Perspective on Vision: The Visual System as a Black Box

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Vision is a complex phenomenon that can be addressed from different points of view. Input to the visual system consists of visual stimuli, the final output is visually guided behavior, while visual perceptions are an intermediate product. Clinicians often start by considering the input-related aspects that can be addressed by medical and surgical means. Patients, on the other hand, may be most concerned about the output aspects, that is, the effect on their daily activities. The relations between these 2 points of view are often misunderstood, which may lead to miscommunication. This perspective—based on more than 4 decades devoted to vision rehabilitation—aims at exploring these differences to bridge the communications gap.

Seemingly similar tests may actually assess different aspects. One example is the relationship between letter chart acuity and reading ability, as demonstrated by the difference between Jaeger's and Snellen's tests. Clinical applications require assessment of individuals. Societal applications deal with groups of people; they include research, public health statistics, and eligibility rules for privileges or benefits. Such applications often rely on the application of formulas to input measurements to estimate the consequences on the output side. The implications of such simplifications should be understood. (Am J Ophthalmol 2021;224:66–73. © 2020 Elsevier Inc. All rights reserved.)

WHAT IS VISION?

WHEN VISION IS THE CENTERPIECE OF OUR PROfessional lives, the question "What is vision" seems simple. When looking closer, however, complexities appear. When asked, most people will say that we see with our eyes. Yet, an isolated eyeball cannot produce any vision, whereas in our dreams the brain can produce visual imagery without any input from the eyes. Why is the role of the brain so often overlooked? This question is particularly important in the context of vision rehabilitation, which aims at supporting patients to perform as well as possible, even with reduced vision. This perspective will discuss the need to address vision from different points of view.

The visual system is the most important source of information for guiding our interactions with the environment. To interact with the environment, we need information about the environment. The eyes provide this. To interpret the visual input, we need complex cognitive brain functions. But creating a visual percept is not the endpoint of visual processing. Because the endpoint is interaction with the environment, an important function of the visual system is to guide motor activities.

For a bird's-eye view of vision-related functioning, I have found it useful to consider 4 aspects, shown in Figure 1.[1,2]

First, at the *tissue* level, we may consider cellular and molecular functioning. Here we need the ophthalmic pathologist to inform us. However, how the tissues function does not tell us how well the *organ* functions, so we also need the clinician to measure organ functions, such as visual acuity and visual field.

But even then, *How each EYE functions* doesn't yet tell us *How the PERSON functions* in various vision-related activities, such as reading (detail vision) and mobility (surround vision). Here we need various rehabilitation workers to work with the patient. Finally, we need to consider the role of vision at the societal level of participation and quality of life.

Comprehensive care requires attention to all aspects, but viewpoints may differ.

Let us start with the *patient's* point of view. She has a complaint about an important daily activity: "Doctor, I cannot read." She is most interested in her Quality of Life, and in how she can perform her daily activities. To her, the aspects on the other side of the center line are of secondary interest.

Compare this to the point of view of the "*eye*" *doctor*. He translates the patient's complaint about her activities, into a statement about the eyes: "The patient lost three lines." To him, structure and function of the eye are his first concern, while the aspects on the other side of the line are of secondary interest.

Failing to understand the differences between these 2 points of view is a frequent cause of miscommunication between doctor and patient.

The American Academy of Ophthalmology expresses the need to embrace both sides in its motto (Figure 2):

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Protecting Sight. Empowering Lives.

THE VISUAL SYSTEM AS A BLACK BOX

THE 2 VIEWPOINTS ARE NOT SPECIFIC TO VISION. COMPARE the point of view of a clock maker, to that of a clock user. The former needs to understand how all parts interact to make the clock run smoothly, yet this knowledge does not explain why a clock with a 25-hour cycle is less useful than one with a 24-hour cycle. Clock users want to organize their day, knowing when it is time to wake up, to go to work, or to have a meal. Clock makers may not be concerned with how their clock will be used, whereas clock users may not care whether the mechanism is mechanical or electronic, or even whether the display is digital or analog. Nevertheless, designing a useful clock requires equal attention to both aspects.

Faced with these 2 very different points of view, how can we widen our understanding to include both viewpoints? Without knowing all details of the system, we can start with considering the visual system as if it were a black box, of which at least the input and the output can be observed.

The *input* to the system consists of various visual stimuli. The *output* is visually guided behavior, that is, the ability of the visual system to guide our continuing interactions with the environment. Some of the differences between the *input* and *output* side are listed in Figure 3.

Most ophthalmic tests deal with the input side, because that is where "eye" doctors can be most effective. Such tests aim at minimizing the demands on the output side (naming a letter, or pressing a button), so that output considerations can be ignored. This may lead to the perception that the function of the visual system is limited to creating a visual percept and is separate from the motor systems that interact with the environment. For the user of vision, however, the output side is the most significant aspect, because the actual role of vision is not to provide and store snapshots but to *continually* guide our motor systems in their interaction with a *dynamic* environment.

• **ASSESSING THE INPUT SIDE:** To assess the input side, we can manipulate the stimuli, usually in an artificial environment, where only the parameter of interest is varied while all the other parameters are kept constant. On a visual acuity chart, only the letter size is varied; on a contrast chart, only the contrast; and on a visual field test, only the location. Because the input side of the visual system features 2 eyes, input measurements must be made for *each eye separately*.

For these tests, we determine the *threshold* stimulus value that results in responses that are 50% better than guessing. That choice of a threshold measurement is not made because it reflects the most relevant level of functioning, but because it is easily defined and reproduced and provides the most precise measurements, because it is on the steepest part of the psychometric curve.

Most common tests ask only for a brief performance, although often repetitively. Because only one parameter is varied, the test results can conveniently be reported as a single number.

• **ASSESSING THE OUTPUT SIDE:** On the output side, we deal with a single brain. Here, measurements must be made with *both eyes open*, since that is how persons live their lives. Note that "with both eyes open" is not the same as "binocular vision." The latter suggests cooperation between the eyes; "both eyes open" does not.

On the output side, we need to observe the *sustainable* performance of *real-life tasks*. Such tasks always involve multiple input parameters and supra-threshold stimulus levels. Recognizing just 50% of the words read, or avoiding only 50% of the obstacles on a mobility course, cannot be labeled as a satisfactory performance. Instead, we need performance at or near the 100% correct level (near the top of the psychometric curve) that can be maintained for a prolonged period of time. Only Olympic athletes are asked to perform at the limit of their ability.

Note that although reading ability is most relevant for patient satisfaction, the conditions under which it is achieved cannot be as precisely controlled as the threshold conditions for letter chart testing.

When describing the actual output, we must report performance *speed* and performance *errors*. One example is reporting reading speed and reading errors. If actual observation is not practical, we may ask for the patient's testimony. The criterion for patient-reported outcomes is often *difficulty*. The advantage of such reports is that they reflect the actual patient experience. The disadvantage is that they are subjective. When averaging group responses, item response theories, such as Rasch analysis,[3] can be used to derive an estimated linear scale from the subjective answers.

• **COMPARISON OF INPUT AND OUTPUT MEASUREMENTS:** It should be clear that input measures, such as letter chart acuity, and output measures, such as reading ability, are very different concepts that are described by different parameters, and with different criteria. The reference standard for letter chart acuity (20/20) is the ability to recognize 1-M letters (average newsprint) at a 1 m distance, while sustainable reading of newsprint is often done at about 40 cm, 2.5 times above that threshold.

When considering possible causes for these differences, we note that letter recognition on a chart should be easier, because the letters are more widely spaced, but that word recognition in a continuous text should be easier, because the context provides additional clues. Those cues make reading of continuous text on an MN-read[4] card about 3

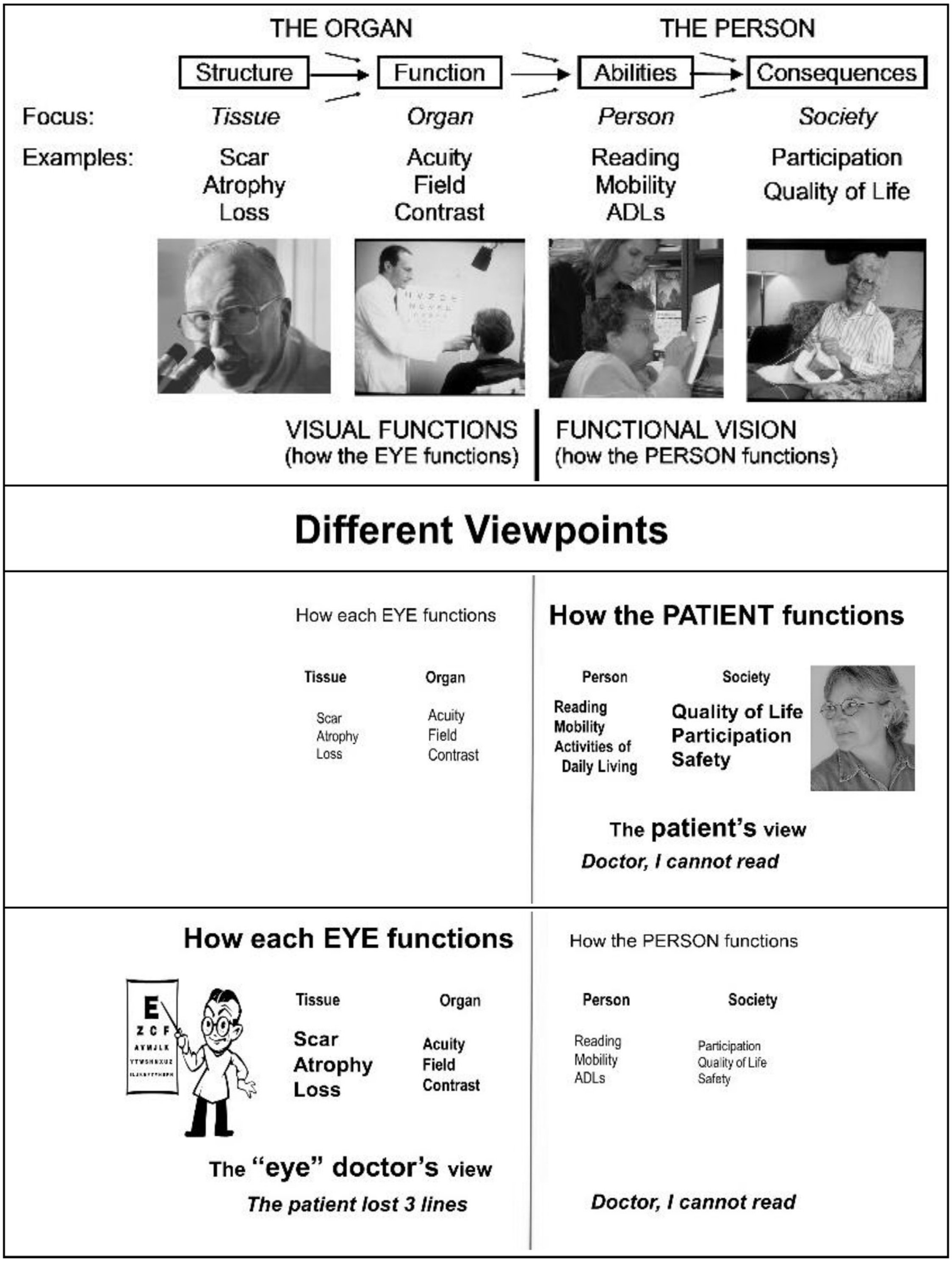

FIGURE 1. Aspects of vision.

times faster than reading of unrelated words on an SK-read[5] card with the same layout. In practice, these factors often cancel each other out, so that practitioners can still use letter chart acuity for an initial estimate of the magnification needed by low vision patients (Kestenbaum's rule[6]). Yet, when prescribing actual reading aids for a specific patient, and for a specific task, we must also explore outliers and address the reasons why the situation of a specific individual may differ from the statistical average.

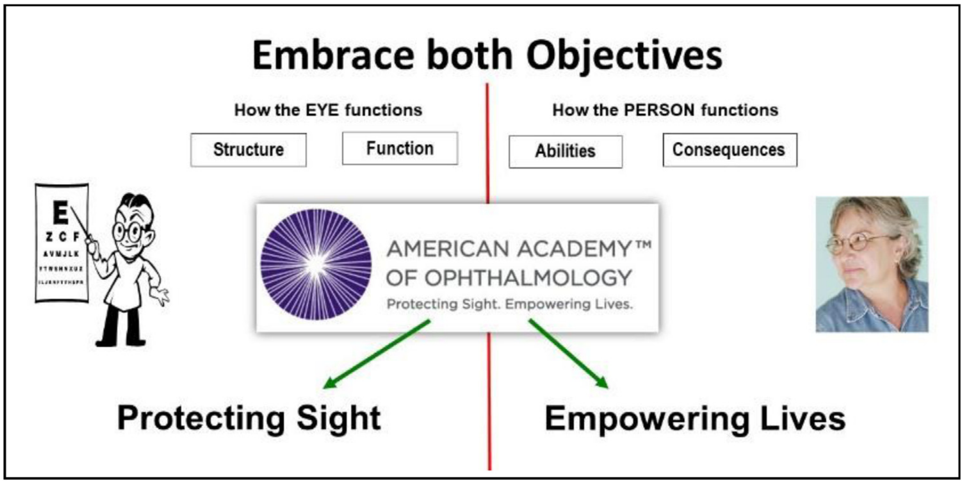

FIGURE 2. Embrace both objectives.

JAEGER VS SNELLEN

SOMETIMES, TESTS USED ON THE INPUT SIDE AND TESTS used on the output side may appear to be similar, but there are subtle differences in their interpretation. One example is the use of reading tests.

Jaeger published his reading samples as an appendix to a book about cataract surgery (1854).[7] As a clinician, he was primarily interested in the result of his interventions, that is, in *How the PATIENT functions* before and after surgery. To sample the visual performance, he chose the reading of continuous text, a near-vision test that is easy to implement, and relevant to the patient's concerns.

The question "can you read newsprint?" does not need a specific viewing distance. Consider 2 patients: one can read newsprint at 50 cm (20″), the other at 25 cm (10″). Both can perform an important daily activity: they can *read the newspaper*. Today, we might object that their visual acuity is very different, but we must remember that the concept of visual acuity, as a numerical measure of *How each EYE functions*, did not exist yet (see below).

To identify his samples, Jaeger used the catalogue numbers from the Vienna State Printing House[8]; such catalogue numbers do not specify a numerical quantity. Later clinicians who wanted Jaeger-like reading samples had to approximate the Vienna fonts with locally available ones. The result is that today's Jaeger numbers vary wildly and unpredictably from chart to chart and cannot be used for comparisons between clinics.

Donders was a scientist, who was interested in *how the eye functions*, and particularly in its optics. When he proposed the concept of visual acuity as a numerical descriptor at an international gathering in Heidelberg (1861), he was working on his epoch-making work on Accommodation and Refraction (1864)[9] that moved the prescription of eyeglasses from trial-and-error at the village fair to a scientific routine. He asked his coworker Snellen to devise a measurement tool.

Snellen was thus faced with a different task than Jaeger. He needed a numerical value for use in optical formulas. That value, the *visual angle*, is defined by the ratio of object *size* and object *distance*. To emphasize the need for both numbers, Snellen devised the fractional notation (numerator = distance, denominator = letter size). He always insisted that both numbers should be specified explicitly. The use of Snellen equivalents, which express only the value of the Snellen fraction, is a later development.

Because reading distances are hard to control, Snellen chose a *distance test*, where accommodation is relaxed and small changes in the viewing distance can be ignored. He chose to present unrelated *letters*, since word recognition (as used by Jaeger) is influenced by the context in which the words appear. At the time, the fonts used for printing often had very thin and very thick parts. So, he designed a new set of symbols with a uniform stroke width, designed on a 5 × 5 grid, specifically for visual acuity measurement. He called them *optotypes*.

Snellen recognized that standardization would be important. So, he first defined a standard observer, as someone capable of recognizing an optotype that subtends 5 minutes of arc. He then described the performance of his subjects by comparing them to this standard observer. If the subject needs letters that are ×2, ×5, or ×10 larger than for the standard observer, visual acuity is said to be 1/2, 1/5, or 1/10, also recorded as 20/40, 20/100, and 20/200 or as 6/12, 6/30, and 6/60.

Snellen also added reading samples to his chart. He used the letter size notation developed for his distance chart, so that visual acuity values for distance and for near could be compared. But his reading tests were secondary. The essence of Snellen's contribution is the numerical visual acuity scale.

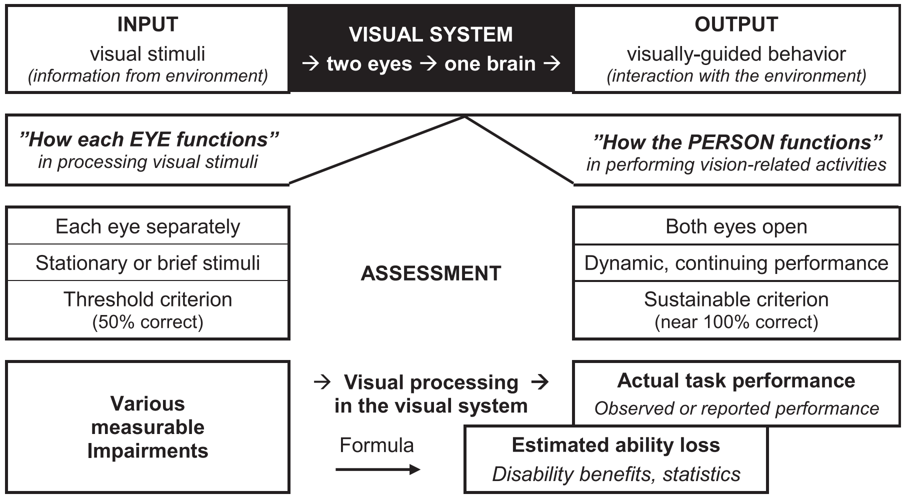

FIGURE 3. Input and output of the visual system.

"Vision" VS VISUAL ACUITY

WHEN SNELLEN PUBLISHED HIS LETTER CHART, HE CHOSE the Latin title "Optotypi ad Visum Determinandum,"[10] in which the word "visus" refers both to vision in general and to its "sharpness" or "acuity" in particular. He thus blurred the distinction between visual acuity, as a property of the eye, and vision, as a property of the person. In Europe, the term "visus" is still used to refer to visual acuity. Elsewhere, it is very common to hear: "Her vision is 20/40," rather than "Her visual acuity is 20/40." In 1862, this distinction was not yet critical. The emphasis was on optics; the ophthalmoscope was merely a decade old, and the study of retinal diseases was in its infancy.

TERMINOLOGY

HAVING DISCUSSED THE CONCEPTS THAT NEED TO BE expressed, we need to define the best terminology to be used. The above examples illustrate why this is so important.

To describe the difference between the input and the output side, the terms *visual functions* and *functional vision* have been used. But these terms are too close and sometimes combined to a hybrid as *vision function*, which blurs the distinction.

On the input side, I prefer to use *How each EYE functions* to capture the various functions that process visual stimuli. These functions include visual acuity, visual field, contrast, brightness, color, depth perception, movement, etc. Reductions of these functions are described as *impairments*. Of these, letter chart acuity is the most commonly measured one. Because the sharpness of vision (visual "acuity") is often treated as if it describes the overall quality of vision, I prefer to use the term *detail vision* to refer to the accumulated information about detail that the brain gathers from many fixations.

Similarly, the term *surround vision* captures more than the visual field. The familiar visual field plot describes retinal sensitivity for a single fixation. Surround vision refers to the accumulated information about our surroundings, captured from many successive fixations. The retinologist needs the visual field plot to assess the retina; an individual needs surround vision to move around the environment.

On the output side, I prefer to capture the *ability* to perform various tasks under *How the PERSON functions*. In an employment setting, one may consider job-specific tasks. More generic assessments usually refer to vision-related activities of daily living (ADL), such as reading, writing, and drawing, for which detail vision is required, and to orientation and mobility (O&M), which require surround vision.

For many vision tests on the input side, the required action is minimal (naming a letter, or pressing a button). This may lead to regarding visual perception as the final output of the visual system. For real-life situations, however, the result that counts is a visually guided action. The perception of the stimulus is only an intermediary step.

The lack or partial lack of *abilities* has been described as a *dis-ability*. Here, again, is an opportunity for confusion. The term *ability* is fairly well-defined as referring to the ability to perform certain tasks. Disability, however, is an umbrella term. In the International Classification of Impairments, Disabilities and Handicaps (ICIDH[11]), it was defined as loss or lack of ability. Its successor, the International Classification of Functioning, Disability and Health (ICF),[12] recognized it as a more vaguely defined umbrella term. In the Americans with Disabilities Act (ADA),[13] it is equivalent to Americans with impairments (column 2 in

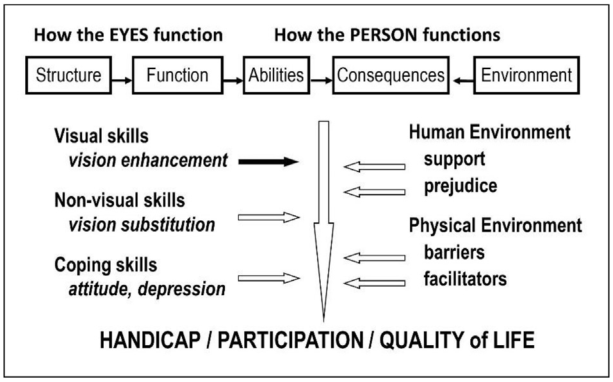

FIGURE 4. Components of quality of life.

Figure 1). In "being on disability" it refers to the socioeconomic condition of receiving disability benefits (column 4 in Figure 1).

Furthermore, the *medical* model of disability views disability as the result of medical conditions. This is the approach of the AMA *Guides to the Evaluation of Permanent Impairment*.[14] The *social* model of disability, on the other hand, defines disability as a societal shortfall in providing adequate compensatory accommodations. Both models are needed, because disability reflects the balance between the abilities of the individual and the accommodations in the environment. The medical model is important for physicians and for workers compensation issues. The social model is important for social workers and others who want to optimize the work environment.

The medical model aims at restoring what was lost. Glasses restore lost focus, cataract surgery restores lost transparency, glaucoma treatments restore lost outflow. The medical model uses an impairment scale, on which 0 indicates no impairment. Vision rehabilitation, on the other hand, builds on what remains. It is better served with an ability scale, which counts in the opposite direction: 0 ability = no ability = total impairment. This distinction is important when communicating with patients. To tell a patient with 20/200 visual acuity "You *are* legally blind" suggests an irreversible condition, and may be followed by the statement that "nothing more" can be done about their eyes. To say that "You *have* a severe visual impairment" is more likely to be followed by "let us explore what can be done to alleviate the consequences and to improve your quality of life."

USE IN DIFFERENT SETTINGS

THE ABOVE DISCUSSION HAS POINTED OUT THE OFTEN-subtle differences between superficially similar tests. Tests that determine *How each EYE functions* are most appropriate for *medical and surgical* settings. Tests of *How well the PERSON functions*, are essential for *vision rehabilitation*, but should not be ignored in routine medical practice,[15] because the goal of all medical and surgical interventions ultimately is to improve the functioning of the person.

A third setting is that of administrative use for *public health statistics* and for *disability benefit* rules.

Public health statistics want to obtain the most information with the least effort, so that large groups can be covered. Because no vision test is easier and faster to administer than a letter chart test, this usually is the only measure on which international statistics that compare the incidence of visual impairment across nation or regions are based. Ignoring other aspects of visual functioning is considered justified because far larger groups can be covered. More specialized research studies that cover smaller populations usually include more parameters.

For eligibility rules, the situation is more complex. Although it might be desirable to always base decisions on actual task performance, in many settings this is not practical. For a driver's license, an on-the-road test is usually required for the initial issuance, but subsequent renewals rarely depend on more than visual acuity.

Many eligibility rules are dichotomous: eligible/not eligible, which necessarily is an oversimplification of a complex situation. For driving, the most common vision requirement is based on achieving 20/40, acuity on a stationary chart, and on the unproven assumption that a daylight driving test and 20/40 visual acuity will predict sustainable performance under adverse conditions, such as in the rain, after dark, in a moving car. Requirements such as these define a *safety margin*. Setting a safety margin is a policy decision, not a scientific measurement. Requirements for professional drivers are usually more stringent, not because their visual environment is different but because a wider safety margin is desirable.

Some disability benefits, such as for workers compensation, are proportional to the performance loss. Here, a choice must be made between basing the compensation on the actual loss of individual ability, or on generic *ability estimates* provided by experts. The advantage of the latter approach is that it is easier to implement uniformly, and that individuals who have made good compensatory adjustments will not be punished by a smaller benefit.

Disability estimates (Figure 3) that apply a formula to the impairment measurement, reflect statistical estimates and are appropriate for administrative use. Individuals, however, may perform better or worse than the statistical estimate. This means that these statistical estimates should not be used to develop individual rehabilitation plans, which may vary based on work conditions and on the adaptability of the individual, The Functional Vision Score (FVS) system[16] provides a coordinated system for deriving visual ability estimates. It was approved by the ISLRR (International Society for Low vision Research and Rehabilitation) and the ICO (International Council of Ophthalmology)[17] and implemented in the AMA *Guides to the Evaluation of Permanent Impairment*.[14]

QUALITY OF LIFE

THE LAST COLUMN OF FIGURE 1 ALSO LISTS *QUALITY OF life*. This is another umbrella term that allows for different points of view. When used properly, quality of life should refer to the discrepancy between the subjective expectations of subjects and their objective abilities. When a big-city dweller is moved to a rural village, or a farmer is transplanted to a big city, both will complain that their quality of life has changed. Many studies, however, define quality of life simply as a reduction of abilities.

Various public health studies have compared the effect of vision loss to that of other losses. The units used for this comparison are disability-adjusted life years (DALYs). The problem is that the estimates vary widely from 0.17 to 0.6.[18] What can explain this?

Apart from variations in the definition of DALYs, one of the reasons is that the entity that is referred to as handicap (ICIDH) or participation (ICO) or quality of life depends on many more variables than just vision alone (Figure 4).

Traditionally, low vision care has focused mainly on magnification to enhance residual vision. Equally important, however, are nonvisual or vision substitution skills (Braille, long cane, talking books), and aids that support the coping skills of the individual. On the environmental side, the human and the physical environment also can be decisive. Social status can be a significant handicap, even in the absence of any disability.

SUMMARY

VISUAL FUNCTIONING IS A COMPLEX PHENOMENON THAT can be explored at different levels, in different settings, and with different amounts of detail. Different viewpoints reveal different aspects; unfortunately, these differences are often overlooked.

A major distinction that is often overlooked is the difference between the parameters that describe the input to the visual system, here described as *How each EYE functions*, and those that describe the output, which is visually guided behavior, here described as *How the PERSON functions*. Distinguishing these details does not require knowledge of the inner workings of the visual system.

Awareness of these differences will hopefully lead to a more precise use of terminology. Better understanding of terminology will contribute to more effective cooperation between the various professionals involved with vision rehabilitation.

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