Design of monocular head-mounted displays, with a case study on fire-fighting

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Abstract: The paper presents a design methodology and a case study for monocular head-mounted displays (HMDs), wherein a user can simultaneously and easily see the physical world by looking through and/or around the display. The design approach is user-focused because of the complexity of the human visual system, and because HMDs are very task, user, and context specific. A literature review of factors related to HMD design is given. This includes considerations for basic optical design, the human visual system, and head and neck biomechanics. General HMD design guidelines are given based on these considerations. For the specific case study on fire-fighting, it is recommended that the HMD be mounted at 15° to 45° below the Frankfurt plane, with a 15° to 40° field of view. A resolution of 20–60 px/deg should be focused at 1 m or farther. The neck joint torque due to the HMD should not exceed about 1 Nm. This equates to a typical maximum weight of 0.5 to 1 kg depending on the mounting location.

Keywords: head-mounted display design, emergency first response, fire-fighting

1 INTRODUCTION

1.1 Literature review: head-mounted displays

Head-mounted displays (HMDs) allow a user to view information on a small screen that is typically mounted on a facepiece, helmet, hat, or special eyeglasses (Fig. 1). A convenient and hands free format is key to the user acceptance of the device. HMDs are classified into three ocular types: monocular – for single eye viewing, biocular – for both eyes, and binocular – for stereovision by presenting a slightly different image perspective to each eye [**1**]. HMDs were first developed in the 1960s by university researchers [**2**–**4**]. More recently, inexpensive flat panel microdisplays have enabled many applications for military pilots and soldiers, virtual reality, entertainment, wearable computing, advanced surgery, auto mechanics, and first responders.

1.2 A 'Framework' for the methodology and organization of the current paper

Ishikawa (1963) and other researchers introduced the 'cause and effect' or 'fishbone' type diagram for analysing any design or manufacturing task that will involve many interrelating parameters [**5**]. Figure 2 shows such a diagram that the authors have prepared for the Case Study on an HMD for firefighting described later. Figure 3 represents the top half of Fig. 2, but with component-based design requirement topics rather than human-based. For example, 'Visual acuity' of the eye in Fig. 2 is replaced with 'Resolution' of the display screen in Fig. 3. The design methodology used is human-based in order to emphasize proper HMD functionality in terms of the capabilities of the user. This is opposed to focusing on component functionality, which may create unnecessary capabilities and functionalities. This in turn increases cost and complexity in a product that must be easy to use and cost-effective. These diagrams are presented here at the beginning of the paper (rather than in section 5) to provide a convenient framework for the reader, prior to describing many of the specific details on optics and ergonomics in the following four main sections:

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Fig. 1 Prototype fire-fighter monocular HMD in facemask

(a) section 2: basic HMD optical design;
(b) section 3: human visual considerations;
(c) section 4: head and neck biomechanics;
(d) section 5: generic design guidelines.

The authors have drawn on the HMD literature to give *generic* human-centred functional requirements (FRs) in sections two through four, and design guidelines for HMDs in section five. Section 6 presents the *specific* design parameters (DPs) for the HMD recommended for fire-fighting ([**6**, **7**], for a review of FRs and DPs). Table 1 provides a summary of some of the nomenclature used throughout.

2 LITERATURE REVIEW OF BASIC HMD OPTICAL DESIGN

2.1 Overview of optical layout

Any HMD needs an optical train from the microdisplay to the eye to magnify the information to a viewable size. A generic example is shown in Fig. 4, where a simple magnifier objective lens, a mirror, and a beamsplitter are used to create a see-through design. When using a simple magnifier, the object, being the microdisplay, is placed at or within the focal length of the lens to obtain a virtual upright image.

2.2 'Look-around' versus 'See-through'

An early design consideration to make is whether the HMD will be an occluded look-around design or a see-through design. A look-around system is a train of optical elements through which one sees the display screen, usually focused to appear at or near infinity. Everything behind the screen is occluded, like looking at a TV. These HMDs are small enough to look to one side of them to see the real world.

Alternatively, the optics may be designed to create a see-through system that reflects light into the pupil via a beamsplitter. The user of such a system would see a virtual image 'floating' in space. The imagery usually adds useful information to the real environment

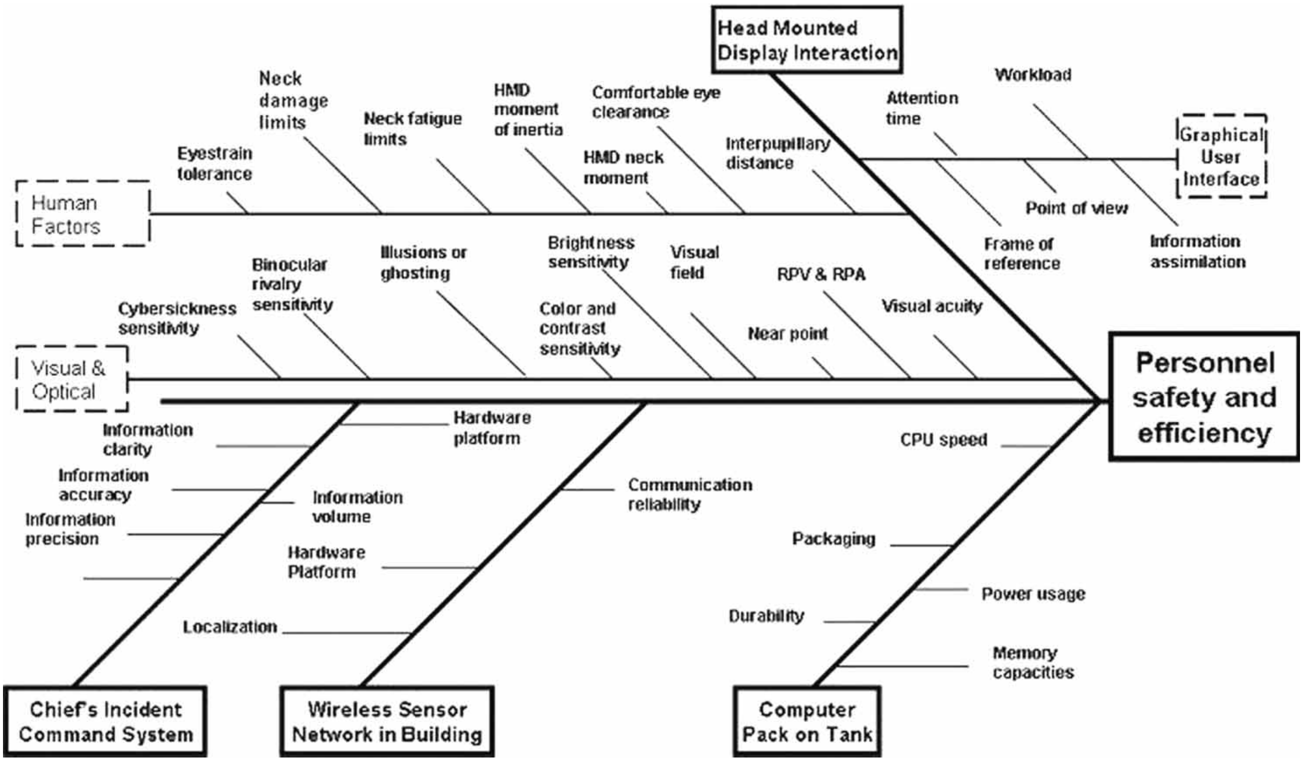

Fig. 2 Fishbone overview diagram of the case study on the HMD for fire-fighting described later in section 5 of the paper

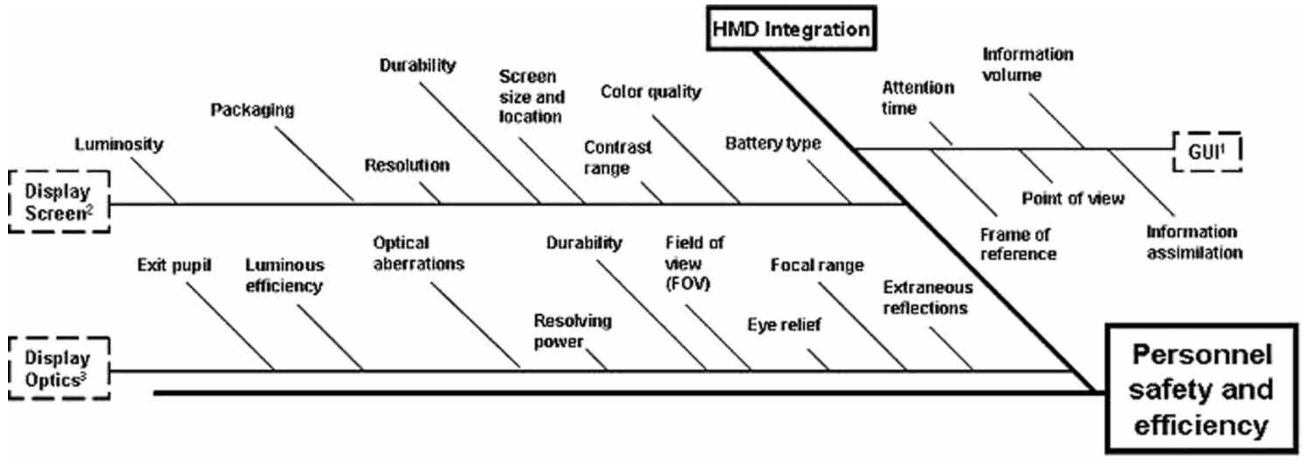

Fig. 3 Top half of Ishikawa diagram, showing component based metrics for an HMD

Table 1 Some human factors nomenclature and definitions for HMDs

Instantaneous field of view	Horizontal and vertical angular visual field
Foveal resolution	Central retinal area of highest visual precision
Luminance and contrast	Sensitivity limits to vision
CFF	Minimum image update rate to avoid display flicker
Interpupillary distance	Horizontal distance between the eye pupils
Near point	Closest location from eye an object can be held in focus
RPV	Location at which eyes converge at rest without a stimulus
Ocular motion effects	How eye position affects vergence and accommodation
Visual problems	Unwanted psychophysical reactions to HMD
Ocular anthropometrics	Measurements of eye locations on faces
Head and neck biomechanics	Effects of added head weight on neck fatigue and damage

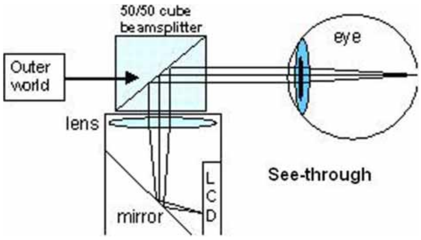

Fig. 4 Example see-through HMD optical layout

by overlaying data onto immediate objects in that scene. Thus, the see-through design may be referred to as an augmented reality display. An automotive mechanic, for example, would likely see a part diagram and installation instructions superimposed on the actual part [**8**].

2.3 Pupil versus non-pupil forming optics

The designer must also consider whether the optical system will be pupil forming, as with a compound microscope, or a non-pupil forming simple magnifier, as in a magnifying glass. A pupil forming system forms the image at a two-dimensional circular area in space, while a non-pupil system forms a conical area allowing more forward-back eye movement without losing the image. Too much movement back will cause the image to vignette, where the periphery blurs and disappears. The basic compound microscope layout is shown in Fig. 5.

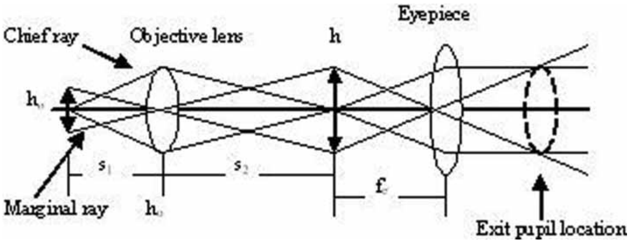

Fig. 5 Diagram of a basic compound microscope showing chief and marginal rays

2.4 Optical design parameters

Table 2 gives metrics commonly used to design a monocular HMD and analyse its optical performance.

The exit pupil determines the screen image location and the light flux reaching the eye. In a pupil forming optical system, the exit pupil location is calculated with the Gaussian lens formula

$$\frac{1}{f} = \frac{1}{d_\mathrm{i}} + \frac{1}{d_\mathrm{o}} \tag{1}$$

Table 2 Typical monocular HMD metrics

Metrics	
Exit pupil location	Eye clearance
Exit pupil diameter	Eye relief
FOV	Eyepiece diameter
Magnification	Resolution
Image focal range	Luminance throughput

This formula is used for paraxial light rays entering the paraxial region of a spherical lens. A paraxial ray is one for which its sine and tangent are very similar, and the paraxial region is that near the optical axis. In the non-pupil example, however, there will be a cone of light in which the eye can be positioned to see the image. The diameter of this cone as a function of the eye distance from the eyepiece is given by

$$D_{\mathrm{ep}} = D_{\mathrm{lens}} - \frac{L_{\mathrm{e}}S}{f} \tag{2}$$

where D_{lens} is the eyepiece diameter, L_{e} is the eye relief, S is the screen diagonal, and f is the focal length. This equation is valid when the microdisplay is positioned at the lens focal point.

The eye relief of the eyepiece is the distance from the last optical element to the cornea of the eye. The eye clearance is the distance from the last physical object on the HMD to the cornea of the eye, and is important for viewing comfort. It is usually the same, as or slightly less than, the eye relief.

The apparent screen image size is given by the field of view (FOV) of the system

$$\mathrm{FOV} = 2 \cdot \arctan\left(\frac{S}{2f_{\mathrm{e}}}\right) \tag{3}$$

where S is the display screen size (horizontal, vertical, or diagonal) and f_{e} is the focal length of the eyepiece.

Magnification can be found in general the ratio of the image height to the object height. For a simple magnifier, it can be found by the ratio of the angular subtense from the aided eye to the object, viewed through the magnifier, to the angular subtense from the unaided eye to the object viewed at the normal near point of 0.25 m [**9**]. When viewing an HMD, this is equivalent to the ratio of the FOV to viewing the display screen unaided at 0.25 m.

$$\mathrm{MP} = \frac{\alpha_{\mathrm{a}}}{\alpha_{\mathrm{u}}} = \frac{\mathrm{FOV}}{\arctan(S/0.25)} \tag{4}$$

Diffraction in a lens causes image points to spread. The diffractive limit of resolution of the eyepiece is found using

$$(\Delta l)_{\min} = \frac{1.22 f_{\mathrm{e}}\lambda}{D} \tag{5}$$

where Δl is the centre to centre separation of two images (e.g. two dots), f_{e} is the focal length of the eyepiece, λ is the wavelength (550 nm for white light), and D is the aperture diameter of the optical system [**9**]. This is rarely the limiting imaging factor in an HMD. It is usually the microdisplay pixel resolution.

Image distortion is a frequent problem and is commonly due to spherical lens aberrations. Spherical lenses are less expensive and more commonly available than parabolic or other aspheric lenses, thus they are more commonly used. When designing with spherical lenses, however, if the paraxial approximation is not followed, then aberrations become quite problematic. Six common types of aberrations are: spherical, coma, astigmatism, distortion, field curvature, and chromatic. Aspheric and achromatic lenses are often used to correct these problems.

2.5 Display selection

Flat panel microdisplays are the most commonly used image source for an HMD. They are produced using MEMS technology, and one must use magnifying optics in order to read what is being displayed. This technology was pushed by a DARPA HMD program in the 1990s as a replacement for the heavier and bulkier cathode ray tube [**10**]. Multiple types of these microdisplays are now being mass-produced. A selection of these is compared in Table 3, with advantages and disadvantages relevant to HMD design. Also included is a retinal scanning display, which is not a flat panel design but is used in a commercial HMD.

Display image quality is often described by resolution, contrast, and luminance. The resolution of a display can be given by the pixel count, for example video graphics array (VGA), being 640 × 480 pixels, or by the angular subtense of a single pixel. The latter is calculated by dividing the FOV seen by the HMD wearer by the number of pixels (N) along that same dimension

$$\mathrm{Resolution} = \frac{\mathrm{FOV}}{N} \tag{6}$$

3 LITERATURE REVIEW OF HUMAN VISUAL CONSIDERATIONS

3.1 Overview of human eye parameters

When designing an HMD, it is important to understand the abilities and limitations of the average human eye. This enables the designer to tailor the optical

Table 3 Advantages and disadvantages of selected microdisplays, referencing data from references [**11**] to [**13**]

Type	Advantages	Disadvantages
AMLCD	Ease of high volume availability, less expensive relative to others here	Limited operational temperature range (0 to +60 °C), slower update time
OLED	Good colour quality, compact, efficient, wide viewing angle, good temperature range (−35 to +70 °C)	Relatively expensive (gradually reducing in price), shorter operating lifetime
Active matrix electro-luminescent	High resolution, rugged, wide viewing angle, good temperature range (−40 to +75 °C)	Low luminance, limited colours, less efficient, relatively expensive
Field emission display	High luminance, efficient, high temperature range	Less mature technology, less availability, expensive
Liquid crystal on silicon	Good image quality, high pixel density	Expensive, bulk of light reflecting mirror, less efficient
Retinal scanning display	High resolution and luminance, wide colour gamut	Expensive, bulk of optics, less rugged

design to the eye's requirements. General visual criteria to consider when designing an HMD are listed as follows [**4**]:

(a) Instantaneous monocular field of view;
  (i) Visual field for one eye without eye movement, i.e.using peripheral vision. This is important in determining the area of one's visual field blocked by the HMD,
  (ii) 160° (200° binocular) horizontal by 120° vertical [**14**].
(b) Foveal resolution;
  (i) Central two degrees of vision within the macula of highest cone density [**14**],
  (ii) one arc minute (1/60th degree) for 20/20 visual acuity; or a 75-micron object viewed 25 cm away.
(c) eye pupil diameter;
  (i) 2–8 mm depending on ambient light [**9**].
(d) scotopic and photopic vision sensitivity;
  (i) the luminance levels at which the eye can see,
  (ii) $\sim 10^{-6}$ (scotopic using rods)–10^{6} (photopic using cones) cd/m^2,
  (iii) maximum vernier acuity (detection of discontinuity or misalignment in lines) occurs at 17 cd/m^2 and greater [**15**].
(e) contrast sensitivity;
  (i) dependent on spatial frequency of image, thus must consider the modulation transfer function of the eye,
  (ii) maximum at 2–5 cycles/degree (cpd), none above approximately 60 cpd (1 acrmin) [**14**]. In other words, the eye can best resolve images separated by 1/2–1/5th of a degree, and can, therefore, tolerate a minimum contrast between these images. The eye needs maximum contrast to resolve images separated by 1/60th of a degree (one arc minute).
(f) critical flicker fusion (CFF);
  (i) minimum image update rate to avoid display flicker,
  (ii) ~60 Hz under optimal image luminance, spatial frequency, and foveal location.
(g) near point;
  (i) the closest object upon which one can focus,
  (ii) averages about 10 cm in young people, 30–40 in middle aged, and 100 cm after age 60 [**14**].

3.2 Resting points of vergence and accommodation

The resting point of vergence (RPV) is the point on which the eyes converge when relaxed. Humans have evolved to gaze farther off when looking up or straight than down, as when outside, most of the objects higher up are farther away than those on the ground. The horizontal RPV averages 116 cm [**16**, **17**]. Looking upward at 30° increases it to about 135 cm, while looking downward 30° it decreases to 89 cm [**18**]. The resting point of accommodation (RPA), also known as the dark or tonic focus, is not infinity as commonly thought. It averages about 80 cm [**19**].

3.3 Visual concerns

3.3.1 Binocular rivalry

Viewing a monocular HMD creates conflicting images between the eyes. Binocular rivalry can occur when the scenes viewed by each eye are opposing in brightness, pattern (e.g. vertical versus horizontal lines), or spatial characteristics like depth and motion cues. In the case of a see-through HMD, the non-viewing eye is seeing the real world, while the viewing eye is seeing information overlaid onto the real world. In the case of a look-around HMD, the viewing eye is focused on a screen, whereas the non-viewing eye may be looking at anything from the real world to the side of one's nose.

Rivalry between the eyes can be more problematic with a look-around design, especially when the occluded FOV is high enough to seem immersive. Peli [**20**] found eyestrain problems in a word processing experiment with such an HMD [**21**]. It is especially problematic over long periods (hours) of frequent use.

See-through designs, however, can also cause problems. Apache helicopter pilots use the integrated helmet and display sighting system (IHADSS) see-through monocular HMD on multi-hour night missions. One eye views a dark cockpit and night scene, and the other a bright image overlaid onto this scene. They report rivalry symptoms, and after-effects including visual fatigue and headaches [**22**].

3.3.2 Other problems

Other documented concerns include visual nausea and the Pulfrich phenomenon. Visual nausea, or cybersickness, occurs due to latency in visual versus vestibular motion cues. This is more common in immersive virtual reality displays with head tracking. The display imagery will lag behind one's sense of motion, causing dizziness and nausea. The Pulfrich phenomenon occurs under ocular luminosity differences. An image delay to the darker adapted eye results in depth illusions for laterally moving objects [**4**]. Further visual problems can occur in accommodating to the HMD screen. If the screen is not focused at the same distance as objects viewed in the real world, the user will have to re-accommodate when switching between the different depth cues.

Instrument myopia, common with microscopes, is return of the accommodative state of the eye to an intermediate distance when viewing an optical instrument such as an HMD [**23**]. Recall that the RPA is at less than a metre. The instrument may be focused at infinity, but the eye eventually involuntarily accommodates closer, resulting in a blurry image. This creates visual discomfort and can result in headaches or eyestrain.

Similar to instrument myopia is the 'near response' that can occur when an instrument like a microscope or HMD is brought near the eye [**24**, **25**]. The brain processes stimuli to determine how far away an object is. There is conflicting information from the knowledge that the instrument is very close to the eye, and the image is focused far away. A response may occur in which the eyes converge and accommodate inward more than needed.

4 HEAD AND NECK BIOMECHANICAL CONSIDERATIONS

This section discusses how the location and weight of the HMD interact with the user's head and neck. Parameters of these body parts must be taken into account in the design in order to achieve user comfort. These include facial anthropometrical data, head inertial parameters, static neck strength, and biodynamic data. Referring to the Ishikawa diagram in Fig. 2, this section focuses on many of the functional requirement topics in the upper left 'Human factors' segment. The literature will be referenced for head and neck data. This data will be used for an analysis of the relationship between HMD mass and the mounting location relative the head in order to avoid neck fatigue.

4.1 Literature review of head and neck biomechanics

4.1.1 Facial anthropometrics

The HMD must have a range of motion such that it can be adjusted to any given user's face. Facial anthropometrics for this discussion refers to the location of the viewing eye relative to other features of the face. The most important measures are the inter-pupillary distance (IPD) and the vertical position of the eye. The IPD is the distance between the centres of each pupil, and is more important in designing biocular or binocular than monocular HMDs for proper alignment to both eyes. IPD averages 63 mm and varies from 53–73 mm [**26**]. The vertical position of the pupil is often measured with respect to the Frankfurt plane. The Frankfurt plane passes horizontally through the tragion flap forward of the ear orifices and the orbital notch at the base of the eye sockets. This plane rotates with the head (Fig. 6).

4.1.2 Head and neck strength

An HMD can cause injury to the neck if it is too heavy. The allowable weight depends on the location relative to the head, the physical characteristics of the user, and on the intended use. Many HMDs are used under near static conditions with very low magnitude head

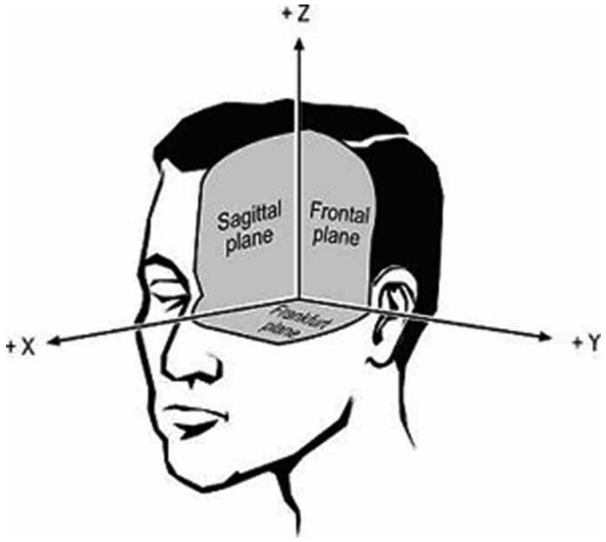

Fig. 6 Anatomical coordinate system of head (adapted from [**4**])

accelerations, such as standing and walking. Under these conditions, a heavier system may be allowable and user discomfort is most likely to be realized as neck fatigue. Military pilots, however, will encounter high accelerations creating dangerous g-forces. Too much weight on the head will cause neck damage under these conditions. For this discussion, the focus will be on static or near static conditions.

In static conditions, human muscles can hold an isometric contraction of about 15 per cent of the muscle's maximum strength for an indefinite period of time with minimal fatigue [**27**]. The anatomical motion of interest for an HMD is extension, or tilting the head back, for which the dorsal neck muscles posterior to the spine are responsible. Studies have shown maximum voluntary moments of 25.9 Nm during extension, and average dorsal cervical muscle strength of 131.8 N [**28**, **29**]. Using the 15 per cent finding, the maximum allowable dorsal muscle force to avoid fatigue will be approximated as 20 N.

A head anatomical coordinate system can be defined by the intersection of the sagittal, Frankfurt, and frontal planes (Fig. 6). Using this system, the centre of mass of the head is located at approximately $(1, 0, 3)$ cm. This is shown in Fig. 7 as point CM. The point at which the atlas (cervical vertebra C1) attaches to the base of the skull is the occipital condyle, located at point O, roughly (−2.5, 0, −2.5) cm [**1**].

4.2 Analysis of allowable HMD weight

The head and neck are essentially modelled as a sphere (the head) connected to a rod (the neck) via a ball joint (the occipital condyle). The model depicted here is a simplification of the anatomy, as the neck contains over 20 pairs of muscles and eight joints [**30**]. In the case of static loading, a joint torque occurs at the occipital condyle in which the neck muscles counteract the HMD weight. This is given by

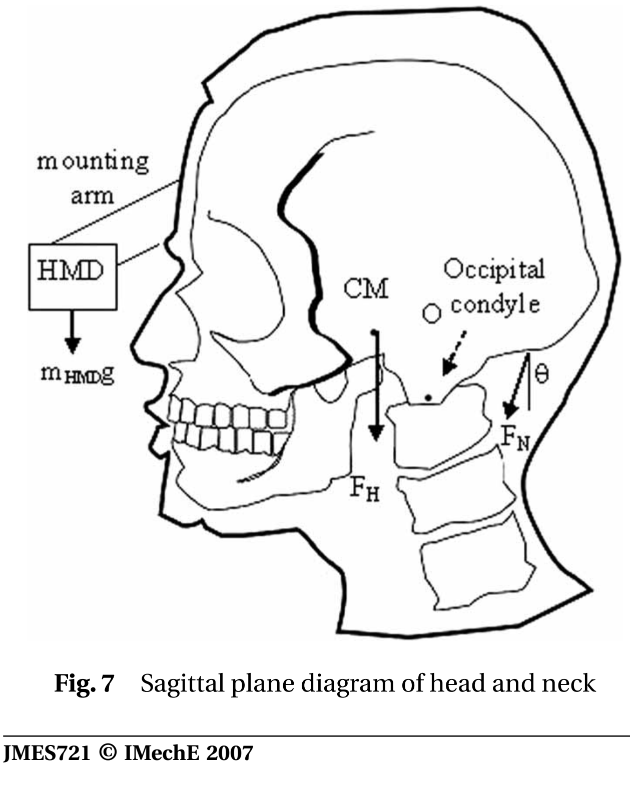

Fig. 7 Sagittal plane diagram of head and neck

$$\begin{aligned}\sum M_{\mathrm{O}} &= 0\\ &= F_{\mathrm{HMD}}(r^2_{\mathrm{HMD}x} + r^2_{\mathrm{HMD}y})^{0.5}\\ &\quad + \boldsymbol{F}_{\mathrm{H}}(r^2_{\mathrm{H}x} + r^2_{\mathrm{H}y})^{0.5} - \boldsymbol{F}_N \cos(\theta)(r^2_{\mathrm{N}z} + r^2_{\mathrm{N}y})^{0.5}\\ &\quad + \boldsymbol{F}_{\mathrm{N}}(r^2_{\mathrm{N}z} + r^2_{\mathrm{N}y})^{0.5}\sin(\theta) \qquad (7)\end{aligned}$$

where $\boldsymbol{F}_{\mathrm{H}}$ is the head force for an average head mass of 5.5 kg (54 N) [**31**], r_{H} the head centre of mass moment arm about O, $\boldsymbol{F}_{\mathrm{N}}$ the allowable non-fatiguing force on the dorsal neck muscles (20 N), r_{N} the neck muscle moment arm for the $\boldsymbol{F}_{\mathrm{N}}$ force vector from the approximate muscle attachment at the skull (located at $\sim(-5, 2, 1)$ cm) to the occipital condyle [**32**], θ the angle between the dorsal neck muscles and the z-axis, $\sim 5°$ [**32**], r_{HMD} the HMD moment arm from the HMD centre of mass to the occipital condyle (varies with HMD placement) (Note that this analysis is a basic approximation for the overall neck force due to all the muscles active during extension. Morphological data used are for the average person and vary between individuals.).

A simplifying assumption is made that the neck muscles apply force to a single attachment point at the base of the skull, when in fact there are many muscles and attachment points. This point is the estimated centre of the muscle attachments, at (−5, 2, 1) cm [**32**, **33**].

The neck joint torque due to the mass of the head ($\boldsymbol{F}_{\mathrm{H}}$ term) is already taken into account in measurements of dorsal strength. Furthermore, the x-component of the dorsal muscle force is negligible because θ is small. Thus the approximate allowable mass of the HMD to avoid static fatigue is given by

$$m_{\mathrm{HMD}} = \frac{\boldsymbol{F}_{\mathrm{N}}\cos(\theta)\left(r^2_{\mathrm{N}x} + r^2_{\mathrm{N}y}\right)^{1/2}}{g\left(r^2_{\mathrm{HMD}x} + r^2_{\mathrm{HMD}y}\right)^{1/2}} \qquad (8)$$

Figure 8 shows the relationship between the HMD moment arm and the allowable mass. This gives an allowable joint torque at the occipital condoyle of roughly 1 Nm. For a typical HMD mounting location three centimetres in front of one eye ($r_{\mathrm{HMD}} \approx 14$ cm), the allowable HMD mass is 0.7–0.8 kg.

There are other issues to consider with regard to user comfort. If the HMD is to be integrated into glasses, then the weight will be carried largely on the bridge of one's nose. Half a kilogram or more would be very uncomfortable. In this case, 70 g has been suggested

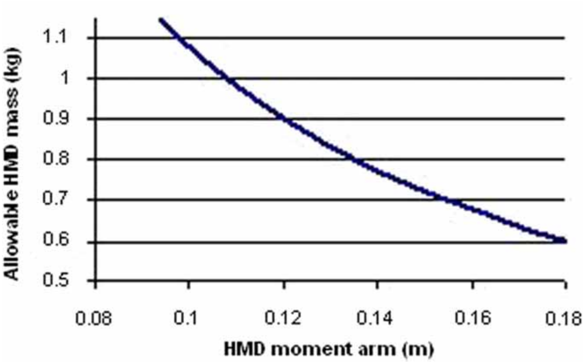

Fig. 8 Relationship between HMD moment arm and allowable mass

as a reasonable glasses-mounted weight for adequate user comfort [**34**].

4.3 Biodynamic considerations

Various studies testing neck forces under dynamic loading have been performed, primarily for military testing of pilot helmets and HMDs. The tests are done under extreme conditions to mimic emergency incidents such as ejection from the cockpit. The high accelerations present in these situations create large forces on the neck. Results indicate that the head-mounted weight should be about 1.8 kg or less, mounted as close to the head as possible to minimize joint torque due to leveraging of weight on the neck [**27**].

5 GENERIC DESIGN GUIDELINES

To improve user performance, the HMD design should be focused toward ergonomic requirements, task requirements, and user needs. Task requirements and user needs are specific to the application. Ergonomic requirements, however, are more generic and design guidelines will be given in terms of these requirements. The first part of this section gives a literature review of typical optical specifications for any HMD design, shown in Table 4. The second part elaborates upon and supplements these specifications to focus on generic guidelines for monocular HMDs.

Table 4 Typical optical specifications for an HMD from Fischer [**35**]

Parameter	Typical specification
FOV	30°
Focal range	3 m if fixed
Exit pupil diameter	⩾7 mm
Eye clearance	⩾25 mm (for glasses use)
Resolution	20 px/deg for video viewing
Optical distortion	<5%

5.1 Literature review of general HMD optical design parameters

Table 4 gives important design parameters and their typical specifications for an HMD. Some characteristics, such as FOV, will vary greatly depending on the type of HMD and its intended task. Others, such as exit pupil diameter and distortion, should be consistent across all designs.

5.1.1 Focal range

Ideally, the HMD image distance should be adjustable over a wide range, from 1 m to infinity, to allow for different users and tasks. At the least, it should appear at or farther than the RPV for maximum viewing comfort. If elderly people are to be users, their near point may be upwards of 100 cm, and the image must be at least this distant. Depending on the application, however, corrective lenses may be worn to give normal vision when viewing an HMD.

A common misconception is that the image is best focused at infinity. This, however, may not be optimal based on tonic accommodation data and user task requirements. As previously noted, given no visual stimulus (e.g. pitch black conditions), the eye naturally accommodates to about 80 cm. Furthermore, when using an infinite conjugate instrument, instrument myopia can occur. Ankrum [**36**] found that for a desktop monitor, moving beyond one's RPV does not produce additional benefits. It is reasonable to assume that focusing the image to a distance similar to objects being viewed in the real world is appropriate.

5.1.2 Exit pupil and luminance throughput

According to Fischer, the diameter of the human pupil ranges in size from roughly 2.5–7 mm. An HMD exit pupil diameter of at least 7 mm allows for movement of the eye relative to the HMD in all but the darkest conditions. This will reduce the need for HMD position adjustments, thereby improving user satisfaction.

The exit pupil diameter determines the light flux entering the eye. As previously noted, maximum vernier acuity occurs at 17 cd/m^2. In good reading light, luminance from a white piece of paper is about an order of magnitude higher [**37**]. Many microdisplays have a luminance of about 100 cd/m^2. Note that a typical simple optical system with a few elements reduces the display luminance by about 10 per cent, and a beamsplitter will reduce throughput by its transmission ratio, which is generally about 50 per cent.

5.1.3 *Eye clearance*

Eye clearance is an important parameter in designing for viewing comfort. Too close and the HMD may be intrusive, especially with a look-around HMD. As eye clearance decreases, the apparent level of immersion and brightness will increase. The FOV of the physical HMD will also increase, which decreases the visual field of the real world. This will increase the likelihood of visual problems, such as binocular rivalry.

See-through HMDs are less intrusive by design, and less clearance may be acceptable. Intrusiveness also depends on the mounting location. If glasses are to be used, Fischer recommends a clearance of at least 25 mm for adequate comfort.

5.1.4 *Resolution and frame rate*

To match the one arc minute resolution of normal vision, the screen must have at least 60 px/deg. Such high resolution, however, may not be necessary depending on the detail of information that needs to be shown. One-third of this amount is adequate for-video viewing [**35**].

Frame rate of the display must exceed the eye's CFF for the appearance of smooth imagery. Given that the CFF of the eye can be over 60 Hz, the frame rate should be 60 Hz or more for fast moving images. Davis [**14**] recommends a display update rate (frequency at which the image is updated) of 30 Hz for slow moving objects.

5.2 Optical design considerations for monocular HMDs

5.2.1 *Field of view*

A tradeoff comes into play in designing an HMD between how much information one would like to see on the screen, and how much of one's visual field is blocked when wearing the HMD. This is shown in Fig. 9 for horizontal vision. The data points occur at three standard microdisplay sizes of 320, 640, and 800 pixels. FOV is calculated for a focal length of 21.4 mm. Normally this is a linear relationship, however the 800 × 600 display data are from an eMagin organic light emitting diode (OLED), while the others are Kopin LCDs, thus the pixel density is not constant.

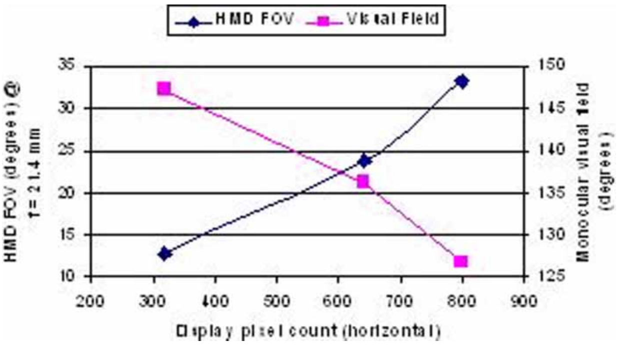

Fig. 9 Tradeoff between horizontal display size and visual field

The allowable amount of visual field that can be blocked will depend on the task at hand and user preferences. The designer must weigh the costs and benefits of having more information available or easier to see versus the extra distraction caused by blocking more of a person's 160° × 120° monocular visual field.

For an immersive application such as virtual reality, the designer would strive for a wide FOV HMD. Monocular HMDs, however, are generally used in non-immersive applications. Examples include those from Liteye, Eyetop, and Microoptical, which have a 20–40° FOV [**38**]. This typically allows one to clearly see a VGA or super video graphics array (SVGA) sized screen. Proper placement in the visual field or the ability to swing the HMD out of the way minimizes distraction.

5.2.2 *Pupil versus non-pupil forming*

The simple magnifier can be as simple as a single convex lens. Many simple magnifiers, however, have additional optical elements to cancel aberrations, or image errors. Advantages of the simple magnifier over the microscope design include less cost, a shorter optical path length creating smaller size, less weight, and better light transmission due to fewer optical elements. The longer optical path length of the compound microscope may be an advantage, however, if the designer folds the optical path around the wearer's head. In this way, the optics can be closer to the head, making the centre of mass of the HMD closer to the head. This in turn reduces neck fatigue. Finally, the compound microscope has the ability to magnify the object more than a simple magnifier, as its magnification is the product of its objective and eyepiece magnifications.

5.2.3 *'Look-around' versus 'See-through'*

The optical system may be see-through or look-around. Each has its advantages and disadvantages in different types of tasks. The see-through has the advantage of being able to more quickly and seamlessly glance between displayed information and the surrounding environment, because the information is overlaid onto the real world. The look-around requires some time for the eye to adjust to the new setting. Both designs may require accommodation in the transition. See-through disadvantages include the extra bulk, weight, and cost of the optics, viewing difficulty against bright backgrounds, and typically a 40–60 per cent loss in luminance throughput due to reflection and transmission at the beamsplitter. Thus a see-through will require more power for equivalent luminance.

The see-through is well suited to tasks that require one to directly relate objects in the real world to information on the display. These are augmented reality applications. Apache pilots, for example, use the IHADSS see-through HMDs so that they can target objects while flying [**39**]. The look-around is well suited to applications requiring a large FOV fully immersive display that purposefully excludes the real environment. It is also suited to a small peripheral non-distracting display that minimizes immersion and distraction. The information presented may be text or non-local information that is not usefully overlaid onto one's immediate environment, and that would otherwise be difficult to discern against a bright or highly contrasting background.

5.3 Location in the visual field

The monocular HMD must be mounted such that the entire screen is within the FOV of one of the eyes. The right eye is commonly chosen because about 70 per cent of people are right-eye dominant [**40**, **41**]. Some people, however, have poorer vision in one eye, thus it is beneficial to design for use with either eye.

There are arguments for mounting an HMD low in one's visual field. Ripple [**42**] found it is less fatiguing to converge one's eyes on a near object when looking down. The extraocular muscles of the eye control up–down movement, and the medial recti muscles control ocular vergence. When the extraoculars rotate the eye upward, they apply a divergent force that must be overcome by the medial rectis. Thus converging while looking downward is more comfortable [**43–45**]. This can be seen when a person naturally looks down to read, and is one reason why Burgess–Limerick *et al.* [**46**] suggest that a desktop monitor should be at least 15° below one's normal horizontal line of sight.

An HMD should not obstruct one's vision while walking. Many obstacles are seen in peripheral vision, but a person may glance down to see an obstacle. If, for example, a six-foot person is looking at an object 10 ft away on the ground while walking, the angle of ocular vergence is about 30° downward. This is commonly accompanied by tilting the head down, however, which can reduce the required ocular vergence to less than 10°. Thus, an occluded HMD should be small enough that the user can easily see around it, and mounted at least 15° below the horizontal line of sight for obstacle avoidance. A maximum of 45° is recommended to avoid eyestrain due to excessive downward ocular motion.

5.4 Visual concerns

Many of the visual concerns explained in section 3.3 are more problematic in an immersive HMD. A larger FOV and an occluded design increases immersion into the virtual world of the computer. To reduce visual problems, the design should maximize the feeling of being in the real world, and minimize dizzying video imagery such as screen rotations and disorienting object movements. Other helpful features include a small FOV design mounted below one's horizontal line of sight, see-through optics, minimal information latency (especially regarding movement), a light meter to automate brightness, and a graphical user interface (GUI) that is clear and non-distracting.

6 CASE STUDY ON FIRE-FIGHTING

The Fire Information and Rescue Equipment Project is researching ways of giving all critical information and decision support tools to all firefighters involved at an incident (Fires account for more deaths in the United States than all natural disasters combined. An average of 4000 people die per year with billions lost in property damage. The World Trade Centre attack itself cost New York City $33.4 billion in property damage (USFA, 2003), and over 2800 lives, 350 of whom were firefighters (McKinsey, 2002). The McKinsey Report following 9/11 is just one case study arguing for more effective rescue operations.). The main goals are to improve efficiency and save more lives. One of the key components is a monocular HMD (Fig. 10). This case study discusses its design as an example of using the above guidelines, and gives more specific HMD design recommendations for emergency response.

6.1 User needs gathering

Understanding the needs of the user is critical in designing a device with which humans interface. Over 50 firefighters and three fire chiefs from the Chicago and Berkeley Fire Departments were interviewed (see [**47**, **48**] for a more complete overview of the current study). Prototypes were developed in an iterative process, wherein feedback was incorporated into the next rendition, demonstrated and tested again, and redesigned. The most important needs found concerned ease of use and maintenance, durability, and minimal distraction, while presenting useful information in an intuitive manner.

Screening and scoring weighted decision matrices were created based on the user needs data. The resulting design choices tended toward Occam's razor [**49**],

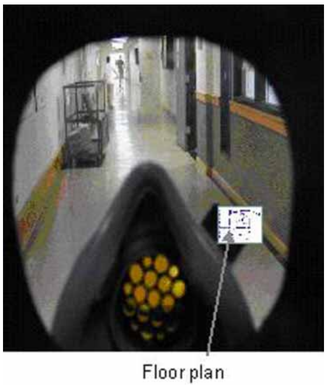

Fig. 10 HMD map GUI in firefighter face mask

Table 5 Specific design guidelines for monocular HMDs based on the fire-fighting case study

Metric	Guideline
FOV	15°–40°
Image focal range	1 m–∞ (about 3 m if fixed)
Exit pupil diameter	$\geqslant$7 mm
Luminance throughput	$\geqslant$100 cd/m^2
Eye clearance	$\geqslant$25 mm (for glasses use)
Resolution	60 px/deg; 20 px/deg for video viewing
Optical distortion	<5%
Magnification	10X
Mounting location	15°–45° below Frankfurt plane
Weight	Max. of 0.5–1 kg (Fig. 8)

i.e., fulfilling the core needs via the least complex approach and avoiding feature creep while maintaining necessary adjustability for a wide range of users. Three concepts were selected for prototyping: a 320 × 240 pixel see-through, and 320 × 240 and 640 × 480 pixel look-arounds, all with LCD screens mounted inside the facemask. Based on the current study, specific design guidelines are given in Table 5 for a firefighter monocular HMD.

6.2 Human factors design

The HMD was shaped to fit the inner contours of the facemask, and to minimize protrusion into the user's face. It was mounted 30° below horizontal line of sight based on the user needs studies with firefighters and related studies from section 5.3 [**47**]. This location minimized blocking of the outside world and maintained local situation awareness. The unit was mounted very close to the face and was lightweight, which minimized the amount of strain placed on the user's neck due to off-axis weight. Parameters are given in Table 6.

Table 6 Mounting and mass parameters of the HMD and facepiece unit

Centre of mass	(10, −4, −7) cm
Moment arm	8 cm
Weight	0.9 kg
Joint torque at O	0.7 Nm

From equation (2), the allowable HMD weight for its mounting position and moment arm was 1.3 kg. The 0.9 kg weight of the mask and HMD unit was within this limit. Adding a typical 1.5 kg firefighter's helmet increased the head-mounted weight to 2.4 kg. The helmet is approximately centred over the head, however, and in typical upright movement conditions does not appreciably add to the neck joint torque. Usability feedback on comfort was positive. Users did not complain of neck fatigue after walking around with the unit for 25+ min.

The HMD included adjustable parameters for user comfort. There was a focus wheel allowing +/− three diopters of accommodation. For a fixed focus case, we found a three-metre image distance to work well for use while walking. The display could be rotated parallel to the user's frontal, sagittal, and Frankfurt planes via a ball joint to align with most users' eyes. It could also be translated up–down and right–left.

Custom packaging was designed in SolidWorks and built on a fused deposition modelling machine for both prototypes from ABS plastic. The final prototype is shown in Fig. 11. The packaging was impact and water-resistant. It helped to protect the electronics from rapid temperature gradients, salty sweat that would quickly rust the wires, and vibrations and impacts that would eventually break the fragile electronics and optics. The casing closed with three screws for higher strength and security than a snap fit. Finally, the packaging was designed to be injection moulded, making it inexpensive to mass-produce.

The HMD was mounted to the flexible nose cup for impact durability and ease of removal. The user's face supported the nose cup, which minimized jarring or vibrations. The HMD and nose cup took an order of

Fig. 11 Final look-around prototype

magnitude more force to move than they weighed, and were not found to move unexpectedly.

6.3 Microdisplay selection

The microdisplays chosen were VGA (640 × 480) and QVGA (320 × 240) active matrix liquid crystal display (AMLCDs) for their low cost and ease of availability. These had 24 bit color, a 75 Hz frame rate, were durable (6 Gs at 20–2000 Hz for 10 min), and were small enough (VGA: 12 × 9 × 5 mm) to fit inside the facepiece. Luminance was 160 cd/m^2, contrast was 100:1, and the operating temperature range was 0–60 °C [**50**]. Although an OLED, for example, has a higher operating temperature capability (−35–70 °C), its much higher cost outweighed its benefits for prototyping and was too expensive for most fire department budgets. Furthermore, the decision to mount the HMD inside the facepiece limited the range of temperatures encountered to acceptable under most conditions.

Figure 12 gives a tradeoff between the amount of floor plan seen in the HMD and the amount of the firefighter's visual field that is blocked. The firefighter's facepiece gives an approximately 100° horizontal visual field.

The screen size chosen was based on this tradeoff. In interviews and usability studies, firefighters reported that they did not want the HMD to be 'in your face' and therefore blocking much of their visual field [**47**]. Yet it was desired that the screen be large enough to read room numbers on a typical ∼30 000 square foot high-rise floor plan without having to zoom in and pan the screen. The VGA screen size was a good balance, however some found it to be too small.

6.4 Optical design

A simple magnifier eyepiece was chosen as the main optical element, creating a non-pupil forming system. The look-around design is shown in Fig. 13.

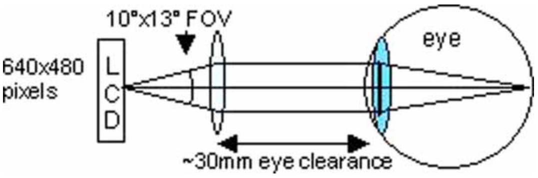

Fig. 13 Occluded look-around design

A see-through design was created by adding a cube beamsplitter, as shown previously in Fig. 4. A problem found with the cube beamsplitter was extraneous reflections. Above and below the desired image, a user saw a thin band of images, being inverted reflections from below. If the floor had anything bright, such as something white reflecting in the light, it could be especially distracting to the user. This was mitigated by occluding the top and bottom areas of the prism, without occluding any of the images intended to be seen by the user.

The eyepiece was a polycarbonate aspheric lens. This shape minimized aberrations and adequately magnified the image with less than 5 per cent pincushion or barrel distortion. This allowed the use of only one lens in the system for lighter weight, smaller size, and ease of manufacturing.

In user testing, most preferred the look-around because it would not fade out against bright backgrounds, and was about 50 per cent brighter than the see-through. It provided an overall luminance throughput (after the last optical element) of at least 100 cd/m^2, which was adequate for typical real-world conditions. It was also less expensive and lighter weight, both of which were important for emergency responders. Another consideration was that users might tend to look at it for shorter periods of time, because it was not see-through and did not encourage one to stare for long while walking. This was desirable for emergency responders because minimizing continual usage time would help them to retain local situation awareness and reduce visual problems like binocular rivalry. Selected parameters for the final look-around prototype are given in Table 7.

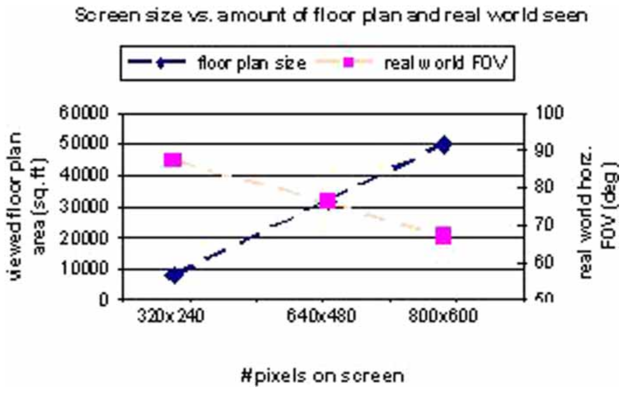

Fig. 12 Tradeoff between area of floor plan seen and visual field blocked by the HMD

6.5 Performance evaluation

A study was performed in which 21 subjects were asked to efficiently find target locations in unknown environments under low visibility conditions with and without the look-around VGA HMD. Five were female, eight

Table 7 Selected optical parameters for the look-around VGA HMD

Eye clearance	Exit pupil diameter	Total magnification	Resolution (arcmin/pixel)	FOV (horizontal)
25 mm	7.4 mm	11.5 X	2.2	23.8°

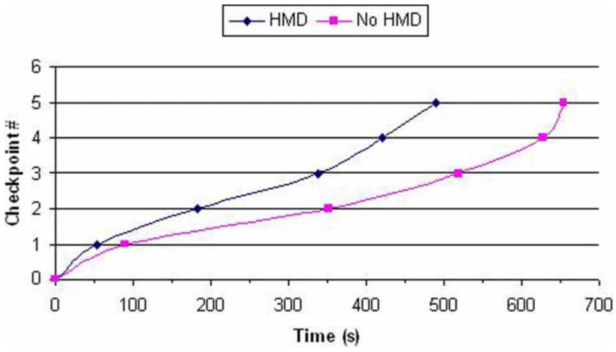

Fig. 14 Average time to each checkpoint, shown as checkpoint reached versus time

were firefighters, and ages ranged from 23 to 39. Time, distance, and the number of navigation errors made were recorded. Subjects were continually monitored by the experimenter in their behavior, including posture, path taken, gait, speed, obstacle avoidance, other movements, and any comments made. Finally, subjects were given a questionnaire in which they rated the HMD in its effectiveness, comfort, and design. Most results regarding navigation will be given in a different paper. This discussion will focus on the experimenter observations and questionnaire feedback, which is more relevant to the physical design of the HMD.

The average times to five checkpoints were measured (Fig. 14). The slope of each plot indicates efficiency to each checkpoint. Subjects with the HMD were more efficient than those without the HMD. When using the HMD, subjects tended to walk at a consistent pace, whereas when not using it, their pace appeared to change based on navigation confidence. This can be seen from the more stable slope of the HMD group. Also evident is some degree of learning, as the HMD slope becomes gradually steeper near its end. This is especially true in the last segment of the No HMD group, where subjects recognized that they were partially retracing their first segment in reverse to arrive back at the starting point. The relative lack of recognition on the part of the HMD group suggests that improved HMD usage training is in order to avoid over-reliance.

Table 8 gives results from selected post-study questions of the questionnaire that analyze comfort, size, distraction, and location in the visual field. Subjects were asked whether they experienced any eyestrain or otherwise discomfort while using the display.

Table 8 Subject responses to selected post-study questions

Eyestrain/discomfort?	SD (7)	D (8)	N (2)	A (4)	SA (0)
Different screen size?	No (14)	Larger (7)		Smaller (0)	
Different location?	Yes (0)			No (21)	

A Likert scale was used, where in Table 8, SD refers to Strongly Disagree, D refers to Disagree, N refers to Neither Agree nor Disagree, A refers to Agree, and SA refers to Strongly Agree [**51**].

Those who answered N or A had to strain their eyes to read room numbers. The focus was properly adjusted, but the font size was too small. This was the only comfort-related complaint regarding the HMD. No subjects commented on discomfort due to positioning of the HMD. Subjects were often seen tilting their head forward at about 30° when studying the HMD. This gave rise to postural concerns, although after two 15 to 30 min usage periods, no subjects experienced fatigue due to head-mounted weight. Only two subjects commented that 'it feels heavy', but did not voice or otherwise show any discomfort or fatigue. This suggests that the weight and mounting location are adequate for biomechanical comfort under normal operating conditions.

Fourteen subjects responded that they would not have preferred a different screen size. The remaining seven thought it should be larger, commenting that this would allow them to more easily read the font. No subjects preferred a different location for the screen. No comments were made indicating that the screen was distracting or too large.

Minor problems were observed. Subjects encountered obstacles at or above the horizontal line-of-sight more frequently when using the HMD. These were primarily walls. This was due to staring too long at the HMD while walking. Subjects were also observed to move more slowly. Average speed with the HMD was 0.55 m/s with the HMD versus 0.61 m/s without, however large standard deviations resulted in no significant difference in these values (alpha $= 0.05$, $p = 0.54$).

The problem of bumping walls suggests that a see-through HMD mounted at the horizontal line-of-sight may be beneficial. This, however, would cause one to view the HMD more continuously, which may limit use of peripheral vision and may not be desirable in maintaining local situation awareness. In this case, obstacles below the horizontal may be more frequently encountered. Further study is warranted in HMD optical design and visual field location for situation awareness and navigation tasks. The questionnaire results suggest that the screen FOV is adequate for the navigation task, and the complimentary obstructed visual field is not problematic. A future study is warranted to determine whether a larger FOV will improve task effectiveness without causing increased distraction.

7 CONCLUSIONS

When designing a HMD, there are many human interface issues and tradeoffs that the designer must consider. Multiple disciplinary realms must be included due to the complexity of the human visual system. These include mechatronic design, ergonomics, vision science, and optics.

The case study on fire-fighting resulted in the following guidelines specific to a small monocular display used for emergency operations. Note that although recommendations are given for FOV and visual field location based on first responder feedback and the navigation study, further studies are needed to more clearly determine proper FOV, see-through versus look-around optical design, and visual field location.

1. A 15 to 40° FOV balances the tradeoff between information shown and distraction. It is large enough to show adequate information for navigation and building features, yet small enough to easily see around. The ideal size depends on the amount of information that must be shown. For first responders, aim for the minimum size that will show the required information.
2. The HMD should be mounted 15 to 45° below the Frankfurt plane in the visual field to allow ease of viewing while walking or crawling, and to minimize staring time and distraction.
3. The HMD weight should be no greater than 0.5 to 1 kg to avoid neck fatigue.
4. The look-around design is generally preferred for non-augmented reality applications such as a firefighter viewing a floor plan. It has advantages of simplicity, smaller size, lighter weight, lower power consumption, and ease of viewing against bright backgrounds.

Future work will be to design improved HMDs based on the study results, and to perform further experiments with firefighters. New HMDs will have up to a 40° FOV, SVGA or higher resolution, and both see-through and look-around versions mounted in varying locations. This will allow more thorough testing of the tradeoffs of FOV, optical design, and visual field location in achieving greater effectiveness and user acceptance. Furthermore, proper training procedures will be better understood with additional experimentation, so that all users can use the HMD to increase their job safety and efficacy.

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APPENDIX

Notation

CM	centre of mass
D	diameter
f	focal length
L_e	eye relief
N	number of pixels
O	occipital condyle
r	moment arm distance
S	display screen size
λ	wavelength