accommodative vergence/accommodation (AC/A) and vergence accommodation/vergence (CA/C) in response to voluntary effort. The responses of accommodation and vergence were measured simultaneously with a dual Purkinje image eye tracker and infrared optometer while subjects viewed a Maltese cross monocularly through a pinhole pupil and made voluntary efforts to imaginary changes in target distance. The accommodation and vergence evoked by voluntary efforts occurred in a ratio that was similar to the response AC/A ratio and different from the response CA/C ratio. One exceptional subject was found who could voluntarily accommodate with one eye occluded without the usual concomitant change in vergence. These results indicate that it is primarily the focusing response that is adjusted during voluntary efforts in the near response. Invest Ophthalmol Vis Sci 29:1739–1746, 1988

Most people can voluntarily cross their eyes and change their accommodation, but it is not obvious whether they are primarily accommodating, converging or exercising both voluntarily. A number of investigators have studied voluntary accommodation. Marg1 studied seven optometry students who professed the ability to change their accommodation voluntarily. While fixating a target monocularly, with accommodation closed loop, most were able to both positively and negatively accommodate from the target. Westheimer2 had his subjects think of objects near and far and noted accommodative changes of 0.5 diopters. However, Campbell and Westheimer3 recorded voluntary accommodative changes of over 3 diopters and found responses of accommodation to blur combined with size change to be like voluntary changes of accommodation. Others have studied voluntary accommodation and training. Randle4 trained subjects to change accommodation voluntarily and Cornsweet and Crane5 also trained accommodation. Malmstrom and Randle6 found naive subjects could affect accommodation with visual imagery. Provine and Enoch7 demonstrated trained subjects could use voluntary accommodation to overcome the blur induced by a −9 diopter contact lens. While these studies generally noticed that voluntary accommodation also elicited a vergence change, it was not determined whether accommodation was following vergence or vice versa.

Eskridge8 reported effects of voluntary effort upon accommodation and vergence. He found the “blur AC/A” ratio to be equivalent to changes in accommodation and vergence during voluntary vergence. Bobier9 measured the velocity of binocular vergence movements and reported that the velocity of convergence increased with practice and was faster than reflex vergence responses to disparity. From this, he concluded that the movements were voluntary. Accommodation associated with voluntary vergence was not measured in his experiments. Randle and Murphy10 found that the velocity of accommodation increased with practice. These reports indicate a voluntary component in vergence and accommodation that has a higher velocity limit than reflex responses to disparity and blur respectively.

We examined both accommodation and vergence when voluntary changes were made to imagined changes in target distance and found that accommodation and vergence had a ratio similar to the blur driven AC/A ratio but not the disparity driven CA/C ratio. Accommodation appears to be driving the vergence response.

Materials and Methods

Visual Stimulus

The target was a Maltese cross produced on a high resolution (640 × 480 pixel) video monitor. The cross appeared as white on a dark background. The edges
of the cross formed angles of 36° at the center. The experiments were run in a dark room so that the Maltese cross target was the only visible target. The monitor screen was placed at a distance 67 cm from points of the apparatus that were conjugate to the subject's entrance pupils for each eye. Its size was approximately 46 mm at 67 cm (4°).

**Apparatus**

An SRI binocular eye tracking system composed of a fifth generation, two-dimensional dual-Purkinge-image (DPI) eyetracker and an infrared optometer were used to continuously track horizontal and vertical eye position and accommodation. The apparatus also had a three-dimensional visual stimulus deflector for each eye that was used to change the stimulus to accommodation and position of the target. This instrument has a resolution and noise level for eye position of approximately 1 minute of arc and is essentially free of the artifacts of head and eye translation. Its dynamic infrared optometer measured accommodation to 0.1 diopter. This optometer measured accommodation of the right eye. It is based on the Scheiner principle and operates from a retinally reflected infrared beam.

The three-dimensional visual stimulus deflector allowed movement of the stimulus object while its brightness and visual angle remain fixed. A pair of lenses was used to form an image that was viewed through a telecentric Badal system. Movement of one of these lenses caused a change in the spherical power of the system without a change in position, size or brightness. This spherical power is linearly related to the axial position in diopters. This lens could be moved by a servomotor controlled by the computer or by hand.

An IBM AT computer was used to generate step changes in blur by moving a lens of the visual stimulus deflector or to generate step changes in absolute disparity by rotating a mirror galvanometer. The responses of accommodation and vergence along with the stimulus were continuously recorded on a strip chart. In order to reduce possible crosstalk of accommodation or to generate step changes in absolute disparity, the stimulus were continuously recorded on a strip chart. In order to reduce possible crosstalk of accommodation or to generate step changes in absolute disparity, the stimulus were continuously recorded on a strip chart. In order to reduce possible crosstalk of accommodation or to generate step changes in absolute disparity, the stimulus were continuously recorded on a strip chart. In order to reduce possible crosstalk of accommodation or to generate step changes in absolute disparity, the stimulus were continuously recorded on a strip chart. In order to reduce possible crosstalk of accommodation or to generate step changes in absolute disparity, the stimulus were continuously recorded on a strip chart. In order to reduce possible crosstalk of accommodation or to generate step changes in absolute disparity, the stimulus were continuously recorded on a strip chart. In order to reduce possible crosstalk of accommodation or to generate step changes in absolute disparity, the stimulus were continuously recorded on a strip chart.

The accommodative loop could be opened by placing a 0.5 mm pinhole pupils at points conjugate to the pupils of the eyes. With these pupils in place, our subjects would not detect or respond to ±3 diopters change in accommodative stimulus. Ripps et al. have shown that a reduction in pupil size can essentially eliminate the optical stimulus to accommodation for low levels of accommodative stimulus. Ward and Charman recently confirmed that a 0.5 mm pupil will produce open-loop accommodation.

**Experimental Procedures**

The subjects' pupils were dilated with 2.5% phenylephrine hydrochloride, a weak sympathomimetic, at the start of the experimental sessions in order to prevent pupillary artifacts in the measurement of accommodation and vergence. Phenylephrine does not change the AC/A ratio. A mouthbite and forehead rest were used to avoid artifacts from movement of the subject. In this experiment the Maltese cross always remained the same size (4°) and the subject viewed the cross monocularly through a 0.5 mm pinhole pupil. The room was darkened so that the white cross was the only object visible to the subjects. The subject was told to “think near or look near” or “think far or look far” in order to elicit changes in accommodation and vergence. They were to do this while always maintaining fixation on the center of the Maltese cross. Initially, they were given some feedback by the experimenter as to the direction and magnitude of their motor responses to these voluntary efforts. The experimenter watched the strip chart during the responses and if accommodation and vergence increased on command the subjects were given the verbal feedback to continue their current response. If the response was so large that the recording was saturated, they were told to reduce their response. The subjects would generally stop increasing accommodation and convergence when told to do so. For comparison to the blur driven AC/A ratio, a “voluntary AC/A ratio” was computed by dividing the changes in vergence by the changes in accommodation to voluntary efforts. Three to five responses were averaged to determine the voluntary AC/A ratio for each subject. For comparison to the disparity driven CA/C ratio, a “voluntary CA/C ratio” was computed by dividing the changes in accommodation by the changes in vergence to voluntary efforts.

The blur driven AC/A ratio was determined from the responses of accommodation and vergence to monocular step changes in blur of 1 and 2 diopters. The blur stimulus was approximately the magnitude of the voluntary changes in accommodation that the subjects made. At least three responses were averaged in order to determine the AC/A ratio. The blur stimulus was generated with a Badal type stimulus optometer so that target size and brightness did not change with the changes in blur. The subjects viewed the targets monocularly through a 4 mm artificial pupil. The disparity driven CA/C ratio was determined from the responses of accommodation and vergence...
to an asymmetric step disparity stimulus of 5 or 10 prism diopters to the left eye. The disparity stimulus was asymmetric to avoid changes in position of the right eye that might influence the measurement of that eye’s accommodation. At least three responses were averaged in order to determine each subject’s CA/C ratio. The subjects viewed the center of the cross binocularly through 0.5 mm pinhole pupils for this determination of the CA/C ratio. The order of the types of measurements was randomized.

Subjects

Eight subjects, ages 18 to 38, were used. All subjects had normal stereopsis and acuities that were correctable to at least 20/20 in each eye. Any refractive errors were corrected by adjustment of the visual stimulus deflector at the start of the experiment. Their amplitudes of accommodation were normal for their ages. One of the subjects, PH, had a divergence excess of 15 prism diopters at distance that was well controlled. This subject had orthoptics in the past and had worked as an orthoptist. Each subject was informed of the nature of the procedures and their informed consent was obtained prior to their participation in the study.

Results

Voluntary Responses of Accommodation and Vergence Compared to the Blur AC/A Ratio

Figure 1 plots the blur AC/A ratio against the voluntary AC/A ratio. The units are meter angles per diopter for both of these response AC/A ratios. The dashed line is the 1:1 line and a good correlation is obvious ($r = 0.9298$). Only one point by inspection appears to be significantly off the 1:1 line. To check whether the blur AC/A ratio is significantly different from the voluntary AC/A ratio a paired t-test was done and there was not a significant difference ($t_7 = -1.40, P = 0.20$).

Voluntary Responses of Accommodation and Vergence Compared to the Disparity CA/C Ratio

Figure 2 plots the disparity CA/C ratio against the voluntary CA/C ratio and the points are well scattered ($r = 0.4499$). Voluntary effort causes accommodation and vergence to respond in amounts more characteristic of the AC/A ratio than the CA/C ratio. A paired t-test between the disparity CA/C ratio and the voluntary CA/C ratio shows a significant difference ($t_7 = -2.55, P = 0.038$). Only one point is obviously on the 1:1 line.

One way to interpret the results of the raw recordings is to examine the amplitude of convergence in meter angles relative to the amplitude of the accommodative response. A typical example is shown for subject HB in Figure 3. For the “blur AC/A ratio” (Fig. 3a) the accommodative response is larger than the vergence response, but for the “disparity CA/C ratio” (Fig. 3b) the vergence response is larger than the accommodative response. For the voluntary change (Fig. 3c), the accommodative response is also larger than the vergence response. This is the pattern for seven of the eight subjects for AC/A and five of the eight subjects for CA/C.

Subject PK in Figure 4 is atypical in that he has an AC/A ratio that is much higher than the others. How-
ever this subject is typical in that his voluntary effort causes changes in accommodation and vergence that are more like his AC/A ratio than his CA/C ratio. The one subject that is off the line for blur AC/A ratio vs. voluntary AC/A ratio (Fig. 1) is on the line for disparity CA/C ratio vs. voluntary CA/C ratio (Fig. 2). This is subject PH who has a divergence excess (exophoria higher at far than near).

General Observations

Generally, the subjects required very little instruction in order to have them elicit voluntary changes in vergence and accommodation. They would be able to make responses and at the same time maintain fixation on the center of the cross on their first attempt. However, one of the subjects used in another study was unable to make voluntary changes in accommodation and vergence. Another subject, required two sessions in order to “learn” to make voluntary responses. While they could easily make these voluntary changes, they were generally unable to verbalize what they were doing.

There was variability between subjects in the magnitude of the accommodative responses from 0.5 to over 4 diopters and the vergence from 2 prism diopters to over 15 prism diopters. One of the subjects would sometimes reduce accommodation when told to “think near” and increase accommodation when told to “think far.” At other times she would respond in the appropriate directions. She was unable to verbalize just what the difference was in the two responses.

One subject, unexpectedly, was found to have two types of voluntary response. Usually, her voluntary efforts evoked accommodation and vergence equal to her blur AC/A ratio but she also demonstrated some voluntary responses which consisted of accommodation of up to 3 diopters and little or no vergence even though one eye was occluded. This was unlike her AC/A and CA/C ratios. Figure 5 shows these different responses. We subsequently tested this subject several times. However, by trial and error we discovered that she would accommodate without converging when told to look through the center of the cross. This instruction would repeatedly elicit accommodation with little or no vergence and this was very different from her usual voluntary response. To rule out the possibility of vertical movements causing an artifact in the accommodative recording, vertical position was recorded. Vertical eye movements were not present when she voluntarily accommodated without...
Voluntary Accommodation and the AC/A Ratio

The voluntary changes in accommodation and vergence of our subjects had a ratio equal to the blur AC/A ratio. Eskridge, in a study of voluntary vergence, found accommodative vergence to be no different than voluntary vergence. Unfortunately, accommodation was not open-loop in his experiment. Despite this, he concluded that "voluntary vergence" appears to be produced voluntarily through the stimulation of accommodative vergence. We measured voluntary changes with both accommodation and vergence open-loop and came to the same conclusion as Eskridge. Voluntary efforts of accommodation resulted in an accommodative vergence response.

Accommodation Without Vergence

While attempting voluntary accommodation, with one eye occluded, one subject was able to respond without any accommodative vergence. This discovery of accommodation that was not associated with vergence was surprising. Though we were only able to elicit this response in one subject, we speculate that it may be present in others. We hypothesize that this voluntary accommodative response may be present in some unusual accommodative vergence responses that we have encountered. In these responses, the accommodative vergence velocity appears to be unusually low compared to the accommodative velocity after a blur stimulus is presented.

For example, in Figure 6, accommodative convergence occurs gradually while accommodative divergence occurs at the normal abrupt rate. This reduc-
Fig. 5. Subject RP. (a) Accommodative and vergence responses to step increases and decreases in blur of 1.75 diopters. Convergence and accommodation increased with downward movement of the lines. The subject viewed the Maltese cross monocularly through a normal sized pupil. The AC/A ratio is determined by dividing the change in vergence by the change in accommodation. (b) Accommodative and vergence responses to step increases and decreases in disparity of 5 prism diopters. Convergence and accommodation increased with downward movement of the lines. The subject viewed the Maltese cross binocularly through pinhole pupils. The CA/C ratio is determined by dividing the change in accommodation by the change in vergence. (c) Accommodative and vergence responses to voluntary effort. Convergence and accommodation increased with downward movement of the lines. The subject fixated the center of the Maltese cross monocularly through a pinhole pupil. Down arrows indicate instructions to the subject to “think near” and up arrows to “think far.” For comparison to the blur driven AC/A ratio, a voluntary AC/A ratio is determined by dividing the change in vergence by the change in accommodation. For comparison to the disparity driven CA/C ratio, a voluntary CA/C ratio is determined by dividing the change in accommodation by the change in vergence. (d) These are the same conditions as in Figure 6c, with the same subject RP. The responses, however, are markedly different. Accommodation is responding without an associated vergence response.

Fig. 6. Response of accommodation and vergence to 1 and 2 diopter blur stimulus for subject TY. The accommodative vergence response is unusual in that it increases much more gradually than accommodation. This might be explained by voluntary effort causing the initial steep response of accommodation. Increased accommodation is in a downward direction in the top curve.

VOLUNTARY CHANCE

Increased in accommodative vergence velocity was produced by having the subject track repetitive step changes in blur (0.5 Hz) for several minutes. It is possible that with fatigue of optical reflex accommodation that volitional accommodation is used to assist the response. If volitional accommodation is used to assist the response there would be a quick response of accommodation alone, and as the normal phasic optical reflex accommodative controller takes over, a gradual increase in accommodative vergence could occur. A related effect is the reduction of accommodative convergence produced by fatigue of accommodation by repeated measures of AC/A ratios shown in Figure 7. Initially accommodative convergence follows accommodation but with fatigue, accommodative convergence is reduced.

We did not find any cases of voluntary effort resulting in vergence without a change in accommodation. Hofstetter, Morgan, Ogle and Martens, Alpern and others have all found evidence for proximal vergence that is generally assumed to be independent of accommodation.

Proximal Accommodation

Proximal accommodation, which is defined as an involuntary accommodative response to monocular
distance cues, is one possible explanation for the voluntary responses that were elicited. A "voluntary" perceived distance may be driving accommodation and accommodative vergence may be responding through the AC/A crosslink. Ittleson and Ames\textsuperscript{22} have reported proximal accommodation. The accommodative responses to size variation reported by Kruger and Pola\textsuperscript{23} might also be due to proximal accommodation. Perhaps visual imagery was used to produce the proximal accommodation. Malmstrom and Randle\textsuperscript{6} and Westheimer\textsuperscript{2} both found that visual imagery could be used to produce changes in accommodation. Indeed, some of the subjects reported that they used visual imagery when making voluntary changes in accommodation and vergence.

Proximal vergence, on the other hand, is not consistent with our results. If proximal vergence were the driving force for our voluntary responses, then a CA/C ratio response or a vergence response independent of accommodation would have been found rather than an AC/A ratio response.

Interactions in Blur Driven and Voluntary Accommodation

The easy elicitation, without time-consuming training, of voluntary changes in vergence and accommodation suggests that voluntary effort may be an important component of accommodation in everyday situations. Cornsweet and Crane\textsuperscript{24} have pointed out that any cue might train the accommodative reflex. They add that a natural cue, such as changes in retinal image size that accompany the feedback of blur of the retinal image, might easily train the accommodative system. McLin, Schor and Kruger\textsuperscript{25} found an AC/A response to changing size, which suggests that changing size may be eliciting a type of voluntary response.

Campbell and Westheimer\textsuperscript{3} reported that the accommodative recordings were similar when voluntarily accommodating or responding to a blur stimulus combined with size cues. However, responses to blur alone were more irregular than voluntary responses or responses to combined size and blur change. This implies that voluntary effort is significantly influencing the response.

Variations in the accommodative response characteristics to sinusoidal gratings have been partially attributed to the varying instructions given to the subjects.\textsuperscript{26-28} Different subjects, as pointed out by Tucker et al,\textsuperscript{28} may use different accommodative strategies, and accommodation is not a simple reflex mechanism. In considering whether blur or the disparity stimulus is the primary stimulus to accommodation in natural environments, voluntary effects should also be considered. A "voluntary" accommodation may be an important component of accommodative vergence.

Effect of Training on Accommodation

Randle and Murphy\textsuperscript{10} studied the dynamic response of accommodation over a 7 day period and found the velocity of accommodation to increase. Similarly, Liu et al\textsuperscript{29} showed that in subjects with dynamic insufficiencies of accommodation, orthoptics treatment was associated with significant increases in the velocity of the accommodative response. These increases in the response of accommodation with repetition and training may be explained by a voluntary accommodation contributing to the response. In these cases, this voluntary accommodation can not be attributed to convergence accommodation because the subjects were stimulated monocularly.

The exceptional case of PH, in whom voluntary efforts produced a ratio of accommodation and vergence equal to the CA/C ratio rather than AC/A ratio, suggests that perhaps, in some cases, voluntary effort is directly driving vergence rather than accommodation. With PH's extensive background in orthoptics, perhaps she has somehow trained a different voluntary response for the vergence system that is analogous to voluntary responses of the accommodative system seen in other naive subjects.

Training or orthoptics might be expected to enhance a subject's awareness of the direction of voluntary accommodation. While these accommodative responses were easily elicited, some subjects did not
have a precise sense of where in space they were focusing or converging. In particular, subject LS would sometimes decrease her accommodation and vergence when told to focus at near. Similarly, Marg had two of seven subjects negatively accommodate when attempting positive voluntary accommodation. The ability to sense direction of responses could be developed in a natural environment where there is feedback from blur.

Summary

With only minimal instruction and some verbal feedback of their responses, subjects could voluntarily elicit changes in accommodation and vergence. The accommodation and vergence responded in amounts typical of an AC/A ratio rather than a CA/C ratio. This implies that voluntary effort is driving accommodation primarily and that vergence is a secondary response through an AC/A crosslink. There may be other possible voluntary responses and one subject demonstrated voluntary accommodation without converging.

Key words: voluntary, response AC/A ratio, response CA/C ratio, accommodative convergence, vergence accommodation

References