Human Factors and Aging:
Identifying and Compensating
for Age-related Deficits in Sensory and Cognitive Function

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Introduction

Human factors is an interdisciplinary field organized around the central endeavor of fitting the designed environment to the individual. The process of achieving optimal person-environment interaction requires knowledge about the broad range of human functional capacity; including -- but not limited to -- anthropometry, biomechanics, sensory processes and cognitive psychology.

It has been said that "theory and practice are the same in theory but different in practice". Nowhere is this predicament more true than in the field of human factors. Although primarily regarded as an *applied* field of science, those who practice human factors on a daily basis must rely heavily upon theory and principles generated through *basic* research. This reliance upon sound theoretical constructs is made necessary by the fact that design solutions to person-environment interface problems rarely generalize across situations. Rather, it is the theoretical constructs that explain human behavior and the principles they generate that are transferable across design domains. Thus, human factors as a practice is intimately bound to its theoretical principles. Practice cannot proceed without theory.

This chapter attempts to provide the reader with a introduction to the theoretical principles of experimental psychology as they relate to the more specific domain of aging and technology. This survey is limited in its scope in so far as it pertains only to the area of cognitive psychology. As such, it explores the age-related changes in sensory processes, attention and memory that present challenges to an older person's ability to interact with his or her environment. Some opportunities for applying this knowledge toward the optimization of the person-environment interface are presented. Hopefully, the basic research findings and principles reviewed herein -- and the accompanying examples and recommendations for improving functional capacity -- will inspire the reader to generate innovative approaches toward designing a better fit between the designed environment and persons of all ages.

Vision

Anatomical Changes

The maximum diameter of the pupil declines with advancing adult age (a condition known as *senile miosis*). Under low light conditions, the resting diameter of the pupil falls from 7 mm at age 20 to approximately 4 mm at 80 years of age (Lowenfeld, 1979). Although senile miosis reduces the amount of light reaching the retina, there is reason to suspect that smaller pupil diameters may actually benefit visual performance in older adults in many situations by increasing the contrast of the retinal image (see Sloane, Owlsey & Alvarez, 1988).

The crystalline lens of the eye becomes increasingly opaque as individuals grow older. This loss of transparency appears to be particularly pronounced at short wavelengths; that is, for blue light (Said & Weale, 1959). This opacification appears to be nearly universal. For example, a large-scale epidemiological study reported that more than 90% of those 75-85 years of age demonstrated significant opacification of the lens (Kahn, et al., 1977). The combined effects of lenticular opacity and diminished pupil size contribute to diminished retinal illumination. Weale (1961) has estimated that only one-third of the light reaching the retina of a 20 year old will reach that of a 70 year old. Half of those over 65 years of age suffer from lenticular opacity that is severe enough to be classified as cataract. Approximately, 1.5 million cataract surgery procedures are performed each year in the United States. Ninety percent of these procedures result in a measurable improvement in visual function (Desai, Pratt, Lentzner & Robinson, 2001).

At the level of the retina, there is some evidence of photoreceptor and ganglion cell loss with advancing age (e.g., Curcio & Drucker, 1993; Youdelis & Henderson, 1986). Curcio, Millican, Allan and Kalina (1993) reported that nearly 30% of the rods in the central 30 degrees of vision are lost by 90 years of age. The prevalence of retinal diseases that impair visual function increases remarkably with advancing age. Noticeable degrees of macular degeneration afflict 18% of persons 70-74 years of age and upwards of 47% among those over 85 years of age. Nearly 8% of those over 65 years of age suffer from glaucoma. Unlike age-related macular degeneration, however, glaucoma often responds well to treatment. Unfortunately, nearly half of those with glaucoma remain unaware of their condition (Desai, Pratt, Lentzner & Robinson, 2001).

Oculomotor Function

Small but systematic declines in the latency, velocity and accuracy of saccadic eye movements have been observed among older adults (e.g., Huaman & Sharpe, 1993; Whitaker, Shoptaugh & Haywood, 1986). Pitt and Rawles (1988) found that peak saccadic velocity decreased by approximately 0.25 percent per year from 20 to 68 years of age. However, the ability to maintain fixation stability appear to remain intact (Kosnik, Kline, Fikre & Sekuler, 1987). Kline and Scialfa (1997) point out that such changes probably affect performance on everyday tasks as evidenced by the fact that age differences in visual search vanished when oculomotor differences were statistically eliminated (Scialfa, Thomas & Joffe, 1994).

Studies of pursuit eye movements show that younger observers can accurately track targets with angular velocities up to 30 degrees per second whereas pursuit accuracy among older observers breaks down for targets exceeding 10 degrees per second (Hutton, Nagel & Lowenstein, 1983; Sharpe & Sylvester, 1978). Kaufman and Abel (1986) reported that age-related decrements in pursuit accuracy are exacerbated in the presence of distracting background stimuli. The extent of upward gaze (i.e., the maximum vertical extent of gaze that can be achieved without the use of head movements) among young and middle-aged observes is approximately 42 degrees but drops to 32.9 degrees among older individuals (Huaman & Sharpe, 1993).

The regulation of eye movements is strongly influenced by vestibular processes (i.e., input from the organ of "balance" located within the inner ear). Several studies have demonstrated that vestibular contributions to ocular function break down among older adults (e.g., Demer, 1994; Paige, 1994). Such findings suggest that visual guidance of locomotion would become increasingly important among older adults due to a diminished sense of balance. In fact, recent studies have shown that older persons with a history of serious falls are much more reliant upon visual input to maintain postural stability (see Fozard, 2000 for a review).

Dark Adaptation

The sudden transition from a high level of ambient illumination to a very low one is accompanied by a significant reduction in visual sensitivity. Some portion of this loss in light sensitivity is typically recovered once the visual system has had a chance to adapt to the lower level of illumination. Such dark adaptation processes occur in two phases: a *photopic* phase (cone vision) lasting 6-8 minutes and a concomitant *scotopic* phase (rod vision) extending approximately 30 minutes (Geldard, 1972). There is evidence of an age-related slowing in the rate of the photopic dark adaptation (Herse, 1995). However, the rate at which full scotopic dark adaptation develops probably does not change as a function of advancing adult age. What is certain, however, is that light sensitivity of older adults is significantly worse than their young counterparts at all phases of the dark adaptation cycle. Eisner, Fleming, Klein and Maudlin (1987) demonstrated that light sensitivity in the fully dark adapted eye declined at a rate of nearly 19% per decade of age. This rate of loss would be even greater for short wavelength light (i.e., blue, green) due to the age-related "yellowing" of the lens. These findings indicate that emergency lighting and guidance systems should use broadband or long wavelength illuminaires and specify intensity levels that meet the needs of the older eye. Other generalization of these dark adaptation findings to human factors applications are limited as very few engineered environments for civilian populations approach such low illumination levels.

Visual Acuity

Visual acuity is a measure of the visual system's ability to resolve fine spatial detail. The ability to resolve well-illuminated, high-contrast spatial features which subtend a visual angle of 1 minute of arc (minarc) represents normal (i.e., 20/20 Snellen) acuity. Since the crystalline lens of the eye must accommodate, or change shape, in order to focus on near targets, separate visual acuities for near (16 inches) versus far (20 feet) targets are often measured. Since small amounts of refractive error in the eye yield reliable decrements in acuity, the acuity test has been widely adopted as the basis for correcting optical aberrations of the eye with eyeglasses or contact lenses (Schieber, 1992).

<u>Near acuity</u>. The human eye is "designed" to focus upon objects that are 20 feet (or farther) away. In order to clearly focus light coming from objects closer than 20 feet, the crystalline lens within each eye needs to increase its light refracting power by bending itself into a more convex shape. As noted above, the crystalline lens becomes less capable of bending as we grow older (i.e., presbyopia). Consequently, by the mid-forties people begin to have difficulty focusing upon printed text that is closer than 'arm's length' in distance (Atchison, Capper & McCabe, 1994). By 60 years of age, the ability to focus upon objects within a range of 3 feet has all but vanished (a finding first quantified by Donders, 1864). Although presbyopia can interfere significantly with the ability to accurately and comfortably perform near work, it can be easily corrected with reading glasses or bifocal "adds" to existing optical corrections.

Far acuity. Until around 70 years of age, the vast majority of problems leading to diminished (far) visual acuity are due to refractive errors that can be corrected using eyeglasses or contact lenses (Pitts, 1982). For example, the *Framingham Eye Study* reported that 98.4% of those 52-64 years of age could be refracted to a far acuity of 20/25 or better. However, this proportion falls to 69.1% for those 75-85 years of age (Kahn, et al., 1977). Recent survey and epidemiological studies reveal that nearly all (92%) of those over 70 years of age wore eyeglasses. Difficulty seeing even when wearing eyeglasses increased from 14% among persons 70-79 years of age to 32% for those 85 years of age or older. Eighteen percent also relied upon hand-held magnifiers for reading and related visually guided activities (Desai, Pratt, Lentzne & Robinson, 2001). The impaired visual acuity observed among those in the 70+ age group is primarily the result of the increased prevalence of diseases of the retina. Even the best available eye glasses can not compensate for pathological deterioration of the retina and related neural structures. However, improved design of products and environments can improve visual functioning for most of this population (Schieber, Fozard, Gordon-Salant & Weiffenbach, 1991).

Age deficits in visual acuity, in both healthy and pathological eyes, are exacerbated under challenging viewing conditions. Haegerstrom-Pornoy, Schneck and Braybyn (1999) have demonstrated that acuity among healthy older adults (but not younger adults) drops precipitously for low luminance and/or low contrast stimuli. Vola, Cornu, Carrvel, Gastaud and Leid (1983) found that age differences in low luminance acuity emerged as early as 50 years of age. Sturr, Kline and Taub (1990) also observed a disproportionate drop in acuity among those over 65 years of age as target luminance fell from 107 to 0.1 cd/m^2. Owsley and Sloane (1990) found that reductions in target letter contrast from 96 to 4 percent had no demonstrable effects upon young observers but that older observers exhibited as much as a 25% decline in visual acuity. Similar results have been reported by other investigators (e.g., Adams, Wong, Wong & Gould, 1988).

Disability Glare

Glare represents another challenging condition in which disproportionate age-related decrements in visual function are observed. The senescent lens scatters significant amounts of "off-axis" light across the retina. This results in a *veiling luminance* across the back of the eye which decreases the contrast of the retinal image (Ijspeert, de Waard, van den Berg & de Jong, 1990). Hence, acuity (and related visual functions) are significantly impaired in the presence of peripheral glare sources (e.g., Haegerstrom-Portnoy, Schneck & Braybyn, 1999; Olson & Sivak, 1989; Schieber & Kline, 1994). These visual disabilities in the presence of glare are especially problematic for low contrast stimuli (Schieber, 1988). The time required to recover lost visual sensitivity in response to a bright transient glare source also increases appreciable with age (Burg, 1967; Elliott & Whitaker, 1990; Schieber, 1994).

Contrast Sensitivity

The capacity to visually detect and identify spatial forms varies as a function of target size, orientation and contrast (Olzak & Thomas, 1985). As a consequence, visual acuity reveals limited information about an individual's ability to detect objects of large to intermediate size or targets of diminished contrast. A more complete assessment of spatial vision is provided by the contrast sensitivity function - a measurement of the minimum contrast needed to detect targets ranging in size from very small to very large. Studies of age differences in the contrast sensitivity function reveal that older adults demonstrate weakened visual sensitivity for stimulus objects much larger than those they can recognize on a standard acuity test (e.g., Owsley, Sekuler & Siemsen, 1983). Age-related declines in contrast sensitivity begin to emerge for critical spatial details as large as 2 cycles per degree of visual angle - or, 15 minarc (see Schieber & Baldwin, 1996). The additional information provided by the contrast sensitivity function - relative to simple measures of acuity - has extended and improved the ability to predict and explain age differences in real-world visual performance (e.g., Dewar, Kline, Schieber & Swanson, 1994; Evans & Ginsburg, 1985; Owsley & Sloane, 1987). These findings have been leveraged to develop computer-based image processing techniques to develop highway signs optimized to the visual needs of older drivers (Kline & Fuchs, 1993; Schieber, 1998). Such techniques hold great potential for optimizing the visual interface between older adults and the engineered environment.

Peripheral Vision

The spatial resolving powers of the visual system decline markedly as targets move away from central vision into the peripheral visual field. Letter size must be increased by a factor of 0.046 (i.e., 2.7 minarc must be added to the height of a letter) for every degree of eccentricity away from the point of fixation (Anstis, 1974). This loss in visual acuity associated with increased eccentricity appears to be more dramatic among older observers. Collins, Brown and Bowman (1989) examined peripheral visual acuity in young and old observers with good central acuity (20/20 or better). A 2.4 minarc (20/40) target was moved into the periphery until it could no longer be resolved. Young observers could identify the target at eccentricities up to 30.8 degrees while older observers failed to accurately identify it beyond 22.8 degrees - a 23% reduction in the "useful field of acuity." The magnitude of this effect was reduced when a larger (4.8 minarc) target was employed. Similar age-related decrements in peripheral visual sensitivity have been observed for contrast sensitivity assessments (e.g., Jaffe, Alvarado & Juster, 1986; Crassini, Brown & Bowman, 1988). Binocular reductions in the extent of peripheral vision are associated with an increased risk of being involved in an automobile driving accident (Johnson & Keltner, 1986). Age-related losses in extrafoveal perception have also been observed in more complex visual tasks. These results are best understood as limitations in mechanisms of attention and are reviewed in another section presented below.

Motion Perception

Numerous studies have demonstrated age-related decrements in motion sensitivity and/or the accuracy of speed perception. Yet, the nature and the magnitude of these effects vary tremendously across investigations (see Schieber & Baldwin, 1996). Buckingham, Whitaker and Banford (1987) measured thresholds for the detection of oscillatory motion with a large visual object. Older adults demonstrated dramatic reductions in motion sensitivity across a wide range of oscillatory frequencies. Similar results have been reported by other investigators (e.g., Schieber, Hiris, Brannan & Williams, 1990;

Whitaker & Elliot, 1989). The careful experimental controls implemented in these studies clearly suggests that such age-related losses are mediated by neural rather than optical mechanisms.

Age differences in thresholds for the detection of motion in depth, or “looming”, have also been reported (e.g., Hills, 1975; Shinar, 1977). Several studies have also reported evidence of age differences in the ability to judge the apparent speed of automobiles (Hills, 1980; Scialfa, Kline, Lyman & Kosnik, 1987). Older females, in particular, appear to exhibit pronounced errors in estimating the “time to arrival” of approaching automobiles in a part-task driving simulator (Schiff, Oldak & Shah, 1992).

Color Vision

Normal observers are capable of distinguishing among more than 100,000 hues in side by side comparisons (Geldard, 1972). Small but systematic age-related declines in this ability to distinguish between similar hues have been demonstrated in numerous studies. Dalderup and Fredricks (1969) reported notable age-related deficiencies in color discrimination ability among those over 70 years of age. Gilbert (1957) conducted a large-scale study of color discrimination ability in observers ranging from 10 to 93 years of age. Although all observers demonstrated more discrimination errors among blues and greens (shorter wavelengths) than among yellows and reds on a hue sequential ordering task, this increased tendency to “confuse” related shades within the blue-green range was especially pronounced among older observers. Numerous other studies have reported that age-related declines in color discrimination are more pronounced for hues in the short wavelength region of the spectrum (e.g., Eisner, Fleming, Klein & Maudlin, 1987; Knoblaugh, Sanders, Kusuda, Hynes, Podgor, Higgins & de Monasterio, 1987; Lakowski, 1958). Early studies attributed this “red shift” in color discrimination to the selective absorption of short wavelength light by the senescent lens (e.g., Weale, 1986). However, more recent investigations suggest this phenomenon may result from a differential loss of sensitivity in short-wavelength photoreceptors and/or their opponent neural projections to the brain (Haegerstrom-Portnoy, 1988; Johnson & Marshall, 1995). As with other visual functions, age-related deficits in color discrimination are exacerbated under low light conditions (e.g., Kraft & Werner, 1999a). Perhaps of greater significance, Knoblauch, et al. (1987) found that age differences in blue-green color discrimination were substantially reduced at high levels of target illumination.

Although the magnitude of the age-related decrements in blue-green color discrimination noted above is small, Cody, Hurd & Bootman (1990) demonstrated that a significant proportion of older adults made errors when trying to distinguish between medicine capsules with similar color-coded markings. Findings like those reported by Knoblauch, et al. (1997) suggest that such errors can probably be minimized when more optimal lighting conditions are employed. Finally, a recent investigation by Kraft and Werner (1999b) demonstrated that *color constancy* mechanisms remain relatively intact among older observers. This suggests that dynamic color adaptation processes may serve to compensate for low-level inefficiencies in short-wavelength mechanisms; thus, normalizing phenomenal color experience and minimizing performance decrements on real-world tasks.

Compensating for Age-Related Visual Deficits

The age differences in the structure and function of the visual system outlined above suggest numerous opportunities for enhancing performance via optimized design. Some guidelines for achieving these ends are listed below. Additional details regarding the optimization of visual environments for older persons can be found in Kline and Scialfa (1997) and Schieber, Fozard, Gordon-Salant and Weiffenbach (1991).

1. In general, increased levels of ambient and task illumination are required to optimized visual performance for older adults. Increased illumination helps overcome the opacity of the ocular media and is known to mitigate age differences in text legibility, object recognition and color discrimination.

2. Increased levels of luminance contrast are required to meet the visual needs of older persons. Blackwell and Blackwell (1971; 1980) have demonstrated that older persons require 2-6 times more luminance contrast to achieve equivalent levels of object detection and recognition performance.

3. Minimize the need to perform "near" work. When *close-up* work cannot be avoided, older persons should be fitted with eyeglasses optimized for the specific working distance required by the task.

4. Chose text font sizes of at least 12 points in character height to accommodate the needs of those 60-75 years of age. Font heights of 18 points are required to accommodate the needs of the 85th percentile 80 year-old (Schieber, et al., 1991; Steenbekkers, 1998).

5. Deploy lighting strategies that minimize the opportunity for disability glare effects. Avoid narrow angles of incidence and/or use indirect lighting schemes where possible. Special text fonts have been developed that mitigate age-related reductions in legibility due to a form of disability glare known as irradiation effects (i.e., the *Clearview*™ highway sign font; see Garvey, Pietrucha & Meeker, 1998).

6. Minimize dependence upon peripheral vision.

7. Adopt marking strategies that enhance motion perception and/or speed estimation capabilities. For example, the use of vehicle *daytime running lights* may provide disproportionate performance and safety benefits for older drivers (see Koorstra, Bijleveld & Hagenzieker, 1997).

8. Use larger color contrast steps when discrimination between short wavelength (blue, green) colors is required.

9. Explore the use of computer-based image processing techniques for optimizing the legibility of spatial form (e.g., the *recursive-blur* optimization technique - see Schieber, 1998).

Hearing

Anatomical Changes

Age-related changes in the outer ear which might potentially impair hearing function include excess accumulations of ear wax which could block the auditory canal (Corso, 1963) as well as a tendency for the auditory canal to narrow or collapse (Schow, Christensen, Hutchinson & Nerbonne, 1978). In the middle ear, the joints connecting the ossicular bones (malleus, incus and stapes) tend to become arthritic and less elastic with advancing age (Belal, 1975). However, Corso (1981) has concluded that such changes rarely affect sound transmission to the cochlea. The inner ear, and its ascending nervous system connections, are the site of several dramatic age-related changes. There is a significant age-related loss in the number of inner and outer hair cells along the *organ of Corti* (Schuknecht, 1993). The loss of inner hair cells occurs disproportionately among those responsible for the sensory transduction of high-frequency acoustic stimuli; and, hence, contribute to the development of *sensorineural presbycusis* (see below). Finally, there appears to be a large age-related reduction in the number of neurons comprising the auditory nerve (Schuknecht, 1993; Spoendlin & Schrott, 1989; 1990), brainstem auditory nuclei and the auditory cortex (see Willott, 1991).

Absolute Sensitivity

Adult aging is associated with a significant increase in the stimulus intensity required to detect a sound. This age-related loss of sensitivity (known as *presbycusis*) is especially pronounced for high-frequency sounds (Fozard, 1990). This loss of sensitivity proceeds at a rate of approximately 1 dB per year for those beyond 60 years of age; increasing to as high as 1.5 dB per year among those 80-95 years of age (Davis, Ostri & Parving, 1991; Brant & Fozard, 1990). Many studies have also indicated that hearing loss is accelerated among men during middle-age and early old-age. This phenomenon has often been attributed to sex differences in noise exposure at the workplace (Corso, 1981; Kryter, 1983; Moscicki, Elkins, Baum & McNamara, 1985). This pattern of results clearly suggests that hearing in the later years of life might be better preserved given life long protection against noise exposure.

Frequency and Intensity Discrimination

The ability to discriminate small changes in the frequency or intensity of sounds is an important subcomponent of complex auditory processing tasks such as speech recognition and sound localization (Corso, 1981). Numerous studies have reported age-related decrements in these abilities (e.g., Cranford & Stream, 1991; Konig, 1957; Lutman, Gatehouse & Worthington, 1991). More recently, studies by He, Dubno and Mills (1998) and Humes (1996) have demonstrated that older adults were less able to discriminate between similar sounds that differed in intensity and/or frequency. Abel, Krever and Alberti (1990) demonstrated particular age-related difficulties for frequency discrimination tasks with very brief tones (20 msec) relative to longer tones (200 msec);

suggesting that older adults may have greater difficulty processing phonemes (20 msec) than syllables (200 msec) during speech discourse.

Sound Localization

Localization of a sound source is heavily dependent upon the auditory system's ability to process and interpret small differences in intensity and/or time-of-arrival between the two ears (Geldard, 1972). Laboratory studies in which interaural intensity and time-of-arrival have been manipulated reveal significant age-related decrements in the accuracy of sound localization performance (e.g., Herman, Warren & Wagener, 1977; Hausler, Colburn & Marr, 1983; Tillman, Carhardt & Nichols, 1973). Herman, et al. (1977) reported that age-differences in sound localization ability appeared to be due to problems discriminating interaural time-of-arrival rather than interaural intensity differences. Since the localization of low-frequency sound sources is primarily dependent upon discrimination of interaural time-of-arrival cues, Olsho, Harkins and Lenhardt (1985) have suggested that older adults may exhibit particular problems localizing events or objects that emit low-frequency sounds. This possibility has important implications for real-world performance domains such as negotiating busy roadway traffic as either a pedestrian or a driver (Schieber, 1992).

Speech Recognition

Many studies have reported age-related decrements in speech perception. Particularly dramatic effects have been reported in the classic study by Jerger (1973) who found that speech recognition for monosyllabic words decreased from just below 100% at 20 years of age to less than 60% correct for those 80-89 years of age. Age-related decrements in speech intelligibility are exacerbated under challenging listening conditions such as background noise (Jokinen, 1973; Plomp & Mimpen, 1979), architectural echo or reverberation (Bergman, 1971; Helfer & Wilber, 1990; Nabelek & Robinson, 1987) and time compression (Letowski & Poch, 1996; Stricht & Gray, 1969). Recent research in this area has focused upon determining the relative contribution of *peripheral* versus *central* mechanisms to age-related performance decrements. This distinction between peripheral (sensory) and central (cognitive) mechanisms is important. If age-related decrements in speech perception are primarily due to sensory factors, rehabilitation and compensation would involve some sort of signal processing intervention. If decrements are primarily cognitive in nature, rehabilitation might best be accomplished through a comprehensive training approach (Schieber & Baldwin, 1996).

Age-related decrements in the ability to understand speech can be mitigated somewhat when stimulus intensity levels are increased substantially - suggesting that much of the age-related decrement is mediated by peripheral rather than central mechanisms (Gordon-Salant, 1987). However, age-related decrements in the perception of "speeded speech", which are remarkably robust, appear to be mediated by central mechanisms as they are not mitigated by increased stimulus intensity level (e.g., Gordon-Salant & Fitzgibbons, 1999). Most of the classic literature on age differences in speech perception employed single word stimuli that were not embedded within a semantic context. However, when speech stimuli are presented within "sentence" or "paragraph" contexts, age-related deficits in speech intelligibility are reduced (e.g., Gordon-Salant & Fitzgibbons, 1997;

Holtzman, Familant, Deptula & Hoyer, 1986; Wingfield, Poon, Lombardi & Lowe, 1985). These findings clearly suggest that old adults can successfully employ higher-order cognitive mechanisms to compensate for age-related losses in sensory function. What remains to be established is the "attentional costs" of such compensatory processes.

Compensating for Age-Related Hearing Deficits

The age differences in the structure and function of the auditory system outlined above suggest several opportunities for enhancing performance via optimized design. Some guidelines for achieving these ends are listed below. Additional information regarding the optimization of auditory environments for older persons can be found in Kline and Scialfa (1997) and Schieber, Fozard, Gordon-Salant and Weiffenbach (1991).

1. Increase stimulus intensity. Age-related declines in auditory perception, including speech recognition, are often mitigated by increasing stimulus volume.

2. Control background noise. Age differences in auditory perception are exacerbated in the presence of background noise. Background noise can be reduced at the source (e.g., replacing noisy heating/air-conditioning equipment with more quiet models) and through the careful selection of architectural elements that reduce reverberation or absorb stray acoustic energy, etc.

3. Avoid the need to detect and/or recognize high-frequency acoustic information.

4. Long-term exposure to high levels of noise (i.e., 88 dB or greater) should be avoided across the life span in order to minimize the cumulative effects of *presbycusis*.

5. Avoid the need to spatially localize low-frequency sound sources. When this cannot be avoided, provide redundant localization cues such as warning signs or flashing lights. Kline and Scialfa (1997) also suggest that sound localization performance in older adults can be improved by increasing signal "on-time."

6. Speech recognition can be significantly enhanced through the use of semantically well-structured prose that is rich in context and redundant.

7. Speech recognition among older adults is improved when presented at a reasonable and consistent pace.

8. Technological advances in hearing aid development need to be complemented by proper training of users and compensatory adjustments based upon user feedback. Without such a *systems approach*, 25-50% of persons fitted with hearing aids refuse to wear them due to various complaints related to comfort and/or function (see Fozard & Gordon-Salant, *in press*).

9. Embedded computer systems with real-time signal processing capabilities should be combined with the increasingly ubiquitous internet infrastructure (in public and commercial buildings) to provide anytime/anywhere assistive listening support to older adults and other hearing impaired individuals.

Attention

Attention is a nebulous yet central construct for modern cognitive science. It at once encompasses both the capacity and component operations of human information processing. That is, attention is comprised of both "resources" and "processes". An essential characteristic of attention is that it is highly limited. As such, its functional capacity (i.e., efficiency) can benefit greatly from the application of top-down management or "executive control". These interacting aspects of attention can be organized into four functional categories: (1) attention span, (2) selective attention, (3) divided attention and (4) sustained attention. Important age-related developments in each of these areas will be introduced in the sections which follow.

Attention Span (or Useful Field of View)

Binocular light sensitivity extends across the full (150-180 degree) field of peripheral vision. However, the ability to accurately identify and discriminate visual stimuli (without making an eye movement) is restricted to a much smaller region of the visual field. The size of this region, often called the *useful field of view* (UFOV), varies with display characteristics and task demands. For example, UFOV size decreases when attentional demands are increased through the addition of a secondary discrimination task in central vision (Ball, Beard, Roenker, Miller & Griggs, 1988) or when the number of background stimuli is increased (Sekuler & Ball, 1986; Scialfa, Kline & Lyman, 1987).

Sekuler and Ball (1986) reported that the spatial extent of the useful field of view was restricted in many older adults. These results were soon replicated and extended in additional studies (e.g., Cerella, 1985; Scialfa, Kline & Lyman, 1987; Ball, et al., 1988). Ball, Roenker & Bruni (1990) reported that UFOV spatial extent decreased under dual-task and brief exposure conditions and that the size of these effects was magnified among their older observers. Although the exact cause of age-related restrictions in the useful field of view remain unclear, it is apparent that much of the age-related variation in its spatial extent can be attributed to cognitive and attentional mechanisms rather than to sensory limitations.

Significant age-related reductions in the area over which visual attention can effectively operate have obvious implications for real-world performance. For example, in a noteworthy series of studies, Ball and her colleagues (Ball & Owsley, 1991; Owsley, et al., 1998) have demonstrated that significant reductions in UFOV (assessed under conditions were processing time was greatly restricted) were highly predictive of past and/or future involvement in "at-fault" automobile driving accidents. In what may prove to be a remarkable development, Ball, et al. (1988) also demonstrated that age-related

UFOV deficits could be reversed following extended practice using a perceptual training protocol. Maintenance of these beneficial training results were still observed at a 6 month follow-up assessment. If age-related UFOV restriction is associated with widely observed deficits in visual information processing (see below), then it follows that perceptual training holds great potential for remediation of a wide variety of performance deficits. These and related possibilities are currently being investigated by cognitive scientists around the world.

Selective Attention

At any given moment the human senses generate massive amount of information about the environment. It is self-evident that conscious awareness is limited to a select subset of this information as organized by interacting perceptual and cognitive mechanisms. Selective attention is a mechanism whereby incoming sensory-perceptual information is routed to higher-order cognitive mechanisms for additional processing. Selective attention is a "gatekeeper" that assigns priority based upon a complex interaction between the perceptual features of incoming information and the current goals and intentions of the observer.

The classic study of age-related changes in selective attention was reported by Rabbitt (1965). Rabbitt found that older observers became disproportionately disadvantaged in their ability to discern target stimuli from non-target (distracter) stimuli as the number of distracters increased. He concluded that older observers had "difficulty ignoring irrelevant information". Recent reviews of the selective attention literature (e.g., McDowd and Shaw, 2000; Plude, Schwartz and Murphy, 1996) point out that such age-related deficits in selective attention are ubiquitous but not universal. Contemporary research appears to be focused upon (1) delineating the boundary conditions within which age-related deficits occur and (2) isolating the mechanisms of age-related deficits in selective attention. While the boundary conditions have yet to be established, many mechanisms have been proposed to account for such age differences in performance. Among the most likely general mechanisms are: slowing in the rate of information processing (see Salthouse, 1985), diminished availability and/or executive control of attentional resources (Salthouse, et al., 1984; Madden, 1986); and inhibition insufficiency (Hasher & Zachs, 1988). Unfortunately, these mechanisms are not mutually exclusive and are difficult to distinguish from one another experimentally (see Hartley, 1992).

The vast majority of research on age-related changes in selective attention has been conducted using some variant of the visual search paradigm. Plude and Doussard-Roosevelt (1989) investigated age-differences in visual search within the context of Treisman and Gelade's (1980) influential *Feature Integration Theory* of attention. This theory holds that the objects of visual cognition are constructed via a 2-stage process of encoding: namely, *feature extraction* and *feature integration*. The feature extraction process selects information based upon primitive perceptual characteristics (such as color, orientation, luminance, contrast, etc.). Since these properties are automatically segregated by perceptual systems, feature extraction is fast, efficient, conducted in parallel with other feature extraction operations, and consumes very few cognitive resources. *Feature integration* processes, however, can not take advantage of perceptual automaticity and are therefore slow, sequential operations that consume significant cognitive resources. Plude and Doussard-Roosevelt (1989) compared young and older observers on visual search under conditions where target discrimination was limited by the feature extraction process (i.e., feature search) or feature integration (i.e., conjunction search). No age differences in performance were observed in the feature search condition (where there was no overlap between the target color and the color of the background distracters). Search time was independent of the variation in the number of distracters across trials indicating that fast, efficient, automatic feature extraction processes appeared to be intact in the older observers. However, sizable age-differences in performance were observed in the conjunction search condition. As is typically the case for a conjunction search (where multiple perceptual features must be combined by attentional processes to distinguish targets from distracters), search time increased as the number of background distracter stimuli grew. However, the search costs for older observers increased at a rate of 50 msec per distracter compared to only 25 msec/distracter for their younger counterparts. These results indicate that feature integration processes deteriorate with increasing adult age and suggests that age differences in visual search are mediated by encoding inefficiency rather than a selection deficit, per se.

Other studies have provided evidence for more specific mechanisms of age-related failure of selective attention in visual search tasks. Posner, Inhoff, Friedrich and Cohen (1987) depict the deployment of attention in visual search tasks as three sequential operations: engagement, disengagement and movement of the locus of attention.

Employing this conceptualization, D'Aloisio & Klein (1990) have presented evidence that age-related declines in visual search performance result from a difficulty in the disengagement of attention from previously inspected targets. McDowd, Filion & Oseas-Kreger, 1991 (cited by Cavanaugh, 1996) showed that when task relevant and irrelevant stimuli were presented in the same sense modality (e.g., both in the visual or both in the auditory domain), older persons failed to demonstrate good selectivity and attended equally to both relevant and irrelevant information alike. However, when relevant and irrelevant information were presented in *separate sense modalities* (e.g., visual versus auditory) older observers demonstrated improved selective performance. This finding is consistent with *multiple resource theories* of attention (e.g., Wickens, 1984) and may have important implications for the design of complex human-computer interfaces such as those being developed for advanced technology automobile instrument panels.

Scialfa, Thomas & Joffe (1994) examined age differences in visual search while simultaneously monitoring gaze location using a corneal reflectance eye tracker. Age-differences in visual search for targets requiring feature integration comparable to those demonstrated by Plude and Doussard-roosevelt (1989) were obtained . These same differences were also reflected in the eye movement data. Older observers required a greater number of saccadic eye movements in order to find the target. This finding clearly suggests that older persons process smaller "chunks" of visual information at any given moment - a trend which is exacerbated as the width of the visual search area increases from 3.82 to 13.94 degrees (Scialfa & Joffe, 1997). Scialfa and his colleagues propose that reductions in the spatial extent of the "useful field of view" (UFOV) may be an important contributing factor to age-related declines in the efficiency of visual information processing. If this conclusion is correct then training programs that increase the effective size of the UFOV may generalize to improved performance upon a variety of visual search tasks both inside and outside of the laboratory.

In domains where individuals have developed high levels of expertise through many years of practice, such as the interpretation of medical x-ray images, older experts outperform younger novices despite exhibiting normative search decrements on laboratory visual search tasks (Clancey & Hoyer, 1994). A likely explanation for this phenomenon is that prolonged and repeated practice eventually results in a qualitative shift in the manner in which skill-based tasks are processed. According to Shiffrin and Schneider (1977), highly practiced skills develop as slow, sequential, and resource-consuming *effortful* processes used to accomplish a task are gradually replaced by fast, parallel, and resource-efficient *automatic* processes. Hence, the automatization of skill-based behaviors results in a reduction in the demand for scarce attentional resources and may explain why expertise developed during one's young and middle-aged years appears to be particularly resistant to the deleterious effects of aging (see Salthouse, 1990). What remains to be seen is whether attentional automaticity can be developed after one has reached their later years of the life span.

Fisk and his colleagues (e.g., Fisk, McGee & Giambra, 1988; Fisk & Rogers, 1991) have conducted several studies exploring the development of automaticity in the domain of visual information processing. This work has employed extensive training protocols previously shown to lead to the development of automaticity in young observers (i.e., a "consistent stimulus mapping" strategy in which target and distracter feature sets remain mutually exclusive throughout the acquisition phase of skill development). Unfortunately, however, these researchers have consistently demonstrated a failure to achieve automaticity of visual search skills among older adults (even when the training regimen exceeded 5000 trials). Fisk, et al. have concluded that attentional skills are resistant to the development of automaticity in old age. It is interesting to note that Ball, et al. (1988) were highly successful in applying perceptual training to expand and maintain the spatial extent of the useful field of view among older research participants. Additional research is needed to ascertain the mechanisms mediating these different patterns of results across such similar visual information processing domains.

Divided Attention

Divided attention refers to processes by which attention is allocated and controlled to successfully perform two or more tasks simultaneously. Laboratory measures of divided attention typically employ the dual-task paradigm in which two tasks are performed both separately as well as concomitantly. The cost of "dividing" attention is typically quantified by measuring the difference in performance upon a given task when performed under "dual task" conditions relative to performance on the same component task assessed under "single task" (baseline) conditions. Laboratory measures of divided attention are of particular significance in the field of human factors since they have been shown to be predictive of complex performance in real-world domains such as aviation

(Damos, 1978; Gopher, 1982) and automobile driving (Avolio, Kroeck & Panek, 1985; Ball & Owsley , 1991).

According to several major reviews of the literature, large and robust age-related declines have been consistently observed in studies of dual-task performance (Craik, 1977; Hartley, 1992; Kramer & Larish, 1996). Some investigators have attributed these deficits to insufficient, inefficient and/or mismanaged cognitive resources (e.g., McDowd & Craik, 1988; Korteling, 1991; Park, Smith, Dudley & Lafronza, 1989). Consistent with this view, the magnitude of the age-related increase in multitasking "costs" grows as the complexity or information processing demands of the component tasks increase (e.g., Somberg and Salthouse, 1982; Salthouse, Rogan & Prill, 1984). Other investigators have suggested that age-related declines in dual-task performance are mediated by a difficulty with switching attention between task domains (e.g., D'Aloisio & Klein, 1990; McDowd, Vercruyssen & Birren, 1991; Hawkins, Kramer & Capaldi, 1992).

Ponds, Brouwer and van Wolffelar (1988) examined age differences in the ability to divide visual attention in a simulated driving task. The primary task measure was lane keeping accuracy in a compensatory steering (cancellation of “side winds”) driving simulation. The secondary task consisted of a rapid “dot counting” protocol. An interesting aspect of the Ponds, et al. study was that the difficulty level of each task, when performed in isolation, was matched to each individual’s unique capacity. That is, the difficulty of the steering task was manipulated to maintain 90% “time on target” accuracy for each individual; whereas, self-pacing was used to equate the information-processing load imposed by the dot-counting task. When drivers of different ages were tested in the dual-task condition, it was found that the introduction of the dot-counting task significantly reduced simulated driving performance in the old (mean age: 68.6) but not the young (mean age: 27.5) or middle-aged (46.7) participants. Hence, older drivers appeared unable to absorb all the “costs” of divided attention. The authors speculated that this age-related simulated driving performance deficit emerged as the result of diminished “supervisory task control”. However, they also offered an alternative explanation which has received some addition support in subsequent investigations. Namely, that the elderly had excessive difficulty coordinating the two different motor programs required to execute the dual-task responses (steering vs. button-pressing) into one smoothly operating motor plan. It would appear that an age-related problem due to a motor-level coordination deficit would be much easier to compensate via engineering-based solutions than one resulting from a cognitive-level deficit.

Brouwer and his colleagues (Brouwer, Ickenroth, Ponds & van Wolffelaar, 1990; Ponds, Brouwer and van Wolffelar, 1988) have performed a series of studies which have focused upon age-related problems in divided attention during simulated driving. Older subjects (mean age: 66.2) demonstrated declines in steering performance in the dual-task condition (employing a visual scanning subsidiary task). The performance of their younger subjects (mean age: 30.2) did not vary across the single- versus dual-task conditions. Remarkably, the size of the age-related reduction in steering accuracy under divided attention conditions was cut in half when a vocal response was required on the secondary task (as opposed to a manual response). Similar findings have been reported by van Wolffelaar, Brouwer and Rotthengatter (1991). This pattern of results suggests that both cognitive (i.e., supervisory task control) and motor (i.e., dual response coordination) deficits mediated the age-related performance problems; and, that age-related deficits in driving performance may be offset somewhat by reducing the programming load of the motor channel. These findings appear to have great significance for the design of in-vehicle interfaces which will meet the needs of older drivers without overloading their attentional reserve capacity.

Korteling (1994) has also performed a series of simulator-based studies exploring age differences in the dynamics of divided attention during driving. Young (mean age: 27) and older (mean age: 70) subjects performed a steering and car-following task in an advanced driving simulator. Since both of these component subtasks of driving are such “well learned skills” one would expect that they might not represent sufficiently sensitive instruments for assessing age-related attentional declines in normal, healthy populations. To increase the potential sensitivities of these measures a stimulus-response incompatibility was introduced. That is: during some driving sessions pressing the gas pedal increased acceleration (normal condition) but, in other sessions, its function was reversed — pressing down on the gas pedal caused deceleration (inverted condition). No age-group differences in performance were observed for the “normal” condition, but a fascinating pattern of age-differences emerged for the “inverted” condition. The age-related deficit in performance was found only for the steering task — not for the car following task which required the difficult compensation due to the reversal of a previously overlearned skill. The older drivers clearly tended to focus their attentional resources upon the compensatory activities required to meet the challenges imposed by the “impaired” operational subtask; but at the expense of another important subtask — steering. This result is somewhat surprising since contemporary attention theory would suggest that well-learned skills (such as steering a car) have become “automatized” and, hence, are usually immune to performance deficits during competition for attentional resources. Korteling's (1994) study suggests that there may be complex and unexpected "costs" associated with compensatory behaviors among older adults.

Gopher and his colleagues (Gopher, Weil & Siegel, 1989; Gopher, Weil & Bareket, 1994) have presented evidence that the development of performance in multitask situations is improved when variable priority strategies are implemented. In a variable priority training schedule, the trainee is instructed to progressively increase and then decrease the priority given to one of the component tasks in a multi-task scenario. This continuous variation in task prioritization appear to provide trainees with the opportunity to develop improved skills in the management of cognitive resources. Kramer, Larish and Strayer (1995) recently reported that, compared to fixed priority schedules, older adults demonstrated improved development of dual-task skills as well as increased transfer of training following the adoption of a variable priority strategy.

Sustained Attention

Sustained attention, or vigilance, refers to those processes which enable an observer to continuously monitor, detect and correctly respond to rare environmental events over a prolonged duration. The few studies that are available, when considered together, suggest that (1) older subjects are more likely to "miss" the detection of rare events (rare being defined as 0.01 - 0.25 Hz) and (2) this age-related reduction in sensitivity for rare events is relatively independent of time-on-task (Giambra & Quilter, 1988; Parasuraman, Nestor & Greenwood, 1989; Surwillo & Quilter, 1964). That is, little or no "vigilance decrement" has been observed among healthy persons less than 75 years of age.

Compensating for Age-Related Deficits in Attention

The age differences in attention that were outlined above can be used to generate guidelines for improving the design of products and environments for older persons. Several such guidelines are listed below for consideration. Some are speculative and await verification via "hands on" cognitive engineering and field validation tests. *Caveat emptor*!

1. Stimulus "clutter" should be minimized. Task-irrelevant information may be especially distracting to older observers.

2. Present visual information in smaller "chunks". Reductions in the useful field of view (UFOV) suggest that older persons sample complex visual scenes using spatial windows of restricted size/area. It may follow, therefore, that presenting fewer stimuli distributed within a smaller spatial frame may support improved visual performance. In applying this strategy one must be careful not to pack the stimuli so closely together as to cause "crowding" effects.

3. Minimize the need to search for "conjunctions" of stimulus features. Use well-established perceptual features when developing schemes to highlight text or graphical stimulus materials. Feature integration processes are impaired in older persons while simple feature search appears to remain robust across age.

4. Remove information from dynamic displays (such as computer monitors) as soon as its usefulness has expired. This practice will not only help control visual clutter but may serve to mitigate age-related decrements in the ability to "disengage attention" from sampled displays (i.e., reduce possible attention *hysteresis* effects).

5. Explore the use of multimedia as an aid to selective attention by segregating independent information streams via separate sense modalities (e.g., visual vs. auditory streams).

6. Minimize the need to develop new perceptual skills. The development of "automatized" perceptual grouping appears to be significantly impaired in old age (but note the exception in the case of UFOV training). However, perceptual skills developed earlier in life can be leveraged in design applications as they appear to be well preserved into very old age.

7. Use cognitive task analysis to design multi-tasking operations so that they 1) reduce overall component complexity and 2) distribute task load over multiple resource pools. Age-related decrements in multi-tasking performance are particularly acute when component task complexity is high and/or when resource demands are great. *Multiple resource theory* (e.g., Wickens, 1984) holds particular promise for engineering workstation solutions optimized to the cognitive/attentional capacities of older users.

8. The deployment of voice recognition technology appears to hold some promise for mitigating age-related attentional difficulties in complex multi-tasking environments (e.g., high technology automobile instrument clusters complete with internet access). However, the operational success of such applications may be greatly limited by their high demands upon *recall memory* - which is significantly impaired in old age (see below).

9. Leverage sustained attention capabilities, which remain robust in old age, to redesign multi-tasking procedures when possible.

Memory

Most research in the area of aging and memory has been designed and interpreted within the context of an information processing model such as the one schematically represented in Figure 1. The module labeled STM represents short-term memory processes that serve to mediate awareness and manipulation of sensory input. Primary memory subsumes the static representation of information whereas working memory and executive control processes represent active transformation and manipulation of cognitive objects derived from immediate sensory stimulation or previously acquired knowledge. The box labeled LTM represents long-term memory which is subdivided into 3 separate memory systems:

Semantic memory represents linguistically categorized knowledge. Episodic memory represents the coding of events. Procedural memory represents highly automatized or skilled behaviors. The transformation, or encoding, of incoming sensory information into short-term memory is constrained by previously acquired knowledge and skills as well as current goals and intentions. This influence is represented by the attention loop depicting both upstream and downstream encoding processes. Similarly, the processes driving memory storage and retrieval are represented via the storage/retrieval encoding loop (see Figure 2).

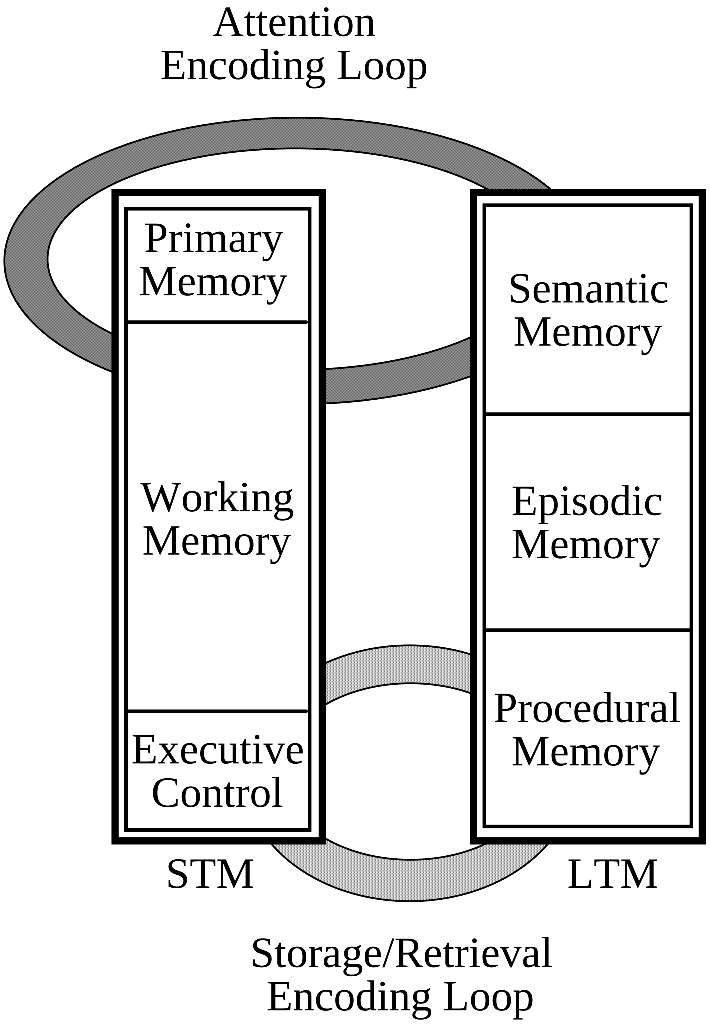

Figure 1. An information processing model of memory.

Primary Memory

The static capacity of primary memory can be assessed using devices such as the digit span or word span test. Individuals are given a list of single digit numerals or unrelated words and then required to immediately repeat the list (usually in the same order in which it was presented). Static memory capacity is given by the length of the longest list that can be remembered without error. Extensive studies of young individuals reveal that the average capacity of primary memory is 7 items with the entire normal population being encompasses by plus or minus 2 items about this mean value (Miller, 1956). Studies examining age differences in the static capacity of primary memory reveal systematic but very small age-related declines. For example, Parkinson (1982) reported mean digit span scores of 6.6 and 5.8 for his younger and older subjects, respectively. Similar findings have been confirmed in numerous studies (e.g., Johansson & Berg, 1989; Salthouse & Babcock 1991).

Another important dimension of primary memory function is the rate at which its contents decay over time. Such measures are usually obtained using some variant of the Brown-Peterson technique. Individuals are presented with a short list of stimuli to be remembered. However, the recall of the stimulus items is delayed by the imposition of a "distraction task" that prevents active rehearsal of the to-be-remembered material (e.g., counting backwards by 3's). Recall is then measured after various delay intervals. The contents of primary memory usually fade away completely within 20-30 seconds, depending upon the initial memory load (Brown, 1985; Peterson & Peterson, 1959). Research comparing young and older participants shows that the persistence of primary memory contents remains unchanged as a function of old age (e.g., Craik, 1977; Puckett & Stockberger, 1988).

Primary Memory Access Speed

Rigorous protocols have been developed for measuring the speed with which one can access, or scan through, the limited contents of short-term memory. Short-term memory contents appear to be accessed via an exhaustive, serial search process (Sternberg, 1966). Numerous studies have shown that while the capacity of primary memory remains relatively intact, scanning speed through primary or short-term memory slows significantly with age. For example, Strayer, Wickens and Braune (1987) examined memory scanning speed using the *Sternberg paradigm* in participants ranging from 20 to 65 years of age. They found that average scanning speed was 41 msec per item for young (20-26 years olds) and 57 msec per item for older (53-65 years old) participants. Similar rates of age-relating slowing for accessing the contents of short-term memory have been reported by other investigators (e.g., Anders & Fozard, 1973; Madden & Nebes, 1980). Findings such as these mean that an older person, on average, would take approximately one-tenth of a second longer to determine if a given 7-digit telephone number contained the numeral "5" in it. The significance of this type of slowing for real-world operational performance is not readily apparent and, instead, must be interpreted through the theoretical context in which it is being applied.

Working Memory

Working memory is the *dynamic* extension of primary memory. It is the "system that performs the task of temporarily manipulating information" (Baddeley, 1989, p. 36). An important aspect of the working memory construct is the "executive control" process which coordinates the allocation of cognitive/attentional resources required to mediate goal-directed transformations of short-term memory contents. There is overwhelming evidence that normal adult aging is accompanied by a working memory deficit . That is, when the contents of short-term memory must be manipulated significant age differences in memory capacity become evident. Craik (1986), for example, had young and older participants perform a modified version of the word span test of primary memory capacity. Participants were required to recall short lists of stimulus words in alphabetical order rather than the random order in which the stimuli had been presented (requiring an in-memory manipulation of stimulus information that is *not* required on a simple test of primary memory capacity). The addition of this simple information processing requirement resulted in the occurrence of large age-related declines in the capacity of dynamic or "working" memory. Similar results have been reported in numerous studies (e.g., Wingfield, Stine, Lubar & Aberdeen, 1988; Dobbs & Rule, 1989).

The magnitude of the age-related deficit in working memory capacity increases with the complexity of the cognitive processing or in-memory transformation requirements (Craik, Morris & Glick, 1990; Salthouse, Mitchell, Skovronek & Babcock, 1989). Salthouse (1990) has argued that such age-related differences in working memory can be attributed to reductions in the ability to monitor and/or coordinate concurrent processing demands rather than a structural limitation in memory capacity, *per se*. A similar, but more specific mechanism, has been proposed by Hasher and Zacks (1988). Their *inhibition insufficiency hypothesis* holds that older adults have weakened inhibitory control processes. As a result, task irrelevant recollections can accumulate in short-term memory and lead to a functional decline in the ability to perform cognitive work. The resulting "cluttered" memory space yields what appears to be a decline in working memory capacity. This mechanism is also compatible with the age-related declines in selective attention outlined above.

Long-Term Memory

Long-term memory, like any complex system, can be partitioned into several functional parts. Tulving (1972) has proposed an influential repartitioning of memory into several complementary subsystems: namely, the episodic, semantic and procedural memory systems. The *episodic memory system* mediates the "storage and retrieval of temporally dated, spatially located and personally experienced events or episodes" while the *semantic memory system* mediates the "storage and utilization of knowledge about words and concepts, their properties and interrelations" (Tulving & Thompson, 1973, p. 354; Benjafield, 1992). One's understanding of the phrase "internet browser" is rooted in semantic memory whereas the recollection of "having used an internet browser while at work yesterday morning to look-up a stock quote" would be the stuff of episodic memory. *Procedural memory,* on the other hand, refers to the implicit (i.e., unconscious) representation of the rules for various domains of skilled performance. One's ability to ride a bicycle or "touch type" would be housed within the procedural memory system.

There is general agreement that episodic memory performance declines with age while procedural and semantic memory performance remains relatively intact (Kaussler, 1991; Salthouse, 1982; Smith & Earles, 1996). As such, the remainder of this section will provide a survey of research findings regarding aging of episodic memory performance.

Recall versus Recognition

Schonfield & Robertson (1966) presented a list of to-be-remembered words to participants in five groups ranging in age from 20 to 70 years old. Memory for these words was then immediately assessed using either free recall or a multiple choice recognition procedure. Sizable age-related decrements in memory were observed with the free recall procedure. However, no significant age differences in performance were observed with the recognition memory task. Numerous studies have replicated this classic study of aging (e.g., Craik & McDowd, 1987; Smith, 1975). Clearly, age differences in episodic memory are reduced (and sometimes eliminated) when recognition procedures are used rather than free recall.

Encoding Insufficiency

It is commonly presumed that sensory-perceptual input to higher cognitive systems must first be transformed into a complex hierarchical (and ultimately meaningful) representational network. This process of transforming a signal from a proximal sensory code into a representation contextualized by an individual's accumulated world knowledge is known as *encoding*. The breadth and depth of the encoding processes can vary greatly depending upon the individual's goal, available cognitive resources and effort and environmental context/constraints. It is generally assumed that memory retrieval must recapitulate encoding processes during acquisition (i.e., storage). This notion, known as the *encoding specificity principle* (Tulving & Thomas, 1973), suggests that the level and richness of encoding during memory acquisition sets the limits upon its subsequent accessibility.

Under conditions where cognitive resources are restricted (e.g., multi-tasking, divided attention situations) individuals tend to encode events in a more stimulus-driven, automatic fashion and are less likely to mentally elaborate events in rich or contextually meaningful ways. As a result, subsequent memory performance is often impaired for information acquired during these conditions. Normal adult aging, with its apparent reduction in available cognitive resources, may result in a similar bias toward more shallow encoding processes (Craik & Simon, 1980; Hasher & Zacks, 1979; Rabinowitz, Craik & Ackerman, 1982). In fact, there is a large body of evidence that suggests many age-related decrements in memory performance can be attributed to inefficient encoding during storage and/or retrieval – the so-called *encoding insufficiency hypothesis* (Craik & Jennings, 1992). Hence, any manipulation or technology that could support systematic encoding of stimulus information would provide potential opportunities for improving memory-based performance among older adults.

Memory Source Monitoring

Older people appear much more likely to demonstrate *source monitoring* errors. That is, although they may recognize or recall a given object or event, they are much more likely to forget the source or context in which that information was originally acquired

(Hashtroudi, Johnson & Chrosnak, 1989; McIntyre & Craik, 1987). A similar age-related decrement has been reported by Cohen and Faulkner (1989) who studied memory for actions that had been actually performed by subjects as opposed to those that had merely been vicariously observed or imagined. When source monitoring errors did occur, young subjects reported high confidence in their erroneous source attributions about 9% of the time. However, older participants reported high confidence for 37% of their misattribution or source monitoring errors. This result stands in stark contrast to research reporting that metamemorial processes involving the accuracy of semantic memory (e.g., world knowledge) remain relatively intact among healthy older adults (Lachman & Lachman, 1980). Hence, older folks may “know what they know and what they do not know” with regard to semantic memory but may not be so accurate in knowing “from whence” their episodic memories have originated. This so-called “source amnesia” may have important implications for the reliability of eye witness testimonials from older observers (see Craik & Jennings, 1992; Howard, 1996) and/or predispose older persons to *action slips* - a type of error in which one emits an unintended action (Craik & Jacoby, 1996, p. 120).

Prospective Memory

Prospective memory involves remembering to carry out an action that is scheduled for some time in the future (i.e., remembering to remember). Several studies have demonstrated significant age-related increases in the rate of prospective memory errors (e.g., Cockburn & Smith, 1991; Dobbs & Rule, 1987). However, Maylor (1990) reported that many older persons charged with remembering to perform a future action spontaneously adopted the use of some form of external memory aid (such as notes, calendar entries, etc.). In fact, older persons who did employ such external memory aids actually tended to outperform their younger counterparts on perspective memory tasks. Other studies have also found that age differences in perspective memory can be mitigated through the use of environmental supports (e.g., Einstein, Smith, McDaniel & Shaw, 1997; Loewen, Shaw & Craik, 1990).

Automatic versus Volitional Memory Processes

Memory can be conceptualized as consisting of both *automatic* and *volitional* component processes. Automatic memory processes activate a web of preexisting associations between stimulus features and long term memory representations and occur rapidly, effortlessly and below the level of conscious awareness. These "implicit" memory processes are essential for perceiving and understanding any stimulus. Volitional or "explicit" memory, on the contrary, involves slow, effortful, consciously controlled strategic processes such as those that guide the study of materials to be remembered and when later retrieved. Most of the accumulated literature on aging and memory has focused upon volitional (i.e., explicit) memory. Recently, however, significant resources have been invested to investigate age differences in automatic (i.e., implicit) memory using stimulus priming procedures and assessing their subsequent impact upon critical dependent measures such as lexical decision-making and work stem completion. Currently, the emerging consensus among the cognitive aging research community appears to be that automatic memory processes (e.g., spreading activation) remain relatively intact with advancing adult age (see reviews by Craik & Jacoby, 1996; Light &

LaVoie, 1993). This consensus opinion is well represented in a quote taken from a recent review of the implicit memory literature by Howard (1996):

> There appears to be no decline with normal aging in the extent to which processing a stimulus automatically results in some alteration of preexisting perceptual pathways and conceptual representations; one way in which this alteration can be viewed is as a continuing activation of the relevant pathways and representations (though it is not yet clear how long any such activation continues). This hypothesis follows from the finding that, when perceptual and conceptual priming of facilitation materials are examined, age differences in priming are either nonexistent or minimal (pp. 241-242).

Howard (1996) goes on to describe how this maintenance of implicit or automatic memory function has potentially great implications for everyday functioning, including: cognitive training and intervention programs, differentiation of normal versus pathological aging, susceptibility to unconscious repetition and/or plagiarism, and social cognition (e.g., impression formation and persuasion). Craik and Jacoby (1996, p. 127) note that expanding our knowledge about the conditions that allow for the establishment and maintenance of automatic memory processes will allow for the design of environments and products that improve everyday functioning in older people. Indeed, research has already shown how computer-based technology can be used to leverage implicit memory processes in the service of improved cognitive performance (e.g., Glisky, Schacter & Tulving, 1986; Jennings & Jacoby, 1993; Schacter, 1996).

Environmental Support

The findings reviewed above make a strong case for the notion that age differences in memory performance can be ameliorated by providing environmental supports which

(1) enhance or elaborate the encoding process and/or (2) minimize the demand for diminished cognitive resources. A select survey of a few studies yielding results consistent with this view are summarized below.

Backman (1986) presented a series of short sentences for immediate recall to young and older participants. The presentation rate (slow, fast) and sensory modality (visual, auditory, both visual and auditory) of the stimuli were varied. Age differences in memory performance were reduced when the presentation rate was slowed and when the text passages were redundantly presented in both the visual and auditory modalities simultaneously. Arenberg (1968) reported a similar "auditory augmentation" of recall among older adults. In a now classic study, Canestrari (1963) demonstrated that memory performance of older adults was significantly enhanced by removing stimulus time constraints during the encoding (acquisition) phase of attending to the to-be-remembered verbal stimuli. Hence, it would appear that *stimulus self-pacing* and *multi-media augmentation* may represent valuable opportunities for enhancing memory encoding among older persons via environmental support.

Puglisi, Park, Smith & Dudley (1988) found that memory performance among older adults was improved under certain conditions where stimuli were presented pictorially instead of verbally. A likely explanation for this effect was that the use of pictorial stimuli caused the older participants to switch from a shallow to a more elaborate encoding scheme. However, it should be noted that merely providing pictorial representations of to-be-remembered concepts is no panacea for comprehension or memory problems among the aged (see Morrell, Park & Poon, 1990; Puglisi & Park, 1987). A follow-up study by Park, Smith, Morrell, Puglisi and Dudley (1990) revealed that the encoding benefit of pictorial stimulus presentations was especially helpful for older adults when it served to automatically provide an integrative context linking to-be-remembered content - a dramatic demonstration of improved memory encoding and performance through environmental support.

Finally, it is well known that systematic sociohistoric, or *cohort*, differences exist between young and older groups of adults. The existence of these differences suggest that conceptual information may be biased in such a way that it becomes more meaningful (and, hence, easier to encode) for one (age) generation than another. Barrett and Wright (1981) demonstrated the potential influence of such cohort-mediated effects upon memory performance. Two cohort-specific word lists were constructed. The *young-cohort* list contained words that were more familiar to young college students than to their older counterparts (e.g., *tweeter, gig*, *synthesizer*). The *old-cohort* list contained words that were more familiar to old than young participants (e.g., *poultice*, *fedora*, *vamp*). Tests performed using these two word lists revealed that each age group demonstrated superior memory acquisition performance for the list of words that was optimized for their particular cohort. Remarkably, the performance of the old group was superior to that of the young group when the *old-cohort* stimuli were used. This finding suggests yet another means of using environmental supports to enhance learning and memory performance among older populations. The development of cohort-specific lexicons and knowledge-bases might provide important new tools for the application of cognitive engineering to implement technology-based interventions designed to optimize high-level performance among people of all ages.

Compensating for Age-Related Deficits in Memory

Some of the key age-related differences in memory performance outlined above have been translated into the list of design guidelines which follow. Again, several of these guidelines must be considered as speculative until validated by field application data. Nonetheless, they provide a starting point for considering ways in which technological developments may provide design opportunities for enhancing higher-order cognitive function for those entering the later years of life.

1. Minimize the need to manipulate or transform information in short-term memory. Age-related decrements in the capacity of *working memory* increase dramatically when "in-line" transformations are required. Tasks can be redesigned or augmented via technology interfaces to off-load such demands.

2. Apply guidelines for mitigating selective attention problems (outlined above) in the service of optimizing working memory capacity. Attentional capture of "irrelevant" stimuli may inefficiently "tie up" working memory capacity as well as interfere with "in-line" memory operations (see Hasher & Zacks, 1988).

3. Leverage recognition memory, which is relatively robust in old age, to redesign tasks that rely upon recall memory.

4. Design environmental supports to guide and/or enhance memory encoding processes. This can be accomplished via:

    a. Systematic cueing.
    b. Enriching perceptual and/or semantic contexts.
    c. Leveraging *cohort-specific* stimulus representational networks.
    d. Using pictorial formats to aid integration of multiple stimulus items into a predictable and unitary concept.

5. Avoid reliance upon *source memory*.

6. Provide environmental structural supports and prompts to aid *prospective memory*. Parks (1992) provides a comprehensive set of guidelines for implementing such supports to augment adherence to medication schedules among older adults.

7. Leverage intact *automatic* memory processes (such as semantic priming) to support or off-load *volitional* memory processes. Of course, this is much easier said than done. However, several encouraging prototype applications of this cognitive engineering approach can be seen in the "method of vanishing cues" (Schacter, 1996) and "method of gradual shaping" (Jennings & Jacoby, 1993). The growing pervasiveness of *embedded computer systems* will contribute greatly to the opportunity to develop and deploy such subtle, yet potentially powerful, cognitive enhancement strategies.

8. Avoid (or control) stimulus "pacing" effects which can interfere with encoding and response selection during both the acquisition and retrieval phases of memory operations. Technological interfaces need to be carefully designed to algorithmically optimize the rate of stimulus presentation or implement "user-paced" I/O strategies.

9. Explore the potential of multisensory/multimedia presentation formats for improving the encoding and retention of to-be-remembered information.

Concluding Commentary

This chapter has presented an overview of the major age-related changes in information-processing capacity that may constrain the ability of older people to interact with a technological environment that is becoming increasingly complex. There are significant structural and conceptual challenges facing those who will attempt to translate the theoretical knowledge of scientific gerontology into products and designs that will optimize behavioral functioning among our growing cohort of older adults. Yet, these difficulties are tempered by the great potential that the fusion of scientific theory and practice hold for enhancing the quality of life in our later years.

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