Accommodation, cognition, and virtual image displays: A review of the literature

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Abstract

This paper reviews the literature on factors that influence the visual (ocular) accommodation response when using see-through virtual image displays (VIDs) such as head-up and helmet-mounted displays. This review suggests that the overall accommodation response is determined by a complex interaction of many factors, some of which are associated with the visual stimulus (such as blur and chromatic aberration) and some of which are cognitive in nature (such as workload and attention). When using VIDs, the effects of these different influences on the accommodation response may not be congruent, leading to the level of accommodation being inappropriate for the task.

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1. Introduction

The aim of this review is to consider what, at first sight, appears to be a fairly straightforward issue – the effect of using virtual image displays on the visual accommodation response (the focusing response of the eye). Unfortunately, this is not a straightforward area. The visual accommodation response although superficially a simple stimulus-driven response is influenced by a large number of factors. Individual studies have often examined different combinations of these factors and have obtained different results – not necessarily because any particular study is flawed, but because they are looking at different aspects of the same ‘big picture’. The aim of this review is to try and sketch out the nature of the interacting influences on the visual accommodation response and so demonstrate how apparently disparate results can be reconciled within a wider debate. This review also attempts to draw out the implications of the various factors for display design and to suggest a direction for future research.

Visual head-up displays (HUDs) have been a feature of many military aircraft cockpits for a number of years and are now being installed in civil aircraft and automobiles. More recently, helmet-mounted displays (HMDs) have been introduced. The basic principle of both HUDs and HMDs is similar and so, although the following discussion will refer primarily to HUDs, the issues are likely to be equally relevant to HMDs. Indeed, in this review, the more general term ‘virtual image display’ (VID) will be used unless referring specifically to HUDs or HMDs. Most of the discussion will concentrate on the use of VIDs in aircraft displays as this is perhaps the most demanding application. VIDs present symbology and/or imagery to the user as a virtual image by reflecting images off a transparent surface in the line of sight of the user. This transparent surface might be the combiner glass of a HUD, the visor of a helmet, or an automobile windshield. The imagery (in aircraft displays) is usually collimated so that it appears to lie at or near infinity. In principle the images presented on the VID should appear to overlay, and be in the same plane as, the outside world. As a result, there should be no parallax (differential motion) of the VID symbology as compared to the outside world, or any physiological diplopia (double vision) due to eye vergence in a different plane. In theory, one advantage of presenting information in this way is that a pilot can remain ‘head-up’ and can view the VID imagery and the outside world without having to change the level of accommodation or vergence of the eyes.

If a VID image is collimated to infinity, the ‘correct’ accommodation level for the pilot (when ‘head up’) should also be at, or near, infinity. The level of accommodation is obviously of crucial importance in a flying task as inappropriate levels of accommodation may lead to elevated thresholds for detecting external targets, loss of visible texture and, possibly in conjunction with changes in eye vergence and other factors, may contribute to misperceptions of size and distance. There have been numerous studies that have examined the impact of VIDs on the visual accommodation response. Unfortunately, while some studies suggest that VIDs do affect the accommodation response, other studies seem to present equally compelling evidence that they do not. The following review will briefly discuss the studies that have examined the accommodation response associated with VIDs and will then attempt to reconcile the apparently conflicting findings of these different studies.

Early reports of visual problems in flight have been provided by Bauer [6] who describes early tests of accommodation and the problem of ‘latent hyperopia’ (a lapse of accommodation from infinity and a corresponding loss of acuity) as a result of fatigue or stress. Whiteside [153] reported that, particularly when viewing clear skies, pilots may show an inappropriate accommodation response; possibly even focusing on spots on the aircraft canopy. Whiteside also demonstrated that collimated images could be used to improve the detection of distant targets. This is perhaps the earliest investigation of a collimated image leading to improved accommodation performance in an applied setting but was published in the same year as the results of another study [13] which suggested that, if the subject did not know where the targets were to appear, a collimated image did not improve detection thresholds. These early studies did not measure accommodation levels directly but inferred them from changes in detection threshold. Later studies [53,114] have, however, measured accommodation directly and have suggested that a collimated virtual image may provide a poorer stimulus to accommodation than a real one (viewed directly on a monitor). Roscoe
suggested some aircraft landing problems (such as those reported by Kraft [68]) may be associated with inappropriate accommodation – and that collimated images in general (and HUDs in particular) may contribute to such a response. This possibility was investigated in studies using collimated virtual image displays [50,105] which demonstrated myopic (short-sighted) shifts of accommodation. A study using an aircraft HUD [55] indicated that HUD use ‘released’ accommodation to lapse towards the resting position. Roscoe expressed his concern over the effects of HUD use in a short note in the Human Factors Society Bulletin [119]. A lively and ongoing debate ensued [22,104,120,136,148,149], which appeared to centre on whether the advantages of using a HUD outweigh the disadvantages (such as accommodation problems) rather than whether HUDs really do contribute to changes in accommodation.

There have, however, been other studies following the original Whiteside paper suggesting that collimated images may either improve or have no effect on the accommodation response. Leitner and Haines [76] conducted a study using a HUD and suggested that the collimated HUD image was sufficient to maintain accommodation at optical infinity. The definition of optical infinity used in this study was, however, derived from the accommodation response to another collimated virtual image. As the comparison was between the accommodation response to two virtual images there is actually no way of knowing if the accommodation response was really at optical infinity in either condition. Indeed, subsequent research [123] demonstrated that the accommodation response to virtual images of the sort used for comparison with the HUD is typically not at optical infinity. Thus, the Leitner and Haines study cannot be taken as evidence to suggest that HUDs help maintain accommodation at optical infinity. Sheehy and Gish [134] found that the optical distance of a virtual image had no significant effect on the accommodation response to another (real or virtual) stimulus presented at optical infinity. Matthews et al. [91] found that, in a visual search task of a clear field, detection rates improved by about 30% if an accommodative aid was located at optical infinity. Another study [150] found that overlaying a collimated HUD image on a runway scene moved accommodation further out towards infinity.

Most of the studies mentioned above have referred to HUDs, but a number of investigators have discussed the possibility that accommodation problems may occur with other displays. Displays investigated include: ‘look through’ HMDs [63]; night vision goggles (NVGs) [66,135]; virtual image displays where the image may not be collimated such as automobile HUDs [140,144,163] and stereoscopic displays such as virtual reality (VR) systems [4,21,29,48,57,60,84,95,97]. As with aircraft HUDs there is some evidence that these effects may not always be clear-cut [49,107,111] – especially as the change in the underlying accommodation response may differ between users that show overt visual symptoms (e.g. difficulty focusing, blurred vision, dizziness, headache, etc) and those that do not [99].

From the preceding discussion it is clear that there is no simple relationship between the use of a virtual image display and the associated accommodation response. The nature of the study appears to affect strongly the results obtained suggesting that the overall accommodation response is influenced by the interaction of a number of different factors. Indeed a number of investigators have suggested that the nature of the experimental task [55], relative image quality of virtual image and background [149] and attentional factors [22,31,63] may all influence the overall accommodation response to a virtual image.

Thus, in an effort to reconcile the studies discussed above, the following review will review the literature on different influences on the visual accommodation response, concentrating particularly on the interactions between these factors and the use of virtual image displays. The review is split into four broad sections. The first section reviews very briefly the mechanism and measurement of accommodation and defines some of the terms used in the area. The second section concentrates on aspects of the stimulus, and the physiology of the visual system, that influence accommodation, whereas the third section considers cognitive influences on the accommodation response. Within the second and third sections the possible influences on the accommodation response are treated separately and are discussed in terms of the theory concerning their action, followed by a consideration of the implications of this action for VIDs. The last section draws together and summarises the issues raised in the previous sections and provides an overview of the factors that are likely to influence the accommodation response when using a VID. The discussion will concentrate on VIDs that provide a see-through virtual image display focused at optical infinity.

2. The mechanism and measurement of accommodation

In order to see an object clearly it is necessary for light from stimuli in the outside world to be focused on the retina at the back of the eye. This focusing is achieved by two components of the eye, the cornea and the lens. The cornea is the transparent front surface of the eye and it is actually the cornea that does most of the focusing of incoming light, although it is not adjustable. The fine tuning of the focusing to take account of objects at different distances is achieved by the lens that lies behind the cornea. The lens is a crystalline structure attached to the ciliary muscles that surround it. To allow the lens to ‘accommodate’ to objects at different distances, it is necessary for the power of the lens to change. There have been at least four theories as to how this might be done [23,44,143,157] but all agree that the level of accommodation is controlled by the constriction and dilation of the ciliary body surrounding the lens with the ciliary muscles controlled by the joint actions of the sympathetic and parasympathetic nervous system.
The action of the ciliary muscles changes the thickness and curvature of the lens, and hence its optical power.

The level of accommodation is expressed in dioptres (D). This is the reciprocal of the distance, in metres, at which the lens is focused. For example, if the eye is focused at ‘infinity’ the level of accommodation will be 0 D. If the eye is focused at 2 m, the level of accommodation will be 0.5 D. Objects may, however, still appear clear even if the level of accommodation is not quite correct for that object. This is because the eye has a certain depth-of-focus, which is a range of accommodation within which objects will appear acceptably sharp.

There have been a number of different methods employed to measure the level of accommodation. These can be loosely divided into what have been termed ‘subjective’ and ‘objective’ techniques. Subjective techniques are those that require some response from the participant, such as a judgement as to the direction of movement of a laser pattern. Two widely used subjective technique are the laser optometer [47] and the vernier optometer [137]. These devices have an advantage in that they are relatively cheap and can be adapted to make continuous real-time measurements of accommodation [162].

These subjective techniques have now largely been supplanted in research studies by objective techniques, the most common of which is the use of an infrared optometer [24]. These are usually commercial instruments, the most widely used being the Canon Autoref R-1 (now out of production) and the Shin-Nippon SRW-5000. These devices use infra-red light reflected from the retina of the eye to measure the level of accommodation. They do not require any response from the participant and can be adapted to make continuous real-time measurements of accommodation [162].

3. Physiological factors and physical components of the stimulus affecting the accommodation response

This section will consider influences on the accommodation response that are associated with the physical characteristics of the stimulus such as its colour or whether it appears blurred. Physiological aspects of the visual system will also be considered, such as the effect of the vergence of the two eyes on the accommodation response and the finding that there is a natural ‘resting’ position for the accommodation response.

3.1. Blur

3.1.1. Theory

The most obvious stimulus to drive the accommodation response is image blur, with the level of accommodation adjusted until the image appears optimally sharp. This represents a closed-loop system with the level of perceived blur providing feedback to drive the accommodation system. An excellent review of the early theories of accommodation is provided by Wade [145]. These early theories show a good understanding of the need for the eye to focus to produce a sharp image on the retina, but differ in the mechanism by which this might be achieved. More recently, work has concentrated on the aspects of a stimulus that could be used to drive the closed-loop accommodation response. It has been suggested [18] that the accommodation system may use low spatial frequencies to bring the accommodation response to approximately the right level and then use high spatial frequencies to refine it. This has intuitive appeal as high spatial frequencies will be effectively invisible in a very blurred image but will become more ‘visible’ (corresponding to finer detail becoming evident) when the image is ‘sharpened up’. If only high or low spatial frequencies are present then the accommodation response may be less accurate. One factor that will influence the accuracy of accommodation under closed-loop conditions is the depth-of-field of the eye which will, in turn, depend upon pupil size. Estimates of the depth of field of the human eye range from about 1 to 3 D with a 1 mm pupil to about 0.3 D with a pupil size greater than 2 mm [17,20].

3.1.2. Practical and design implications

There is no reason why introducing a virtual image display (if it is correctly adjusted) should influence the blur-driven accommodation response. Any blur cues in the far domain (outside world) should still be there and as long as these are congruent with those provided by the VID there should be no additional problems. Problems may, however, occur if the far domain and the VID are at different optical distances. This may be the case if the VID is incorrectly set-up (or if the focal plane of the lens system is curved) or, alternatively, if the cockpit canopy acts as an optical element to alter the optical distance of the far domain [38,39]. The canopy acting as an optical element may occur with or without a VID but becomes a problem if a VID is introduced that presents an image at a different distance and thus provides conflicting blur (and vergence) cues.

Thus, the use of VIDs should not adversely affect the blur-driven accommodation response and indeed, if other blur-cues are poor, may lead to a more appropriate accommodation response. The crucial aspect is that the optical distance of the far domain and the VID image should be congruent.

3.2. Vergence

3.2.1. Theory

As an individual changes fixation to objects at different distances it is necessary for the vergence angle between the lines of sight of the two eyes to change to maintain alignment of the object image on the two retinas. A number of studies [34,51,155] suggest that vergence and accommoda-
vation are linked; i.e. as one changes so does the other – although the two responses may have different tonic positions (the ‘resting position’ when no stimuli to accommodation or vergence are present) [59,159]. Evidence suggests that vergence is the ‘dominant’ of the two responses – the visual system appears to avoid diplopia (double vision) in preference to avoiding blurring of the image if vergence and accommodation are dissociated [25].

3.2.2. Practical implications

A VID image overlaying the far domain should provide vergence cues that are congruent with those provided by the far domain. If there are depth cues present in a ‘flat’ image (as is the case with a two-dimensional image or indeed with a HUD image overlaying the outside world) then it appears possible for the accommodation level to change without any corresponding vergence change [142]. Although it appears that accommodation and vergence can change independently it has been demonstrated [32,160] that voluntary changes in vergence can be used to drive the accommodation response.

So, in general a VID image will provide excellent vergence cues. Problems may arise, however, if the accommodation and vergence cues are not congruent and this appears to be a possible source of discomfort in virtual reality displays [4,21,29,48,57,60,84,95,97]. These problems are unlikely to occur with a conventional HUD but may be a problem with a HMD, as it is possible with a HMD to change the vergence required to view the display independently of the optical distance. As a (binocular) HMD presents a separate image to each eye it is possible to simulate depth by introducing a disparity between the images to each eye. This can be used to good effect to give symbols at different depths that can be used, for instance, to ‘declutter’ the display (but see the section on attention for possible problems with displays at different depths). Unfortunately, although the disparity changes appropriately to give an impression of depth the focal distance and therefore accommodative demand remains fixed. This creates a conflict between the vergence and accommodation cues that could be problematic.

3.3. Tonic accommodation

3.3.1. Theory

Early theories on accommodation suggested that when no accommodative stimulus was present such as when viewing a featureless field (e.g. in cloud, clear sky, or darkness) the emmetropic (‘normal’) eye would be focused at optical infinity [43]. A large number of studies have since shown that this is true only for a small minority of individuals and that the tonic accommodation (TA) level (sometimes called the ‘resting’ or ‘dark’ focus) is typically at a distance of 0.5–2.0 m (e.g. [16,33,74,108,127,153]). There is thus a tendency for the accommodation response to ‘lapse’ back to this position. It is rather as though accommodation is attached by a spring to this point. Whichever direction (in or out) the accommodation response moves there will be a pull back towards the resting position. The more the accommodation response changes, the more the spring is stretched, and the stronger the pull will be. This is a crude analogy, but gives a feel for how an individual’s resting position of accommodation influences the overall accommodation response.

The tendency for the accommodation response to ‘lapse’ to the tonic position is the basis for a phenomenon known as ‘night myopia’ whereby there is a tendency for the accommodation level of the eye to increase when levels of illumination are low. The earliest published reference to night myopia was that of the then Astronomer Royal, the Reverend Nevil Maskelyne F.R.S [88] (described in [77]). The phenomenon of night myopia is also related to an aspect of the accommodation response (proximal accommodation) that may have a significant impact on the overall accommodation level and which will be discussed later.

Evidence suggests that TA may not influence the overall accommodation response directly [52,127,130] but rather acts as a moderator of other influences. For instance, if there is a shift in accommodation as a result of any of the factors considered in this review, then the tonic accommodation position is likely to influence the direction and/or magnitude of that change.

3.3.2. Practical and design implications

Consistent with the finding that the tonic accommodation position may moderate shifts in accommodation, Iavecchia et al. [55] found that the changes in accommodation whilst using a VID were related to individual subject’s resting focus (TA). This effect is particularly strong under conditions of no, or reduced, visual stimulation. Other studies have found similar results [63,105]. Evidence for TA position being only one of many factors influencing the overall accommodation response comes, however, from other studies using HUDs that have found little or no correlation between changes in accommodation and TA [132,161,163].

One way in which TA may influence the overall accommodation response is that items placed at this distance may act as particularly strong stimuli to accommodation; an effect originally referred to as the ‘Mandelbaum effect’ [82,109]. Unfortunately, most HUD combiners are likely to be placed somewhere within this range and thus could act as a ‘draw’ to accommodation.

The most obvious implication of this for design is that HUD combiners should not be placed within the common TA range (0.5–2 m). Given the space constraints where HUDs are likely to be used this is not entirely helpful. A more practical implication is that every effort should be made to reduce the salience of the combiner by ensuring that the combiner is clean of marks and e.g. making the supports less prominent. The introduction of HMDs may also ameliorate this influence because placing the combining surface near to
the eyes, as is the case with HMDs moves the combiner well away from any individual's TA position.

Another possibility would be to screen potential users so that none had TAs near the position of the HUD combiner. This seems a little extreme and would seriously limit the available pool of candidates. Also, given that (as mentioned above) TA may primarily act as a moderator of other influences on accommodation it would be better to attempt to reduce the impact of these other influences. This is because, as the image distance moves further away from the TA distance (and HUD/HMD image distances tend to be very different to the TA distance) the Mandelbaum effect will be much reduced and it is other influences on accommodation that are likely to have a relatively greater impact (as discussed above).

3.4. Chromatic aberration

3.4.1. Theory

Another factor that could be used to drive a closed-loop accommodation response and one that is not so well provided for by HUD imagery is chromatic aberration (the failure to bring different wavelengths of light to a common focus) introduced by the optics of the eye. As the accommodation level of the eye changes, so does the degree of chromatic aberration introduced into the image. A number of studies [33,70–72] have suggested that chromatic aberration of an image may play an important role in the accommodation response and that some individuals may be more dependent on chromatic aberration cues than others.

3.4.2. Practical and design implications

Most VIDs are chromatically narrow band and thus provide relatively poor chromatic aberration cues which may result in a less accurate accommodation response [1,2,65] – although users may learn to compensate using other cues [19]. There is also evidence that the depth-of-field of the human eye may be lower for monochromatic stimuli than for spectrally broad-band ones [83].

The implication of the above discussion is that the phosphors used for HUDs should be chromatically broad-band (e.g. white). This has to be balanced, however by the consideration that HUD imagery must be visible against a range of backgrounds and a white phosphor image may not be clearly visible (or indeed visible at all) against a bright background such as clouds.

4. Cognitive factors influencing the accommodation response

The discussion so far has concentrated primarily on the effect of visual stimuli (or lack of) on the accommodation response. These visual stimuli are assumed to form part of a closed-loop system. As the accommodation level changes, this leads to a change in some feature of the stimulus (e.g. blur/chromatic aberration) and this change is then used to refine the accommodation response further. It has long been suggested [138], however, that a number of other factors (including cognitive factors) may be influencing the accommodation response. These factors are generally referred to as 'open-loop' factors because they do not form a closed-loop feedback system driving the accommodation response in the same way that blur does.

Open-loop influences on the accommodation response may include such factors as perceived target size and distance, target proximity, and retinal disparity [12,34,42,46,50,56,58,62,79,126,129]. It is theoretically possible that some of the above influences could form a 'closed loop' system. For instance, if perceived distance affected accommodation and the level of accommodation also affected perceived distance (see below), then there would be the potential for closed-loop feedback, so the closed-loop/open-loop distinction is, perhaps, a little artificial. A simple distinction would be to suggest that closed-loop influences are primarily associated with the nature of the visual stimulus whereas open-loop factors are more influenced by task demands and so have a stronger cognitive component that may not be tied to the physical properties of the stimulus. Considering virtual image displays in the aircraft cockpit, it can be seen that many of the cognitive influences described above may be present when using virtual image displays. The discussion will now examine some of these cognitive factors in more detail.

4.1. Perceived distance

4.1.1. Theory

A number of studies have suggested that the perceived distance of a stimulus can influence the accommodation response. The first report of this effect was associated with the use of optical instruments and was termed 'instrument myopia' (e.g. [45,96,131,151]). The underlying theory is that, although stimuli viewed through instruments (such as microscopes) may be optically distant, they are perceived as being closer – and this influences the accommodation response. This effect is particularly evident if other accommodation cues (principally blur) are removed by 'opening' the accommodation loop. There are a number of ways in which the accommodation loop can be opened, but the most common methods are to place the subject in darkness or, if it is necessary for the subject to view stimuli, to view through a small (0.5 mm) pinhole. Using a pinhole in this way increases the depth of focus of the eye to the extent that changes in accommodation have little or no effect on the clarity of the image [147]. Thus, the closed-loop blur driven accommodation response is effectively bypassed and any cognitive effects (such as that of perceived distance) are particularly evident. Experiments of this sort have revealed strong effects of perceived distance on the accommodation response (e.g. [129]), although some part of the accommodation response may be driven by its interaction with the vergence response [154]. Indeed a recent model [27] suggests that, under open loop conditions, proximal (as the accommodation response to perceived distance is generally termed) effects can account for
between 40% and 90% of the overall accommodation response. The model predicts a much smaller effect if the accommodation loop is closed, but even in this case it is still possible to demonstrate that proximal accommodation can exert an influence [96,128]. It is not even necessary for the subject to be fixating a visual stimulus for proximal accommodation to occur – surrounding objects may also have an effect [45,46,78].

Thus items in the ‘outside world’ that would not be considered ‘objects of regard’ may also influence the accommodation response via proximal effects. For instance, the possibility that such items as cockpit window posts could exert such an effect has been suggested by Roscoe [125] following an accident investigation.

A number of studies, however, have shown cognitive effects on accommodation in the absence of any physical stimuli. A number of experiments [58,79,152] have demonstrated that even ‘thinking near’ or ‘thinking far’ can influence the level of accommodation; emphasizing the influence that cognition can exert on the accommodation response.

Not only does perceived distance affect the accommodation response, but it also appears that the converse may be true – i.e. that the level of accommodation may affect the perceived distance of objects. Descartes [26] postulated that oculomotor (eye accommodation and vergence) responses may provide cues to the distance of objects and Berkeley [9] proposed that oculomotor responses and perceived distance may become associated through experience. Since these early theories there has been some debate as to whether it is accommodation, vergence, or some combination of both that influences perceived distance (– for further references see: [30,48,61,106,110,122,145]). Many of these studies have, however, tended to assume that perceived distance is influenced by the absolute level of accommodation rather than by changes of accommodation having a secondary influence on other cues to distance. For instance, inappropriate accommodation may blur the image leading to a loss of visible texture or ability to resolve retinal disparities which might also affect perceived distance [50,85,89,90,92,135]. Thus it may not be changes in accommodation (or vergence) per se that lead to the misperceptions of distance mentioned earlier: perceived distance may also change as a result of blurring of the image that results from shifts in accommodation. Some of the apparently contradictory findings of earlier studies on the influence of accommodation and/or vergence on perceived distance appear to arise from attempts to isolate the effects of accommodation or vergence on perceived distance. As Meehan and Day [93] point out, any effects of accommodation on perceived distance are likely to be as part of a complex interaction with many other factors – and particularly vergence.

4.1.2. Practical and design implications

Imaging displays appear to affect perceived size and possibly distance [115,117,124]. It has, however, been suggested that accommodation and vergence only contribute significantly to perceived distance at distances of less than 1 m [73,75]. Thus it seems unlikely that changes in vergence or accommodation would cause significant changes in perceived distance when using VIDs which typically present images at distances far greater than 1 m (usually close to optical infinity). The key term, of course, is significant change. Given the strong interactions between accommodation, vergence and other distance cues it is possible that accommodation and vergence may still exert some small effect on perceived size and/or distance but as part of an interaction with many other factors. This would not preclude a correlation between changes in accommodation and perceived distance [7,8,50,54,118,121] – it simply means that accommodation need not be the sole cause [93,139]. The judgement of distance certainly appears to involve a number of cues – with distance judgements becoming more veridical as the number of available cues increases [41,94].

Another cue to distance and one that is particularly relevant to the study of VIDs is that of occlusion. Objects that are closer to the viewer may overlap and occlude parts of objects that are further away. Virtual image displays superimpose an image on the ‘outside world’ and occlude parts of it – which may give the appearance that the overlaid image is closer. Indeed, a study by Kotulak and Morse [63] using the Apache helicopter helmet-mounted display found that all the aviators tested reported that the overlaid HMD imagery appeared closer than the background scene.

Kotulak et al. [67] have demonstrated that, under semi-open loop conditions (using an image with degraded spatial frequency and luminance cues – hence providing reduced cues to drive a closed-loop system), knowledge of object distance may be a more powerful cue than optical distance for some individuals (two out of seven in the Kotulak et al. study). A sample of two from seven suggests caution in proposing a large effect of perceived distance on the accommodation response, but it does give an indication that perceived distance may be a powerful cue for some people. The finding that this effect only occurs in some participants, however, also suggests that there may be strong individual differences – as might be expected for cognitive influences. This, of course, may be another reason why some of these effects are difficult to establish or quantify. For instance, other studies [5,45,64,98] have found that under closed-loop conditions (if the perceived distance of an image conflicts with blur cues) there is no effect of perceived distance on the accommodation response. These studies, however, used relatively short stimulus distances (from 0.25 to 2.0 m) and, as already discussed, the absolute (rather than perceived) stimulus distance is likely to affect the direction and/or magnitude of effects on accommodation.

From a practical point of view, it is crucial to decide which is most important: the influence of perceived distance on accommodation – or the influence of accommodation on perceived distance. In many ways, it seems best to concentrate on the effect of perceived distance on accommodation as this is really the primary problem and has
been clearly demonstrated; whereas the reverse effect seems more equivocal.

Thus, the problem now becomes one of assuring that the cues to distance provided by a VID are congruent with the true distance. As mentioned above this involves removing or reducing cues that give a false impression of distance (assuming, and this may be problematic, that all such cues can be identified) – such as occlusion cues with VIDs. One obvious way of doing this is to use conformal imagery – where the VID image is ‘integrated’ into the far domain so that there are fewer, or no, occlusion cues to suggest that the VID image is closer than the far domain. Another problem mentioned briefly above is whether the user is aware of, and responding to, other stimuli (apart from the VID image) that are not at the same distance as the far domain. These includes such things as the VID surround and cockpit supports. As mentioned above, these stimuli may affect the overall level of accommodation as a result of proximal accommodation.

There is, however, one situation where the effect of accommodation on perceived size may be particularly important. This is in the use of a newer class of display – retinal displays (for a description see e.g. [113]). The general principle of these displays is to use a narrow beam of light to project an image directly onto the retina. These can be configured (although may not be) so that [133] the optics of the eye are effectively bypassed – thus the image is always sharp no matter what the level of accommodation. It might be assumed that there would therefore be no problems with accommodation but the possible relationship of accommodation and perceived size/distance suggests that this may not be the case. As the accommodation level of the eye changes the image from a retinal display stays in focus. The only way that this can happen in the ‘real world’ is if the object has moved closer or further away. Thus, the prediction is that as the accommodation level changes the image provided by a retinal display will appear to change in size and/or distance. There are, however, variants of these displays that are able to present parts of the image at different optical distances [133] which should avoid, or at least ameliorate, the problems discussed above.

There is a second problem associated with retinal image displays and this may arise if the image from the retinal display overlays the far domain. In this instance, if there is any change of accommodation from a level appropriate to the far domain, the far domain may appear blurred but the image from the retinal display may not – possibly giving the impression that the far domain and the image are at different distances, with the occlusion cues suggesting that the retinal display image is closer. Certainly this is an area worthy of further investigation.

4.2. Mental workload

4.2.1. Theory

Mental workload, as used in the context of this discussion, is defined as the extra cognitive effort required to handle an increased imposed task load. It is extremely difficult to measure the absolute level of workload generated by a particular task, so studies in this area tend to study the effect of increasing workload in one condition compared to a baseline. A number of studies [10,14,15,30,37,40,69,80,81,112,126,158] have demonstrated an effect of mental processing on the visual accommodation response. These studies have measured accommodation under both open-loop conditions (no blur cues) and also under conditions where both open- and closed-loop influences are active (which should be the case with VIDs).

The complex nature of the influence that cognitive factors such as mental workload may have on the accommodation response is emphasized by research that has indicated that it is not just workload level per se that may affect the accommodation response. Other influences, such as the method of presentation of information to be processed, the nature of the processing task and the distance at which it is presented may also have an influence.

Relevant work concerning the source of information to be processed has been conducted by Winn et al. [158] who found a differential effect on the accommodation response depending upon whether the mental processing task was stimulus dependent (SDT) (performing the task requires information from a visual source) or stimulus independent (SIT) (the information necessary to perform the task does not come from a visual source (e.g. the information to be processed is derived from memory or from a non-visual modality)]. The general finding from this and other studies was that a mental processing task often (but not always) resulted in a change in the level of accommodation and that this change was more pronounced in open-loop SDT conditions. In the aircraft cockpit, information to be processed may come from visual displays (in this case the task is stimulus dependent) or, increasingly, via auditory channels (in which case the task is essentially visually stimulus independent).

Studies of the effect of mental processing on the accommodation response have also tended to report conflicting results regarding the direction of the change in the accommodation level. Some studies [10,81,126] have found that the level of accommodation decreases as a result of mental effort (the focusing point is further away from the individual), whereas other studies [15,69,112,158] have demonstrated that a mental processing task may lead to an increase in the level of accommodation. Bullimore and Gilmore [14] suggest that stimulus distance is an important factor in determining the direction of the accommodation change. A study by Ebenholdz [28] found that the direction of a shift in tonic accommodation following sustained fixation was dependent upon whether the fixation point was at the near- or far-point of accommodation for the individual concerned.

4.2.2. Practical and design implications

As mentioned above, at a fairly simplistic level, two components of workload may be identified: obtaining
information from the ‘outside world’ (which would be a stimulus dependent task assuming the input is visual) and mentally processing such information (stimulus independent). In an aircraft there are essentially two sources of information to be processed – the ‘real world’ and the cockpit displays. If only head-down displays are used then there is a separation of the two sources of information – the pilot may still be processing information from cockpit displays when s/he goes head up – but no new display information is coming in. With a head-up display, however, both sources of information are available simultaneously. The situation becomes complicated when considering the difference between conformal and non-conformal imagery on the VID. As described previously, conformal imagery involves the use of symbology ‘integrated’ with the far domain – so the VID image becomes a part of the outside world rather than overlaying it. Workload may be reduced because the integration of the VID image and outside world means that less processing is required to relate the information displayed on the VID to the far domain. The fact that the ‘real world’ and display information are integrated, however, means that it is more difficult to attend to only one source of information. This leads to the possibility that, although the average workload may be less with a VID (particularly with conformal imagery) the peak workload may be higher (also particularly with conformal imagery).

With respect to accommodation and VIDs, the overall level of workload appears to be important because the effect on the accommodation response increases with workload [163]. If a VID is used then there is potentially more information available for processing at any one time. Thus the peak workload may be greater and the impact on the accommodation response increased. Support for this notion comes from a study by Iavecchia et al. [55] which found that in two conditions both containing a virtual image and all else being equal, there was a larger effect on the accommodation response if information had to be processed in the outside world as well as the HUD – compared to when information only had to be processed on the HUD.

The obvious implication is that workload in the cockpit should not be too high. This is not a particularly helpful recommendation as nobody would set out to design a system with unrealistic workload demands. It is more useful to look at the way in which workload may affect accommodation and design the system to reduce these effects. There appear to be two related ways in which workload may affect the accommodation response with VIDs. These are:

1. High workload appears to lead to resources being diverted away from the ‘outside world’ and a concomitant shift of accommodation inwards.

2. High workload may lead to a concentration of attention on just the VID or just the far domain. If attention is concentrated on the VID then this may increase the salience of cues suggesting the VID image is closer – with a secondary effect on the accommodation response.

The main design implication is in the type of VID to be used. Unfortunately ameliorating one of the effects above appears to exacerbate the other. For instance, using conformal imagery reduces the effects of perceived depth differences between the VID image and the far domain – but may increase the peak workload. Thus VIDs should be designed to keep workload to a reasonable level and, at the same time, reduce the amount of non-conformal imagery on the VID. Although this recommendation is made with a view to reducing inappropriate accommodation responses similar recommendations have been made elsewhere in relation to allocation of attention [156]. Finally, when considering workload level, consideration should be given to whether the workload arises from gathering information, or processing it.

4.3. Attentional factors

4.3.1. Theory

The influence of attention on the accommodation response has already been discussed to some extent in the previous section. Rather than attempt to review the vast literature on attention, this section will only consider whether attentional factors may affect the overall accommodation response when using VIDs.

Kotulak and Morse [63] looked at oculomotor responses with the Apache HMD and found that the change in the level of accommodation was greater if participants attended to the overlaid symbology as opposed to attending to the background scene. A similar study by Schor and Task [132], however, found a much smaller effect on the accommodation response. One crucial difference between these two studies is that in the Kotulak and Morse study, both the far domain and the VID image were viewed monocularly – thereby removing any cues to vergence. In the Schor and Task study, although the VID image was viewed monocularly, the far domain was viewed binocularly, and therefore provided good vergence cues. As already discussed, the vergence and accommodation responses are strongly linked, so the strong vergence cues in the Schor and Task study may have been instrumental in maintaining an appropriate accommodation response.

The underlying mechanism for these attention-related shifts in accommodation is not entirely clear. One possibility is that individuals are allocating attention to a ‘closer’ depth plane defined by the VID image and that the accommodation response is following this shift in attention. Certainly, there is some evidence that attention can be moved in three dimensions [101,103]. There are obvious links between perceived distance and shifts of attention. It is possible that accommodation changes in response to perceived distance as a result of attentional shifts in three dimensions.
Attential influences on the accommodation response may provide an explanation for studies that have found apparently contradictory results. Francis et al. [35] reported that responding to an auditory stimulus had a greater effect on the accommodation response (to a distant target) than responding to a visual stimulus. The opposite effect was found by Edgar and Reeves [31]. The reason for this difference may lie in differences in the experimental design. Edgar and Reeves presented a processing task within a virtual image superimposed on the ‘outside world’ thus providing occlusion cues (absent in the Francis et al. study) giving a strong impression that the VID image was closer. Furthermore, the processing task within the virtual image (in the Edgar and Reeves study) may have acted to draw attention to the image. Thus, the measured shift in accommodation may have been driven by an interaction of perceived distance and allocation of attention. Finally, viewing in the Edgar and Reeves study was monocular, thus removing vergence cues to accommodation. Given that the Edgar and Reeves study used a situation so conducive to a lapse in accommodation, it perhaps explains why the accommodation shifts in this study are relatively large, up to a mean shift of about 0.5 D. This mean change in accommodation is only just outside the minimum depth-of-field of the human eye (see the section on blur) but obviously, for some participants, the shifts in accommodation were larger. Indeed, one participant spontaneously reported a blurring of the stimulus, suggesting that the shift in accommodation was greater than the depth-of-field. This suggests that, if a number of the factors discussed so far are present together, there can be a large enough shift of accommodation to affect the visibility of the stimulus.

4.3.2. Practical and design implications
The problem appears to be that users may perceive the VID image to lie in a different depth plane to the far domain. The VID image, although at the same optical distance as the far domain, does form a particularly well defined plane in that all the imagery (certainly with most VIDs) is likely to be of a single colour and, as suggested by Neisser [102], shared colour is a criterion that may be used when assigning attention to an object. This shared colour, combined with occlusion cues and the knowledge that the image is presented on a proximal combiner may all contribute to a perception of the VID image as a discrete plane. Thus, rather than attending to a single combined image the user attends to one plane or the other. If attention is directed to the VID image then the perception of that image being closer than the far domain may influence the accommodation response – as perceived distance has already been demonstrated as influencing the overall response. Thus the effect on the accommodation response will be increased by a combination of:

1. Anything that increases the perceived depth difference between the VID image and the far domain.
2. Anything that draws attention to the VID image at the expense of the far domain.
3. High workload that limits the availability of resources for dividing attention between external stimuli.

Thus, to avoid attentional factors influencing the accommodation response, these three factors should be reduced as much as possible. A practical solution may be the use of conformal imagery. Even with conformal imagery, however, there are still some cues, such as shared colour, that suggest a discrete plane.

A substantial body of evidence [86,87,100,156] suggests that conformal VID imagery allows attention to be divided more easily between the VID image and the far domain; although in some situations (particularly with automobile HUds) there may be some degree of attentional tunneling (focusing of attention on to a narrow area of the visual field at the expense of areas outside the ‘tunnel’) even with conformal imagery [11,141,146]. Martin-Emerson and Wickers [87] suggest that conformal imagery may only confer a performance advantage when it is necessary to divide attention between the VID and the far domain, as the VID image ideally becomes a part of the far domain, making it easier to ‘spread’ attention across both the VID image and the far domain. If attention is drawn to (and focused on) a discrete event (such as a runway incursion in the far domain) then, although conformal displays may be no better than non-conformal, they are no worse. This may seem obvious, but it is important to bear in mind that it may not always be desirable for attention to be divided. If a serious event (such as a runway incursion) occurs, then it may be advantageous that almost all attentional and processing resources are initially allocated to that event.

The implication from this discussion of attentional issues with VIDs is that as much of the VID image as possible should be made conformal with the far domain. This would represent part of a general approach to reduce any apparent depth differences between the far domain and the VID image. Included in this would be the reduction of the salience of the VID combiner – as this may provide a powerful cue suggesting that the VID image is part of a plane closer than the far domain. There is a problem here, however, for automobile HUds – where it may not be desirable to have the HUD collimated to infinity (there is a greater range of distances for objects in the outside world in driving as opposed to flying). In this case, the possibility of shifts of attention and accommodation from one plane to another is increased. This, of course, is what happens in automobile driving anyway – but the danger is that attention will become ‘tunneled’ onto the HUD. Indeed, it could be argued that attentional tunneling to automobile HUDs is actually more likely than with aircraft – as in a driving task most stimuli are at a range of distances – except for those on the HUD – which are probably going to share a common optical distance. Thus, the VID image
may provide the most coherent distance-plane – and perhaps the strongest draw to attention?

5. Summary and conclusions

The overall accommodation response, far from being a simple response to image blur, appears to be the result of a complex interaction of a number of factors. For instance, the accommodation response may be influenced by perceived distance. Perceived distance in turn may be influenced by the depth plane to which attention is directed (e.g. VID image or outside world) and this in turn may be influenced by the source (or level) of workload. Thus, there are a number of factors that may lead to an inappropriate accommodation response when using a virtual image display. The evidence reviewed here suggests that these factors interact and that their effects are cumulative. The following list suggests some (but quite possibly not all) factors associated with a virtual image display that might contribute to an anomalous accommodation response even if the virtual image is at the same optical distance as the background. This list applies to ‘see through’ virtual image displays (such as HUDs and HMDs), although some factors may still be relevant to ‘closed’ displays (such as some VR systems). These factors are:

(1) The virtual image clearly occludes parts of the background.
(2) The virtual image is displayed via a system proximal to the user (e.g. a HUD combiner).
(3) The image combiner is placed near an individual’s tonic accommodation distance.
(4) The user’s attention is directed to the virtual image.
(5) The virtual image is used to present information to be processed.
(6) There is no requirement for processing information or detecting targets in the ‘outside world’.
(7) The virtual image is monochromatic.
(8) The virtual image provides poor cues to accommodation (in terms of e.g. chromatic or spatial frequency content).
(9) The virtual image is viewed monocularly.
(10) Workload is high.

The large number of interacting factors is almost certainly the reason for the apparently contradictory findings of some of the studies reviewed here. The overall results obtained are likely to depend on which factors are present – and to what extent. Unfortunately, from a practical point of view, simply saying that there are a lot of factors that affect the overall accommodation response and that they all interact is of limited use. The final part of this review will therefore attempt to provide an explanatory framework discussing how these different factors may interact – and suggest directions for future research.

6. Future research directions

The best understood inputs to the overall accommodation response are the closed-loop inputs such as blur and chromatic aberration. If these were the only drivers influencing the overall accommodation response then there should be little problem with VIDs – as they generally provide excellent blur (and vergence) cues. From this review of the literature it becomes clear, however, that there is a strong cognitive input to the accommodation response and it is this cognitive component that is underlying the problems discussed here. This really begs the question, ‘Why, if the closed loop cues are so effective, is it necessary to have any cognitive input at all?’ Despite the obvious importance of this question, there appears to be very little mention of it in the literature. Perhaps it is so simple as to be not worthy of consideration but, given its importance, it will be discussed here. The most likely answer seems to be that closed-loop cues are only completely effective if there is only one stimulus in the visual field – or a number of stimuli all at the same depth. If there are a number of stimuli at different depths then there is a problem with using only a closed loop system – e.g. which blur cues should be used? For instance, consider looking at a distant scene through the branches of a tree. The branches of the tree and the far scene occupy almost the same points in the visual field (and are interleaved) – but provide very different blur and vergence cues. Without any cognitive input it is impossible to fixate and accommodate on one rather than the other. Thus it is necessary for the visual system to ‘decide’ which stimulus should be used to drive the closed-loop response (which rather begs the question of whether the closed-loop response is really a ‘reflex’ response). This decision involves allocation of attention to a certain stimulus and emphasizes the fundamental importance of understanding the role of attention if the interactions described in this review are to be resolved.

Thus, the underlying problem of misaccommodation with VID displays can be reduced to one of cognitive (open loop) influences driving the accommodation response away from the level suggested by closed-loop influences. The suggestion is thus that closed loop and cognitive cues may be driving the overall accommodation response to different positions and an overt problem occurs if the accommodation level suggested by the cognitive cues is not congruent with that suggested by closed-loop influences. Displays that can present parts of an image at different optical distances (e.g. [3,133]) may help to provide better cues for closed-loop accommodation, but the cognitive influences may remain.

The effects of different factors on the accommodation response and how they may act when using a VID have been the subject of this review. The cognitive influences on the accommodation response (particularly attention) appear, however, to be relatively poorly understood. Thus, an area worthy of further research, is the cognitive influences on the accommodation response and, in particular,
the interaction between the VID, visual accommodation, attention and workload. This, unfortunately, is easier said than done, as the interaction is likely to be very complex. For instance, if workload is high this increases the likelihood of attentional tunneling and attention (and accommodation) being drawn to the apparently closer VID image. If workload is low then more attentional resources are available and attention is more likely to be influenced by irrelevant stimuli[126] – such as the VID supports or combiner. This may increase the likelihood of proximal accommodation (discussed earlier). It is, however, important to investigate the interactions between the many factors influencing the accommodation response as it appears to be an interaction of factors, rather than a single factor, that determines the overall accommodation response when using a virtual image display.

References


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