AGE-RELATED SIMILARITIES IN THE ATTENTIONAL VISUAL FIELD

BY

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ABSTRACT

The visual world is cluttered, and adaptive behavior often demands attention to multiple objects. Unfortunately, compared with young adults, older adults seem to show more difficulty in dividing attention across the visual field (e.g. Ball et al., 1988), an effect often interpreted as an age-related constriction of the attentional visual field (AVF). As yet, the mechanisms underlying progressive shrinking of the AVF across lifespan remain unclear. The current work directly gauged *workload capacity, C(t),* calculated based on response time distributions (Townsend & Nozawa, 1995), to isolate the effects of attention and sensory limits across the visual field in young and older adults. Young and older adults made a speeded discrimination of one or two colored target letter(s) presented at varying levels of retinal eccentricity with or without the presence of clutter. In Experiment 1, surprisingly, workload capacity increased with retinal eccentricity and in the presence of clutter, and these effects were larger for older than young adults. Experiment 2 and 3 examined the influence of intertarget contingencies (Mordkoff & Yantis, 1991) on workload capacity under varying levels of clutter and target eccentricity. Data failed to find evidence of an age-related capacity gain either in the absence of intertarget contingencies or under conditions of moderate intertarget contingencies.. Experiment 4 attempted to replicate the age-related benefit found in Experiment 1, but found similarities in attentional performance across young and older adults. Meta-analysis of mean capacity scores across all four experiments indicates general age-related benefit in visual divided capacity. Meta-analyses of effects of eccentricity and clutter indicate the age-related similarities at various eccentricity and benefit in cluttered environments. The findings argue against the suggestion that

peripheral visual losses in older adults are strictly attentional, and suggest instead that they are sensory or perceptual in basis.

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Chapter 1: Introduction

1.1. Age-related declines in the attentional visual field

Everyday and professional tasks, from scanning for road hazards while driving to monitoring a bank of indicators in a power plant, often demand that operators simultaneously process multiple visual items. Unfortunately, the breadth of attention can be severely limited (Sanders, 1970), hindering operators' performance in the visual periphery. The breadth of visual attention has been linked to performance in various tasks. For example, Gramopadhye and colleagues (Gramopadhye, Drury, Jiang, & Sreenivasan, 2002) showed that training designed to expand attentional breadth improved visual search performance in a simulated aircraft inspection task. Searchers with bigger attentional breadth, furthermore, are quicker to identify visual events in a change detection task within natural scenes (Pringle, Irwin, Kramer, & Atchley, 2001). These studies and others (Leachtenauer, 1978; Wood, 2002; Bowers, Peli, Elgin, McGwin, & Owsley, 2005; Clay, Wadley, Edwards, Roth, Roenker, & Ball, 2005) suggest that the ability to divide attention across the visual field plays an important role in real-world tasks.

The breadth of attention across the visual field is not fixed for individuals, but declines with high levels of psychological stress (Bursil, 1958; Easterbrook, 1959; Weltman, Smith, & Edstrom, 1971) and cognitive load (Ikeda & Takeuchi, 1975; Williams, 1982; Atchley & Dressel, 2004). The breadth of attention also appears to shrink with healthy aging (Ball, Beard, Roenker, Miller, & Griggs, 1988; Sekuler, Bennett, & Mamelak, 2000; Poggel, Treutwein, Calmanti, & Strasburger, 2012), more markedly in cluttered displays (Scialfa, Kline, & Lyman, 1987; Scialfa & Kline, 1988), imposing particular difficulty on older adults in attention-demanding environments (e.g. Owsley, Ball, McGwin, Sloane, Roenker, White, & Overley, 1998).

The *attentional visual field* (AVF; also called Useful Field of View, Functional Field of View, and Visual Lobe) is typically defined as the functional visual area in which an observer can acquire information, within a single fixation, to make a judgment at a threshold level of accuracy (e.g. Sanders, 1970; Ball et al., 1988). Studies often require that observers identify target stimuli presented near the center of the visual field (central task) and concurrently localize another stimulus presented at various retinal eccentricities (peripheral task). Performance on the peripheral localization task shows the AVF under focused attention while performance on the peripheral task with the central task shows the AVF under divided attention. Stimulus exposure duration is typically too brief to allow eye movements, and experimenters measure performance declines in the peripheral task as an index of the AVF (Sekular & Ball, 1986; Ball et al., 1988; Scialfa et al., 1987; Sekuler et al., 2000).

Researchers in the earlier AVF studies (Ball, et al., 1988; Scialfa et al., 1987) observed that older adults' visual performance declines at the visual periphery especially among display clutter, an effect larger compared with young adults. They took their findings as evidence for age-related constriction of the AVF, while more recent work has interpreted the findings differently (Sekuler et al., 2000; Seiple, Szlyk, Yang, & Holopigian, 1996), asserting that changes in the AVF are best conceptualized as a spatially uniform decrease in the efficiency of information processing, rather than shrinking of the AVF *per se*. That is, these researchers suggest that changes in attentional performance as a function of retinal eccentricity are similar across young and older subjects (Seiple et al., 1996). These results therefore suggest that performance declines in the AVF task for older adults are not due to the loss of attentive processing in the periphery but to a more general inefficiency of processing across the visual field. As yet, thus, the pattern of AVF changes that occur with age, and the perceptual-cognitive mechanisms that determine the scope of the AVF in young and older adults, remain unclear.

1.2. Limitations of the conventional AVF paradigm

The conventional procedure for measuring the AVF asks subjects to perform concurrent central and peripheral tasks, and collects error rates as a dependent measure (e.g. Ball et al., 1988). Changes in error rate with increasing retinal eccentricity are taken as a gauge of the AVF. Unfortunately, various constraints complicate the interpretation of such data.

Choice of dependent measures in the previous research (e.g. error rates) has often been atheoretical, limiting the interpretation of the data on such measures. More specifically, research has often inferred age-related AVF narrowing from age by eccentricity interactions in error rates. However, such measures generally do not measure theoretic processes of interest directly, but conflate a variety of underlying psychological processes and mechanisms (e.g., Ratcliff, 1978). This is particularly problematic given that an appropriate nonlinear transformation of the measurement scale can remove any non-crossover interaction observed in a dependent performance measure (Loftus, 1978; Wagenmakers, Krypotos, Criss, & Iverson, 2012), including age by eccentricity interactions. Thus, evidence based on non-crossover interactions do not allow clear conclusions of psychological processes (e.g. age-related changes in the mechanisms). For example, an interaction of age by eccentricity that is significant in raw error rates might disappear following a transformation of error rates to log error rates or to a signal detection measure of sensitivity. While various transformations of a dependent measure will support similar conclusions regarding the ordinal differences between experimental conditions, they may lead to differing conclusions concerning magnitude of the differences between conditions.

Non-crossover interactions involving age can obtain even when data are consistent with a uniform underlying process change, for example, age-related general slowing (Salthouse, 1996). Often, researchers in cognitive aging are interested in process-specific age-related changes beyond the global changes that result from the average decline of processing speed (c.f. Kramer & Madden, 2008), and the selection of appropriate theory-motivated dependent measures and analyses is crucial to this endeavor (e.g., Brinley, 1965; Salthouse, 1985; Verhaegen, 2000).

1.3. Current approach.

In order to address the constraints above, the current study directly examines young and older adults' *workload capacity* at different eccentricities. It aims to isolate the effects of attention and sensory limits across the visual field in young and older adults by employing mathematical analysis of RT distribution data (Townsend & Nozawa, 1995; see below). The experimental paradigms in the current project aim to address the limitations of the commonly used measures of the AVF using the the capacity coefficient, $c(t)$, developed by Townsend and colleagues (Townsend & Nozawa, 1995; Townsend & Eidels, 2011) to allow a more rigorous and process-specific characterization of observers' AVF. The capacity coefficient (Townsend & Nozawa, 1995; Townsend & Eidels, 2011), derived from empirical RT distributions, measures the efficiency with which a system processes multiple input channels simultaneously. Because $c(t)$ is a ratio of performance in single and dual target conditions in the redundant-targets task, it effectively removes the effects of general slowing and age-related sensory losses. Furthermore, it not only allows comparisons of performance between subjects, but provides theoretical benchmarks of performance. It therefore offers a measure ideally-suited for comparing attentional processes across young and older adult age groups.

Chapter 2: Aging and the attentional visual field

2.1. The tunnel vision hypothesis

In a widely-used variant of the AVF task, subjects perform the central identification and peripheral localization tasks simultaneously, and experimenters measure performance decline in the peripheral task as a measure of the AVF. For example, Ball and colleagues (1988) asked young (less than 34 years old), middle-age (40-59 years old), and older (60 years or older) observers to make same-different judgments of schematic faces in the central visual field while localizing a target stimulus in the peripheral field. Localization performance declined with increasing retinal eccentricity of the target, more strongly for older than for young observers. These effects did not appear to result strictly from age-related sensory deficits, and the authors interpreted the result as evidence for an age-related constriction of the AVF. They further found that increasing the difficulty of the central task and increasing additional distractors within the display both raised error rates, suggesting that the size of the AVF varied with task demands and stimulus factors (Ball et al., 1988).

Normal aging limits visual performance in the periphery not only in the localization tasks, but also identification tasks as well. Scialfa and his colleagues (1987) presented one of target letters, T or O, and 0, 2, or 19 distractors (X) horizontally on a display, and asked young and older adults to identify the target letter (a two-alternative forced-choice task). The retinal eccentricity of the target stimuli and the number of the distractors varied across trials, and RTs and error rates served as dependent measures. Consistent with Ball et al. (1988)'s findings, older adults performed more poorly when the target appeared at more peripheral than central visual field, compared with young adults, and this age difference was more pronounced in the presence of the distractors than the absence. Slopes of the linear functions relating RTs to retinal eccentricity were greater for older than young adults when displays contained distractors, consistent with the proposal of age-related shrinkage of the AVF (Ball et al., 1988; Sekuler & Ball, 1986).

The presence of clutter is a crucial factor that impacts older adults' AVF performance more than young adults. Research on the relationship between aging and selective attention suggests that the ability to selectively attend to targets within clutter declines disproportionately for older adults than young adults even after controlling for the general slowing (McCarley, Yamani, Kramer, & Mounts, 2012) and for age-related reductions in parafoveal acuity (Plude & Hoyer, 1986). Clutter furthermore degraded the peripheral localization task performance in the conventional AVF paradigm for older more than young adults (Sekular & Ball, 1986; Ball et al., 1988), suggesting that visual noise particularly hinders the ability to divide attention across between different spatial locations at large retinal eccentricities.

These data as well as others (Ball, Owsley, & Beard, 1990) therefore suggest that normal aging accompanies progressively restricting AVF at the peripheral visual field that produces larger performance decrements for older adults, relative to young adults, an account referred to hereafter as *the tunnel vision hypothesis*.

2.2. The general inefficiency hypothesis

The tunnel vision hypothesis holds that older adults attentional performance is disproportionately compromised in the far visual eccentricity. However, recent studies have argued that age-related loss in the AVF are independent of eccentricity. For example, Seiple and his colleagues (1996) employed the conventional AVF task (e.g. Ball et al., 1988) where subjects in young, middle, or older age groups performed the central same-different judgment task on schematic face stimuli and the peripheral localization task at various levels of eccentricity. Their data were comparable with those of Ball et al. (1988): older adults demonstrated more difficulty in the peripheral localization task with increasing target eccentricity. A transformation of the error rate data to differences in error rates between young and older adults, however, eliminated the effect of eccentricity. The comparison between eccentricities on the difference scores allows a direct comparison of error rates that differs as a function of both age and eccentricity. The authors concluded that, because age difference on error rates in the localization task was similar across varying levels of eccentricity, the data supported *the general inefficiency hypothesis* over the tunnel vision hypothesis. The general inefficiency hypothesis states that 1) all subjects have perceptual and attentional loss at the periphery, because peripheral visual performance is generally poorer with increasing eccentricity, and 2) this inefficiency becomes further pronounced with normal aging *independent* of eccentricity.

Other researchers in a larger cross-sectional study (Sekuler, Bennett, & Mamelak, 2000) reached the same conclusion as Seiple et al. (1996). In the study, subjects, ranging from 15 to 84 years of age, performed the central identification task of a target letter and the peripheral localization task. They found that localization error increased at greater eccentricity in a focused attention condition (the localization task only). However, interestingly, while cost of dividing attention between the center and peripheral tasks increased in older age group, error rates remained similar at various eccentricity in the divided attention condition (the central identification and localization tasks concurrently). The lack of eccentricity-dependent performance decline for older adults thus support the general inefficiency hypothesis (e.g. Seiple et al., 1996).

Why did researchers in the previous studies manipulating eccentricity levels find inconsistent results on peripheral visual performance? As Sekuler et al. (2000) noted, when the presentation of distractors precedes the presentation of the target in the localization task, subjects showed smaller eccentricity effects than when the distractors and target appear simultaneously (e.g. Seiple et al., 1996). The distractors presented prior to the target might have allowed subjects to focus to the potential locations of the peripheral target, which might have minimized the effect of eccentricity. However, the difference scores between young and older at different eccentricities did not differ between the different presentations, and therefore the difference in experimental procedures does not account for the inconsistency. The authors in Sekuler et al. (2000) argue that older adults were able to extract information equally across the visual field, with age-related decline in dividing attention to the central and peripheral tasks, and that processing efficiency decreases with aging but this decrease is eccentricity-independent.

2.3. Limitations in the previous AVF research

As noted, studies in the AVF literature have conventionally used error rates (Sekuler & Ball, 1986; Ball et al., 1988; Scialfa & Kline, 1988; Williams, 1989; Ball et al., 1990; Seiple et al., 1990; Scialfa, Thomas, & Joffe, 1994; Sekuler et al., 2000; Richards et al., 2006; and others using the conventional AVF task), RTs (Williams, 1982; Cerella, 1985; Scialfa et al., 1987; Scialfa & Kline, 1988; Scialfa et al., 1994) and saccade number (Scialfa et al., 1994). The previous studies then took age by eccentricity interactions as evidence for age-related changes in the AVF. Unfortunately, choice of dependent measures in the AVF research has often been atheoretical, and generally such measures do not allow direct measurement of theoretic processing of interest (e.g. attentional limits at the visual periphery).

One constraint in the previous approach is that the researchers based their inference about age-related changes in the AVF on age by eccentricity interactions. Non-crossover interactions involving age do not necessarily provide evidence for age-specific changes in cognitive function because the interactions can disappear upon an appropriate nonlinear transformations (Loftus, 1978; Wagenmakers et al., 2012). This constraint is particularly problematic in the literature because theoretical difference between the tunnel vision hypothesis and the general inefficiency hypothesis centers on whether older adults exhibit poorer performance compared with young adults at increasing eccentricities. Because a transformation of the measurement scale can remove non-crossover interactions, theoretically grounded dependent measures are necessary for testing the existing models of the AVF. Furthermore, atheoretical dependent measures might allow inferences for the ordinal differences between experimental conditions, but do not support conclusions concerning magnitude of the differences between conditions.

Non-crossover interactions involving age can result due to not age-specific process change but global age-related changes such as general slowing (Salthouse, 1996) and sensory losses, complicating interpretations of the available data. The goal of cognitive aging research is to isolate specific cognitive processes that differ between younger and older populations while controlling for global cognitive changes such as age-related declines of processing speed (Kramer & Madden, 2008). Therefore, appropriate treatment of the data is necessary for inference about the impact of aging on perceptual-cognitive mechanisms that control the AVF performance beyond the effects of general slowing and age-related sensory losses.

Thus, the selection of theory-driven dependent measures and analyses are crucial for isolating age-specific perceptual-cognitive processes that limit visual performance. The current study directly measured levels of workload capacity at various eccentricities, which provide theoretical benchmarks of performance (e.g. Townsend & Nozawa, 1995. See Chapter 3 for more detail). Furthermore, workload capacity is a ratio of performance in single and dual target conditions, measuring the benefit of processing dual targets compared to processing a single target in the same experimental condition. Thus, workload capacity effectively removes the effects of general slowing and sensory losses and isolate perceptual/attentional processes, allowing a direct comparison of visual performance across young and older adults.

Chapter 3: Theoretical models of information processing system

Cognitive psychology aims to uncover mental information-processing mechanisms by examining the relationships between input stimuli and output behavior (c.f., Townsend, 1984). For human observers, input stimuli and output behavior are directly observable but the psychological mechanisms of information processing are not, causing the 'black box' problem. Experimental control of various factors, however, allows the isolation and characterization of specific psychological operations.

Generally, the information processing system can be considered a collection of inter-connected subsystems of channels processing specific elements of information. Townsend (1974) introduced a mathematically-oriented theoretical framework for characterizing such systems, involving four orthogonal dimensions: *independence, stopping rule, processing architecture,* and *capacity*. In the time since, he and his colleagues have also developed experimental paradigms suited for testing psychological process within each of the four dimension. Together, this theory and the accompanying methodology are known as *systems factorial technology (SFT)* (Townsend & Nozawa, 1995). By employing the paradigms suggested within this theoretical framework, it is possible to unveil the psychological mechanisms that underlie behaviors of the system. Following sections review qualitative and quantitative definitions related to the above framework, along with the currently available methodologies for evaluating systems along each of Townsend's four dimensions.

3.1. Independence

That two processes are independent can mean, at least, either *stochastic independence* or *perceptual independence* (c.f. Ashby & Townsend, 1986). These are not mutually exclusive concepts but signify different phenomena. Stochastic independence refers to the absence of probabilistic dependencies between two processors. For example, consider a model with two processing channels, A and B. Two processes are stochastically independent if the probability that processing in channel A has completed at a given time, *t*, is independent of the probability that channel B has completed at *t*, or

$$P(T_A < t) * P(T_B < t) = P(T_{AB} < t),$$

where $P(T_{AB} < t)$ denotes the probability that processes in both channel A and B complete by a time, t.

On the other hand, perceptual independence arises when perception of one component does not interact with perception of another in multi-dimensional stimuli (Ashby & Townsend, 1986). Ashby and Townsend (1986) offers a set of rigorous tests for perceptual independence within the framework of *general recognition theory* (GRT), a generalization of Gaussian signal detection theory (Green & Swets, 1966; Wickens, 2002). Specifically, one can employ a *complete identification task*, where two components of multidimensional stimuli are factorially manipulated (e.g. shape and color), and observer's identification performance can be analyzed in using GRT for testing independence between perceptual processes of the two components. Stochastic independence does not necessarily imply perceptual independence. Perceptual independence in fact requires that data satisfy a variety of tests such as perceptual separability, decisional separability, and sampling independence (Ashby & Townsend, 1986; Thomas, 1995).

3.2. Stopping rule

A stopping rule determines when the system terminates information processing operations and executes a response (Townsend, 1974; van Zandt & Townsend, 1993). If the system ceases to process as soon as it has found a target, the process is *self-terminating,* and when it ends processing as soon as a single items has finished processing (e.g., when all stimuli are redundant targets), it is more specifically called *first-terminating.* On the other hand, when the system processes all stimuli in order to execute a response, the process is called *exhaustive.* Target-present and target-absent trials in Sternberg's (1966) memory search experiment illustrate this distinction. In memory search tasks, a search set of items is presented to observers before the target item, and as soon as the target item is presented, observers must judge whether the search set contains the target item. On target-present trials, observers can terminate processing as soon as they find the target in memory (self-terminating processing) while they must scan all members of the search set in the target-absent trials (exhaustive processing). In his experiment, subjects produced parallel positive slopes of the search functions in the target present and absent trials, consistent with the exhaustive processing model, even though the task allowed self-termination (Sternberg, 1966).

If possible, the design of an experiment should stipulate which stopping rule the participant employs, because predictions of particular architecture or a paradigm for measuring capacity depend on stopping rules.

3.3. Processing architecture

Processing architecture characterizes the organization of mental processes as *serial, parallel,* or *co-active* (Townsend & Ashby, 1983; Townsend & Nozawa, 1995). In a serial model, the system processes only one item at a time, and only after completing one item can the system proceed to process another. In a parallel model, the system processes multiple items concurrently. In a co-active model, the system accumulates evidence from multiple concurrent channels and the evidence is summed in a single decisional threshold, producing a response when evidence value exceeds the threshold. Co-active processing therefore consolidates activation from multiple processors, and thus can enable a very high level of performance (e.g. fast and accurate).

SFT (SFT; Townsend, 1992; Townsend & Nozawa, 1995; Houpt & Townsend, 2010) extends Donder's (1868) subtractive logic, Sternberg's (1969) additive-factors method, Schweickert's trichomy theory (Schweickert & Townsend, 1989), and other stochastic modeling techniques (Townsend, 1984; Townsend & Ashby, 1983) to provide empirical methods for distinguishing mental architectures. Briefly, in order to dissociate psychological processing stages, both the subtractive and additive-factors methods assume strict seriality of psychological stages. The subtractive method assumes that subtracting RTs for a less complex task (e.g. simple reaction time task) from the RTs for a more complex task (e.g. disjunctive task) reflects the processing time for a particular cognitive stage of interest (e.g. stimulus categorization). The additive-factors method assumes, on the other hand, that an additivity of two independent variables indicates that the two variables affect different processing stages, and that an interaction suggests that the two variables affect the same processing stage. While the additive factors method is currently the most popular technique in dissociating psychological processes, it does not distinguish mental architectures but assumes seriality of individual mental processors.

In SFT, the assumption of serial arrangement of processors is relaxed, and the observed pattern of interactions or additivity between two factorially manipulated independent variables are taken as evidence for different mental architectures (e.g. Schweickert, 1978; Schweickert & Townsend, 1989). Different models predict specific patterns of mean and survivor interaction contrasts (ICs). Mean IC (MIC) is defined as

$$MIC = RT_{1,1} - RT_{2,1} - RT_{1,2} + RT_{2,2},$$

where the first subscript denotes the level of one independent variable and the second for the other variable, and *RT* denotes mean RT in each condition. The survivor IC is based on survivor functions. The survivor function, $S(t)$, represents the probability that the system processes information at a time, t, given that the system has not processed yet, or

$$S(t) = P(T > t) = 1 - P(T < t) = 1 - F(t),\ t > 0,$$

where T represents a time that the system completes processing of information and $F(t)$ is the cumulative distribution function of the RT distribution. Thus, the survivor IC is defined as

$$SIC(t) = S_{1,1}(t) - S_{2,1}(t) - S_{1,2}(t) + S_{2,2}(t),\ t > 0,$$

For serial models, a self-terminating serial model predicts zero (additivity) in mean IC and zero in survivor ICs while an exhaustive serial model predicts zero (additivity) in mean IC and a shift from negative to positive survivor ICs. For parallel models, a self-terminating parallel model predicts positive mean IC (overadditivity) and positive survivor ICs, while an exhaustive parallel model predicts negative mean IC (underadditivity) and negative survivor ICs. A co-active model predicts positive mean IC and a survivor IC that shifts from negative values at small t to positive values at later times.

An experimental paradigm utilizing the SFT can determine mental architecture of a psychological effect of interest. Furthermore, this method avoids the problem of *parallel-serial model mimicry* (Townsend, 1974; Townsend & Ashby, 1983; Townsend, 1990), a mathematical possibility that parallel models mimic predictions of serial models even at RT distribution level. Thus, the SFT provides a powerful tool to distinguish processing architectures under study.

3.4. Capacity

Capacity is the amount of information that a perceptual-cognitive system can process at once. The notion of capacity is prevalent in the literature of attention (e.g. Kahneman, 1973; Navon, 1984; Navon & Gopher, 1979), but it is often defined without quantitative rigor. The mathematical psychology literature, however, has distinguished two types of capacity measures, *processing capacity* (e.g. Wenger & Gibson, 2004) and *workload capacity* (e.g. Wenger & Townsend, 2000; 2004).

3.4.1. Processing capacity

The central idea of processing capacity is to measure the system's ability to process information instantaneously (Townsend & Ashby, 1978). Previous mathematical works (Townsend & Ashby, 1978; Wenger & Gibson, 2004) indicate that the *hazard function* on the RT distribution characterizes this construct well (Townsend & Ashby, 1978). The hazard function is defined as

$$h(t) = f(t)/S(t),$$

where the probability density function of the RT distribution, $f(t)$, is divided by the survivor function, $S(t)$, as defined above. Essentially, the hazard function indicates the probability that the system completes the task in the next moment, given that it has not been completed yet. Note that $h(t) > 0$ when the system is processing at time t but $h(t)$ is undefined once it completes the task because $S(t) = 0$ at task completion. To better capture the cumulative amount of mental work that the system completes at a time, the *integrated hazard function,*

$$H(t) = \int_{t'=0}^{t} h(t')dt',$$

can be derived from the hazard function and possess the desired characteristics of the cumulative capacity measure (Wenger & Gibson, 2004). The integrated hazard function represents the likelihood of the system processing information in the next moment, given that it has not yet processed it, which can be interpreted as the cumulative amount of 'energy' expended in generating a particular response at a certain latency (Townsend & Ashby, 1978). Note that $H(t) > 0$ for all ts, and the value of $H(t)$ at extremely long processing duration becomes extremely large, showing that a processor continues working until it finishes the task if allowed. It is important to note that the integrated hazard function measures processing capacity at a relatively global level of analysis. That is, processing capacity measure considers only the total completion time for a task, not the completion times of individual sub-processors that contribute to the total task completion time such as registration of visual image, decision, and execution of the motor response (Wenger & Gibson, 2004), while workload capacity coefficients (see below) index a level of workload capacity at each RT bin, providing a time-sensitive measure of capacity.

In practice, the ordering of hazard functions, estimated from empirical RT distributions, measures processing capacity of one condition relative to another (Townsend, 1990; Wenger & Gibson, 2004). The analysis of processing capacity therefore provides evidence for superior performance on one condition than another at RT distribution level, which analysis of mean RTs does not allow. In the study of the AVF, the analysis of processing capacity could be applied to RT distributions at various retinal eccentricities, examining whether the increase of mean RT as a function of eccentricities is due to processing capacity decrease observable at the RT distribution level. This approach would confirm that the eccentricity effect on RTs for young and older subjects is not totally driven by some extreme RTs, skewing the overall shapes of the distributions and therefore affecting the mean RTs.

3.4.2. Workload capacity

Another technique to measure the system's capacity is to investigate whether and how information in one channel(s) affects processing rate in another channel. That is, capacity is measured relative to changes in processing load (e.g., number of items to be processed), and thus the measure is termed *workload capacity.* Consider an independent channel, self-terminating, parallel model (the parallel horse-race model; Raab, 1962; Miller, 1982) in which the system processes information in two independent channels concurrently and whichever channel finishes processing first determines the response of the system. Within this model, *unlimited-capacity* processing means that processing on one information channel does not affect that on another channel. *Limited-capacity* processing means that processing on one channel slows that on another, and if the summed amount of information being processed is fixed, the processing is called *fixed-capacity* processing. Finally, processing on one channel facilitates (or speeds) processing on another, which is referred as *super-capacity* processing.

An experimental paradigm suitable for measuring workload capacity is the *redundant-targets paradigm* (e.g. Garner & Felfoldy, 1970; van der Heijden, La Heij, & Boer, 1983; Egeth & Dagenbach, 1991; Wenger & Townsend, 2000; Ben-David & Algom, 2009; Mordkoff & Yantis, 1991, 1993; also double-factorial paradigm, Townsend & Nozawa, 1995), where subjects respond to a target item which can appear singly or redundantly. With the assumption of unlimited capacity processing,

$$H_{1,2}(t) = H_1(t) + H_2(t),\ t > 0,$$

in an independent parallel horse-race model (Raab, 1962), because the amount of information processed in two different channels is equal to the sum of those in the two channels at a given time. With the self-terminating stopping rule, an index of workload capacity is *Townsend's capacity coefficient* (Townsend & Nozawa, 1995; Wenger & Townsend, 2000), or *C(t)*. This measure is a ratio of the integrated hazard function on the redundant condition to the sum of the integrated hazard functions of the single conditions (derived from the equation above), or

$$C(t) = H_{1,2}(t) / [H_1(t) + H_2(t)],\ t > 0.$$

Therefore, this index is equal to one when processing is capacity unlimited, less than zero when capacity limited and 0.5 when capacity-fixed. When capacity is fixed, performance on the redundant condition is equivalent to that on the single condition. The index is greater than one under super-capacity processing. Since the capacity coefficient is calculated at each RT bin, the analysis provides the workload capacity as a function of RT, time course of workload capacity of a system.

If stochastic independence holds (see *Independence* section above), data must meet two inequalities, *Miller's inequality* for the upper bound of performance (e.g. Miller, 1983) and *Grice inequality* for the lower bound of performance (e.g., Grice, Canham, & Boroughs, 1984) in order to be consistent with an independent parallel model. Miller's inequality provides the upper limit of performance that the independent self-terminating parallel model can achieve, holding that

$$P_{1,2}(T_1 \leq t \text{ OR } T_2 \leq t) = P_{1,2}[\min(T_1, T_2) \leq t] \leq P_1(T_1 \leq t) + P_2(T_2 \leq t),\ t > 0.$$

A violation of Miller's inequality (performance exceeds the predictions of Miller's inequality) indicates a departure from the independent parallel model to either a parallel model with facilitatory interactions between channels (Mordkoff & Yantis, 1991; Townsend & Wenger,

2004) or a co-active model (Miller, 1983; Townsend & Nozawa, 1995; Gondan, Riehl, & Blurton, 2011; Mordkoff & Miller, 1993). Data are consistent with the parallel horse-race model when satisfying Miller's inequality. Therefore, redundant-targets effects that do not violate Miller's inequality are likely due to *statistical facilitation* of independent channels of signal processing (Raab, 1962). Grice's inequality (Grice, et al., 1984), on the other hand, sets the lower band of performance predicted by the independent parallel model. It states that

$$max\ [P_1(T_1 \leq t), P_2(T_2 \leq t)] \leq P_{1,2}(T_1 \leq t\ OR\ T_2 \leq t), t > 0.$$

A violation of Grice's inequality suggests a departure from the independent parallel model to a parallel model with extremely limited capacity or inhibitory interactions between channels (Townsend & Wenger, 2004). When Grice's inequality is violated, the system's performance can be close to the level of *fixed capacity,* formally defined as

$$H_{1,2}(t) = 1 / 2[H_1(t) + H_2(t)], t > 0.$$

Recently, boundaries derived from theoretical predictions of the independent parallel model have been extended from a self-terminating (OR) task to an exhaustive (AND) task (Townsend & Eidels, 2011) and workload capacity coefficient in the AND task has been developed[1] (Townsend & Wenger, 2004). In practice, any violation of the inequalities could indicate that the data do not meet the assumptions of the independent parallel race model. The violation of Miller's inequality in the redundant-targets paradigm is often taken as evidence for co-activation (Miller, 1983; Mordkoff & Miller, 1993; Miller, Beutinger, & Ulrich, 2009), leading super-capacity processing. Under severe violations of the inequalities, processing

[1] Capacity coefficient with exhaustive stopping rule, $C(t)_{AND}$, is defined as $C(t)_{AND} = [K_1(t) + K_2(t)]/K_{1,2}(t)$, where the function K(t) is a *reverse hazard function* (Chechile, 2003) analogous to the hazard function with self-terminating stopping rule. Specifically, $K(t) = f(t)/F(t)$ indicating the probability that the system has just completed processing at time t, given that processing completes at or before t (Townsend & Eidels, 2011).

architecture and stochastic independence can be clarified by the SFT method (Townsend & Nozawa, 1995) or experimentation using the GRT (Townsend & Ashby, 1986), respectively.

3.5. Application to AVF research

Thus far, four orthogonal concepts of information processing system have been introduced in detail. The orthogonality of the concepts indicates that any combination of the four concepts represents a specific processing model, such as independent, first-terminating, parallel, capacity-unlimited processing. Identification of a specific processing system may therefore help understanding what causes age-related constriction of the AVF. As briefly discussed above, the SFT method and redundant-target paradigm can unveil processing architecture and workload capacity, respectively. Such analytic methodology that allows mathematical analysis and modeling has not been applied in previous studies of the AVF. Not only methodologically, but also theoretically, this approach is novel in the literature because it helps identifying specific information-processing mechanisms that underlie age-related changes in AVF performance as discussed in the following chapter, while controlling for the influence of the general age-related sensory loss (e.g. Pitts, 1982; Allen, Weber, & Madden, 1994) and slowing of psychomotor processes (e.g. Brinley, 1965; Madden 2001; Salthouse, 2000).

Chapter 4: Summary and hypotheses

Previous research on the AVF has often employed dependent measures not well-tailored for testing theories of age-related narrowing of the AVF. As mentioned above, the workload capacity coefficient, $C(t)$, circumvents the effects of sensory loss and general slowing and provides benchmarks of performance of an information-processing system. In the current work, a series of experiments tested four hypotheses that predict differential patterns of capacity levels at varying retinal eccentricities and clutter. The experiments utilized the redundant-targets paradigm or its variant in order to measure workload capacity at various levels of retinal eccentricity.

4.1. Novelty of the current approach

This experiment is novel in the context of AVF research in at least three ways. First, the current experimental design will allow a direct examination of visual processing capacity levels at varying eccentricities and clutter. Second, it will reveal how aging relates to changes in the workload capacity. Third, it will entail analysis of entire empirical RT distributions, allowing increased statistical power (e.g. Townsend, 1990) relative to conventional measures of AVF performance.

4.2. The tunnel vision hypothesis

Previous studies found that older adults' visual performance was disproportionately worse at the peripheral visual field compared with young adults, and suggested age-driven AVF narrowing (Ball et al., 1988; Scialfa et al., 1987). Reflecting this idea, *the tunnel vision hypothesis* predicts that older adults will show more difficulty processing information at the visual periphery, exhibiting lower workload capacity scores in the peripheral than the central visual field.

4.3. The general inefficiency hypothesis

The general inefficiency hypothesis predicts that older adults have a capacity loss that is not selective for the visual periphery and the presence of clutter. The current task measures performance benefit in the redundant-target condition relative to the single-target condition. However, the ability to divide attention in two spatial locations appears to decline with aging. For example, Bucur and her colleagues (2005) asked young and older subjects perform a go/no-go task. The target dimensions were color and letter, purple and K, and the subjects were instructed to execute a response when they saw either or both target characteristics (purple letters, Ks in any color, or a purple K) and withhold for the other combinations on a color and a letter. The two target features could be part of the same object (focused condition) or different objects (divided condition; e.g. Mordkoff & Yantis, 1993). The magnitude of the redundant-target effect (RTE) of was larger in the focused condition than the divided condition for older adults, while young adults show a trend in the opposite direction. Thus, the data suggested an age-related decline in the ability to divide attention between different spatial locations, consistent with the previous findings (e.g. Maylor & Lavie, 1998; Plude & Doussard-Roosevelt, 1989; Plude & Hoyer, 1986). Thus, the general inefficiency hypothesis predicts lower capacity scores in general, not specifically in the visual periphery and/or clutter, for older than young adults, because older adults are less able to divide spatial attention and integrate information from the different locations.

4.4. The age equivalence hypothesis

The age equivalence hypothesis states that the ability to efficiently process information from multiple locations is preserved with normal aging. Preservation of attentional abilities for older adults can be found in the literature of visual attention (e.g. Madden, 2007, Madden & Kramer, 2004), but it remains unknown whether the aging visual system can efficiently process redundant information across the visual field. The previous AVF research conflates effects of attentional loss and effects of age-related global changes such as general slowing and sensory loss, and thus it is possible that the age-related decline in peripheral performance in the AVF literature reflects generalized slowing effect and/or age-related sensory losses but not attentional processes.

4.5. The inverse effectiveness hypothesis

The inverse effectiveness hypothesis states that the gain of information from multiple channels is larger when single channels are less effective themselves (e.g. Stein & Meredith, 1993; Laurienti, Burdette, Maldjian, & Wallace, 2006; Hugenschmidt, Mozolic, & Laurienti, 2009). One piece of support for this hypothesis comes from a study that investigated relationships between aging and multi-sensory integration (Winneke & Phillips, 2011). Winneke and his colleague (2011) examined whether audiovisual (AV) stimuli can improve speech perception for older and young adults, while recording event-related potentials (ERPs) to investigate age-related difference in the neural processes underlying perception of the AV stimuli. Young and older subjects performed a speeded discrimination task, indicating whether each stimulus, presented in aurally, visually, or both, was a natural or artificial object. Analysis of RT distributions indicated the benefit of AV speech was equivalent for older and young adults[2]. Strikingly, however, AV presentation reduced amplitudes of the auditory P1 and N1 ERP

[2] In a bimodal target detection task, both young and older adults can respond faster to a bimodal target than a unimodal target and showed violations of Miller's race model inequality. Thus, the data indicate the preservation of coactive processing for the integration of multisensory information in older adults (Bucur, Allen, Sanders, Ruthruff, & Murphy, 2005).

components[3], compared with the auditory only condition, and did so disproportionately larger for older than young adults. The authors interpreted the disproportionate reduction in older adults as evidence of multi-sensory efficiency: fewer neural resources were recruited for older than young adults when integrating multi-sensory information, allowing the older adults to use visual speech cues more effectively to improve auditory speech processing, compared with the young adults. Behaviorally, Laurienti and colleagues (2006) demonstrated that older adults were generally slower than young adults in a target discrimination task, but relative benefit of AV stimuli compared to unimodal stimuli (visual or auditory only) was larger for older than young adults (also Hugenschmidt et al., 2009).

In the current context, due to age-related decline of performance in single channels at the visual periphery (e.g. Ball et al., 1988) and in clutter (e.g. Allen, Madden, Groth, & Crozier, 1992), older adults might benefit more from the redundant targets than young adults. Therefore, the inverse effectiveness hypothesis predicts that workload capacity will be greater in the peripheral than the central visual field and in the cluttered than the uncluttered displays, and this benefit will be disproportionately larger for older than young adults.

[3] The auditory N1 and P1 components are members of the P1-N1-P2 complex, a sequence of obligatory brain response for auditory stimuli. The N1 is functionally linked with stimulus detection and encoding of properties of auditory stimuli (Naatanen & Picton, 1987). On the other hand, the P1 is thought to reflect earlier processes in subcortical areas such as the reticular activating system (Erwin & Buchwald, 1987).

Chapter 5: Experiment 1

Older adults seem to show disproportionate difficulty in dividing attention across the visual field (Ball et al., 1988), an effect that is often interpreted as an age-related constriction of the AVF. There are at least two limitations of the common approach of using atheoretical dependent variables such as error rates in the AVF research. First, these measures correspond only indirectly to theoretic concepts of interest. For example, the increase in error rates in the visual periphery might reflect decreases in visual processing capacity, but do not directly gauge the magnitude of capacity limitations. Second, while the previous studies base the claim of the age-related narrowing of the AVF on age by eccentricity interactions on error rates or RTs, transformation of these measurements can remove such non-crossover interactions (Wagenmakers, et al., 2012; Verhaeghen, 2000). That is, in the context of the AVF research, the lack of crossover interactions involving age on an atheoretical measurement (e.g. error rates) could mistakenly imply age-related differences when there are none.

To address these limitations, the current experiment directly measured processing efficiency across the visual field in older and young adults using the workload capacity coefficient, $C(t)$ (Townsend & Nozawa, 1995; Wenger & Townsend, 2000). The capacity coefficient, an element of Townsend's system's factorial technology (see Chapter 3), provides theoretically-rooted benchmarks of efficiency for information-processing systems. Additionally, because the coefficient is a ratio between redundant-target to single-target performance measures, it effectively divides out the effects of general slowing and sensory losses on age-related performance.

In the current experiment, 8 young and 8 older adults made a speeded identification judgments of colored target letters. Targets were presented either singly or redundantly, and appeared at various retinal eccentricities with or without the presence of gray distractors. Analyses gauged workload capacity at various retinal eccentricities in displays with and without clutter, to test four competing hypotheses, the tunnel vision hypothesis, the general capacity reduction hypothesis, the age equivalence hypothesis, and the inverse effectiveness hypothesis.

5.1. Methods

Subjects

Subjects were 8 young adults (4 female; mean age = 21.4 years, SD = 2.7; mean years of education = 14.8, SD = 2.6; mean corrected far acuity = 16/20, SD = 2.4; mean corrected near acuity = 20/20, SD = 0) and 8 older adults (4 female; mean age = 74.0 years, SD = 5.0; mean years of education = 13.6, SD = 1.9; mean corrected far acuity = 23.8/20, SD = 4.2; mean corrected near acuity = 23.8/20, SD = 7.0) recruited from the community of the University of Illinois at Urbana-Champaign. All were screened for normal color vision with the Ishihara color blindness test (1989). All subjects were naive to the purpose of the experiment. All were paid for participation.

Apparatus

Stimuli were presented on a 19'' CRT monitor set to a resolution of 1024 X 768 pixel and a frame rate of 75 Hz. The experiment was controlled by E-Prime 1.1 (Psychology Software Tools, Pittsburgh, PA). Responses were made via a response box. Subjects viewed the screen at distance of 57 cm held fixed by a chin rest. The experiment was conducted in a quiet room with dimmed lights.

Stimuli

Stimuli were letters X and O, 1.38° X 1.38° of visual angle and drawn in stroke of .07°. A display contained one or two target(s) drawn in red (9.0 cd/m^2, x = .64, y = .33) and distractors were drawn in gray (6.5 cd/m^2). Stimuli were presented on a black background and with a .17° fixation cross at the center. Locations for target(s) were 2.0° (near), 6.0° (middle), or 10.0° (far) from the center of the display. Either X or O appeared on the display on single trials, and two Xs or Os appeared on redundant trials. On redundant trials, one target appeared in the upper visual field (UVF) and one in the lower visual field (LVF). On no-clutter trials, target(s) appeared alone. On clutter trials, randomly chosen distractors were additionally presented on all the remaining vertical locations and two distractors always flanked each target letter. The vertical alignment was chosen to minimize a potential confound of the Simon effect (Simon, 1969).

Procedure

Figure 1 A and B present sample displays from the redundant targets condition at the middle eccentricity without and with clutter, respectively. Subjects made a speeded discrimination judgment of target identity by pressing the left key for Xs and the right key for Os on a response box. The subjects were instructed to ignore the distractors, and to make their responses as quickly as possible while maintaining at least 95% accuracy.

Figure 1C illustrates the time course of a trial. Each trial began with a 500 ms blank screen, followed by a fixation display for 400 ms. Then, the imperative display appeared and remained visible until a response was detected or a timeout was reached during the first warm-up block. The exposure duration of the imperative display was limited to 200 ms in order to discourage eye movements during the experimental blocks. Trials ended when a response was detected or the timeout of 2,500 ms was reached. Trials with no response were counted as incorrect responses. A feedback message of gray “+” for a correct response or “x” for an incorrect response was presented for 750 ms at the end of each trial. The next trial started immediately after the feedback display.

Each block contained an equal number of trials for all combinations of target identity (X or O), the number of target (one or two), eccentricity (near, middle, or far), and clutter condition (present or absent). Each subject completed 6 experimental sessions in order to provide data sufficient for analysis of workload capacity based on RT distributions. An experimental session consisted of 1 block of warm-up trials and 12 blocks of 72 experimental trials each. The order of trials within a block was randomized. Subjects were allowed to rest between blocks. Each experimental session lasted approximately 40 minutes.

5.2. Results

For analyses of mean RTs and C(t), trials with incorrect responses were excluded. Preliminary analyses only included the single-target trials and revealed two significant interaction involving age, the three-way interaction of age, eccentricity (near, middle, vs. far) and single-target condition (UVF vs. LVF) and the four-way interaction of age, eccentricity, single-target condition, and clutter (no clutter vs. clutter). RTs were longer for targets in LVF than for those in UVF and this difference was larger at larger eccentricities for older adults, but the difference between UVF and LVF was not reliable for young adults. Furthermore, this data pattern was more pronounced in displays with clutter than without.

To simplify exposition, the analyses below collapsed over UVF and LVF to the single target condition.

Mean RTs and error rates were submitted to separate mixed-model analyses of variance (ANOVAs) with age group (young vs. older) as a between-subject factor and eccentricity (near vs. middle vs. far), clutter (present vs. absent), and target condition (single vs. dual) as within-subject factors. Greenhouse-Geisser corrections for the violation of the sphericity assumption were applied where appropriate.

5.2.1. RTs

Figure 2 presents mean RTs as a function of target condition, eccentricity, and clutter for young subjects and Figure 3 presents the same data for older subjects. As expected, older subjects produced reliably longer RTs than young subjects [$F(1,14) = 10.68$, $p < .01$, $MSE = 45804.20$, $\eta^2_p = .43$], and RTs were longer when the display contained clutter than when it did not [$F(1,14) = 230.80$, $p < .01$, $MSE = 1341.20$, $\eta^2_p = .94$]. Consistent with earlier findings, furthermore, the effect of clutter was more pronounced for older than for young adults [$F(1, 14) = 6.61$, $p =.02$, $MSE = 1341.20$, $\eta^2_p = .32$]. RTs also grew longer as the retinal eccentricity of the target(s) increased [$F(2, 28) = 196.87$, $p < .01$, $MSE = 451.99$, $\eta^2_p = .93$]. Additionally, the increase of RTs with eccentricity was greater with clutter than without [$F(1.44, 20.19) = 96.64$, $p < .01$, $MSE = 519.44$, $\eta^2_p = .87$], and the interaction of clutter by eccentricity was reliably larger for older than young subjects [$F(1.44, 20.19) = 4.17$, $p = .041$, $\eta^2_p = .23$]. Expectedly, the RT increase due to retinal eccentricity was more pronounced for older than young subjects [$F(2, 28) = 11.66$, $p < .01$, $MSE = 451.99$, $\eta^2_p = .45$].

Finally, data showed a clear redundancy gain, [M = 304 ms vs. 322 ms; $F(1, 14) = 47.71$, $p < .01$, $MSE = 309.10$, $\eta^2_p = .77$] that was larger for older than young adults [$F(1, 14) = 6.82$, $p = .02$, $MSE = 309.10$, $\eta^2_p = .32$]. Faster RTs in the redundant- than the single-target conditions suggest that subjects employed the self-terminating stopping rule. The exhaustive models predict that RTs in the redundant-target condition would be longer than the single-target conditions because a response is executed only when subjects identify both targets, and the pattern of responses in the current experiment is the opposite of the prediction. Consistent with the inverse effectiveness hypothesis, the effect of redundant targets was larger in displays with clutter than without [$F(1, 14) = 22.09$, $p < .01$, $MSE = 108.04$, $\eta^2_p = .61$], and this two-way interaction effect of target condition by clutter was greater for older than young adults [$F(1, 14) = 6.31$, $p = .02$, MSE = 108.47.10, $\eta^2_p = .31$].

As further supports for the inverse effectiveness hypothesis, the redundancy gain became greater as retinal eccentricity increased [$F(1, 14) = 16.10$, $p < .01$, $MSE = 73.38$, $\eta^2_p = .53$]. This interactive effect was further greater in the presence of clutter than in the absence [$F(2, 28) = 5.14$, $p =.01$, $MSE = 50.00$, $\eta^2_p = .26$] and was marginally greater for older than young observers [$F(2, 28) = 3.01$, $p = .06$, $MSE = 73.38$, $\eta^2_p = .17$]. The four-way interaction was not reliable [$p = .29$].

5.2.2. Error rates

Error rates were analyzed to test for evidence of speed-accuracy tradeoffs. Figure 4 presents mean error rates as a function of retinal eccentricity for the no-clutter and clutter conditions for young adults, and Figure 5 for older adults. Young and older adults produced similar error rates (M = .03 vs. .04, for young and older adults, respectively) [$F(1,14) = 1.22$, n.s.]. Displays with clutter produced greater error rates than ones without [$F(1,14) = 30.59$, $p < .01$, $MSE = .002$, $\eta^2_p = .68$], and the presence of clutter compromised older adults' accuracy more than young adults [$F(1,14) = 7.22$, $p = .01$, $MSE = .002$, $\eta^2_p = .34$]. Error rates progressively increased with the increase in retinal eccentricity [$F(1.14, 16.03) = 38.04$, $p < .01$, $MSE = .002$, $\eta^2_p = .73$], and the effect of eccentricity was greater when clutter was present than when it was absent [$F(1.11, 15.64) = 36.94$, $p < .01$, $MSE = .002$, $\eta^2_p = .72$] and for older than young observers [$F(1.14, 16.03) = 12.81$, $p < .01$, $MSE = .002$, $\eta^2_p = .47$]. The redundant-target condition produced smaller error rates than the single-target conditions [$F(1, 14) = 60.87$, $p < .01$, $MSE = .0002$, $\eta^2_p = .81$], and this effect was amplified in clutter [$F(1, 14) = 30.39$, $p < .01$, $MSE = .0002$, $\eta^2_p = .68$], with increasing levels of eccentricity [$F(1.62, 22.71) = 22.29$, $p < .01$, $MSE = .0001$, $\eta^2_p = .49$], and for older than young adults [$F(1, 14) = 5.47$, $p =.03$, $MSE = .0002$, $\eta^2_p = .28$]. Aging increased the magnitude of the interaction of clutter by eccentricity [$F(1.11, 15.64) = 14.00$, $p < .01$, $MSE = .002$, $\eta^2_p = .50$] and of condition by eccentricity [$F(1.62, 22.71) = 13.51$, $p < .01$, $MSE = .0001$, $\eta^2_p = .49$]. The effect of three-way interaction between clutter by eccentricity by condition was reliable [$F(1.37, 19.20) = 15.63$, $p < .01$, $MSE = .0002$, $\eta^2_p = .52$], indicating that the benefit of the redundant-target condition increased with greater levels of eccentricity and this increase was greater with heavy clutter. Furthermore, the three-way interaction effect was larger for older than young adults [$F(1.37, 19.20) = 5.53$, $p < =.21$, $MSE = .0002$, $\eta^2_p = .28$]. The three-way interaction of clutter by condition by age was not reliable [$p = .19$]. Overall, the data provide no evidence of speed-accuracy tradeoffs.

5.2.3. Analysis of workload capacity coefficients

For analysis of RT distributions, RTs from each experimental condition were sorted into 10 ms bins. The integrated hazard functions were approximated based on the empirical cumulative distribution functions (CDFs) with top and bottom 5% removed and $C(t)$ was calculated for each RT bin according to the equation described in the section 2.1.2. Values were calculated separately for all combinations of clutter and target eccentricity.

For analysis, geometric means of the capacity coefficient over time were calculated for each subject and entered to a mixed-model ANOVA with age group (young vs. older) as a between-subject factor and eccentricity (near vs. middle vs. far) and clutter (present vs. absent) as within-subject factors. Figure 6 presents geometric means of workload capacity as a function of eccentricity for the no-clutter and clutter conditions for young (top) and older subjects (bottom). In general, older adults exhibited greater levels of workload capacity than young adults (M = .55 vs. .62) [$F(1.14) = 12.97$, $p < .01$, $MSE = .009$, $\eta^2_p = .48$], showing age-related benefit in the efficiency of redundant-target processing. Consistent with the inverse effectiveness hypothesis, furthermore, workload capacity increased when targets were presented in clutter (M = .55 vs. .62) [$F(1, 14) = 32.11$, $p < .01$, $MSE = .003$, $\eta^2_p = .69$], and the magnitude of this effect was greater for older than young subjects [$F(1, 14) = 6.87$, $p = .02$, $MSE = .004$, $\eta^2_p = .32$]. Moreover, workload capacity reliably increased with target eccentricity [$F(2, 28) = 8.16$, $p < .01$, $MSE = .004$, $\eta^2_p = .36$]. The effect of eccentricity manipulation tended to be larger in cluttered than uncluttered display, but the interaction fell short of significance [[$F(2, 28) = 2.63$, $p = .08$, $MSE = .003$, $\eta^2_p = .15$]

The three-way interaction, however, was reliable [$F(2, 28) = 4.96$, $p = .01$, $MSE = .003$, $\eta^2_p = .21$]. A series of one-way ANOVAs with eccentricity as the factor, conducted separately for each combination of age group and clutter, explored this interaction. For older adults, workload capacity increased with retinal eccentricity in uncluttered [$F(2,14) = 6.44$, $p = .01$, $MSE = .005$, $\eta^2_p = .46$], and increased marginally with eccentricity in cluttered displays [$F(2,14) = 3.42$, $p = .$

06, *MSE* = .006, η^2_p = .32]. For young subjects, on the other hand, capacity was progressively greater at the visual periphery than center in cluttered displays [$F(1.15, 8.10) = 6.39$, $p = .03$, *MSE* = .003, η^2_p = .47] but not in displays without clutter [$F < .17$, n.s.]. Thus, the three-way interaction was driven by the lack of eccentricity effect on the uncluttered condition for young adults. The remaining interaction of Eccentricity by Age was not reliable [$F(2, 28) = 1.51$, $p = .23$].

5.3. Discussion

The present experiment examined the impact of aging on the AVF by directly measuring the workload capacity at different retinal eccentricities. Young and older subjects made a speeded discrimination of a single or redundant target letter(s) presented with or without clutter at varying eccentricities.

Surprisingly, workload capacity was higher in the more difficult conditions—specifically, at far eccentricities and in clutter—than in easier conditions, and the effect of clutter was more pronounced for older than young adults. This is consistent with the inverse effectiveness hypothesis, while disconfirming the capacity reduction hypothesis. Workload capacity here measures relative efficiency of processing redundant visual information from multiple sources compared with a single source. Therefore, the current results suggest that the visual system utilizes redundant information from two separate channels more efficiently in more visually demanding environments, and this may serve as a form of compensatory strategy for older adults.

The age-related *benefit* for processing redundant targets in more difficult conditions is counterintuitive because the previous literature on the AVF and aging suggests age-related performance decline in either at the periphery (e.g. Ball et al., 1988) or uniformly across the visual field (Seiple et al., 1996). While controlling for the effects of sensory ocular deficit and general slowing that accompany normal aging, thus isolating the effects of attentive processing, the present results provide novel insights on the aging attentional system operates across the visual field.

The current data concord with the inverse efficiency, but do not provide a specific account of how subjects achieved higher capacity in the difficult conditions. One possibility is that subjects took advantage of inter-target contingencies. In the interacting channels model (Mordkoff & Yantis, 1991, 1993; Mordkoff & Egeth, 1993), processing channels can exchange information each other, facilitating perceptual processing of both channels. The model assumes *intertarget crosstalk,* allowing that information for identification of a target on one channel influences the identification process of another channel. Correlations among the possible target identity, or *interstimulus contingencies,* influences whether or not intertarget crosstalk occurs. In the current experiment, identical targets were always presented on the redundant-targets condition, and it is therefore possible that the information exchange occurred because of the contingency-based advantage.[4] For example, it is possible that one channel facilitates processing on the basis of information received from another channel (e.g. target feature), speeding overall RTs of the system in the redundant-target condition.

However, the data are also consistent with a limited-capacity parallel independent-channel model of information processing (Raab, 1962). Across conditions, mean C(t) was well

[4] The interactive channels model predicts super-capacity processing because one channel identifies a target using information fed by the other channel often faster than processing in a single channel only. The current data in general show limited-capacity processing. This result can be modeled with negative dependency between the two channels (Townsend & Wenger, 2004).

below 1.0, showing limited capacity processing. Given evidence that a co-active architecture can produce limited capacity processing only if processing on individual channels is dramatically slowed by increasing load (Townsend & Wenger, 2004), the C(t) values observed in the data make a co-active architecture in the current circumstances very unlikely. Raab's independent-channels model assumes that a parallel horse race of independent channels in processing information. Given a first-terminating stopping rule, whichever channel finishes processing determines a response. Thus, this model explains the increase of capacity as more efficient concurrent processing of information in visually demanding environments.

Experiment 2 tested whether the age-related benefit in the attention-demanding difficult conditions obtains due to the inter-target contingencies.

Chapter 6. Experiment 2

Experiment 1 gauged workload capacity across different retinal eccentricities and clutter levels for young and older adults to examine how normal aging impacts the ability to divide attention over multiple streams of visual information. Consistent with the inverse effectiveness hypothesis (Stein & Meredith, 1993; Winneke & Phillips, 2011), workload capacity levels increased at the peripheral visual field and in the cluttered displays. Furthermore, contrary to the findings in the previous AVF research, the data suggest older adults' ability to more efficiently process information from multiple concurrent source.

The purpose of Experiment 2 was to investigate how the older adults achieved higher workload capacity than the young adults in Experiment 1. One possibility is that older adults took advantage of intertarget contingencies. That is, more efficient processing of redundant visual information for older adults than young adults might have arisen due to interconnected channels exchanging perceptual information, biasing identification process of each stimulus (Mordkoff & Yantis, 1991). Similarly, both young and older adults might have utilized intertarget contingencies for achieving higher capacity in the difficult conditions.

An alternative model is a limited-capacity independent parallel model (Raab 1962). According to this model, capacity increases in the difficult conditions because the processing speed in the single-target condition is lower in the difficult than easy conditions while that in the redundant-target condition does not decrease as much as in the single-target condition. Since workload capacity is a relative measure, a slow-down of the channels in the single-target conditions more than that in the redundant-target condition will increase overall capacity level in more difficult conditions. Experiment 1 did not distinguish these possibilities.

Experiment 2 removed the intertarget contingencies present in Experiment 1, providing a test of the interacting channels model. To do this, Experiment 2 included mixed trials in which colored targets differed in identity (e.g. a trial with a colored X and a colored O). The mixed trials occurred as frequently as the redundant trials, and the relative frequency of mixed and redundant trials removed the intertarget contingency in Experiment 2. Thus, with the intertarget contingencies removed, subjects in Experiment 2 could no longer employ the compensatory strategy of biasing processing of one channel based on information from the other channel. Therefore, the interactive channels model predicts no capacity increase in the cluttered and far conditions compared with the no-clutter and near conditions as observed in Experiment 1. Accordingly, the persistence of the age-related benefit as well as the difficult condition benefit in the absence of intertarget contingencies would support the capacity-limited independent parallel model.

6.1. Methods

Subjects.

Subjects were 8 young adults (4 female; mean age = 19.5 years, SD = .5; mean years of education = 13.4, SD = .9; mean corrected far acuity = 20/18.1, SD = 2.4; mean corrected near acuity = 20/20, SD = 0) and 8 older adults (6 female; mean age = 68.9 years, SD = 5.9; mean years of education = 16.6, SD = 4.1; mean corrected far acuity = 20/22.5, SD = 3.5; mean corrected near acuity = 20/26, SD = 4.9) recruited from the community of the University of Illinois at Urbana-Champaign. All were screened for normal color vision with the Ishihara color blindness test (Ishihara, 1989). All subjects were naive to the purpose of the experiment. All were paid for participation. None of the subjects had participated in Experiment 1.

Apparatus.

Apparatus for Experiment 2 was identical to that used in Experiment 1.

Stimuli.

Stimuli were identical to those of Experiment 1 except that only two levels of the eccentricity manipulation, near (2.0°) and far (10.0°), were employed.

Procedure.

Procedure was identical to that of Experiment 1 except that Experiment 2 involved a mixed condition, where colored X and O targets appeared at one of the eccentricities. Each block contained equal number of trials of single-target (X or O) condition and dual-target (redundant, X-X and O-O, or mixed X-O and O-X) condition. In the mixed condition, subjects were allowed to press any button to proceed. This response mapping was chosen because it does not introduce another button to press for the mixed condition. Each block contained an equal number of trials for all combinations of target identity (X or O), the number of target (single or dual), eccentricity (near, or far), and clutter condition (present or absent).

6.2. Results

Treatment of the data was identical to that in Experiment 1 except that trials on the mixed condition were removed prior to the analysis.

6.2.1. RTs

Figure 7 presents mean RTs as a function of target condition, eccentricity, and clutter for young subjects. Figure 8 presents the same data for older subjects. RTs for older subjects were reliably longer than those for young subjects [$F(1,14) = 13.56$, $p < .01$, $MSE = 28111.18$, $\eta^2_p = .49$]. Subjects produced longer RTs in displays with clutter than without [$F(1,14) = 180.19$, $p <$.

01, *MSE* = 1512.26, η^2_p = .92], and magnitude of this increase was larger for older than young subjects [$F(1,14) = 9.13$, $p < .01$, *MSE* = 1512.26, η^2_p = .39]. The increase in the retinal eccentricity produced longer RTs [$F(1,14) = 206.41$, $p < .01$, *MSE* = 1097.85, η^2_p = .93]. This effect of Eccentricity was greater in displays with clutter than without [$F(1,14) = 110.22$, $p < .01$, *MSE* = 748.11, η^2_p = .86] and disproportionately greater for older than young subjects [$F(1,14) = 14.96$, $p < .01$, *MSE* = 1097.85, η^2_p = .51]. Furthermore, the effect of the two-way interaction of Clutter by Eccentricity was larger for older than young subjects [$F(1,14) = 8.10$, $p = .01$, *MSE* = 748.11, η^2_p = .36].

Importantly, without the intertarget contingencies, the main effect of target redundancy was no longer statistically reliable [$F(1,14) = 4.31$, $p = .057$, *MSE* = 442.23, η^2_p = .23]. The two-way interaction between Clutter and Condition was reliable, indicating that the redundancy gain obtained with cluttered displays (M = 373 ms vs. 385 ms for redundant- vs single-target conditions, respectively, in the clutter conditions; M = 285 ms vs. 289 ms, respectively, in the no-clutter conditions)[$F(1, 14) = 7.30$, $p = .01$, *MSE* = 73.77, η^2_p = .34]. The remaining effects were not reliable [all *p*s > .15].

Note that the prediction of a redundancy gain holds only under the assumption of a first-terminating stopping rule (van der Heijden, 1983), raising the potential concern that the current task, interjecting occasional mixed-target trials on which subjects were free to select either response, might have eliminated redundancy gains by precipitating an exhaustive stopping rule. However, the rough equivalence between single-target and redundant-target RTs, along with the modest but significant redundancy gains observed in the cluttered conditions, speaks against this possibility. Under highly limited-capacity processing, an exhaustive model predicts that RTs for single-target trials will be shorter than those for redundant trials, since the redundant trials require processing of an additional target item. Thus, the finding that RTs for redundant target trials on average were statistically similar to RTs for the single-target trial, and that redundant-target RTs were shorter than those for single-target trials in the cluttered conditions, rules out the possibility that subjects might have performed the task using an exhaustive stopping rule.

6.2.2. Error rates

Figure 9 and 10 present mean error rates against the retinal eccentricity for the no clutter and clutter conditions for young and older adults, respectively. Error rates were larger in displays with clutter than without [$F(1, 14) = 34.53$, $p < .01$, $MSE = .004$, $\eta^2_p = .71$], and increased with retinal eccentricity of the cued items [$F(1,14) = 41.83$, $p < .01$, $MSE = .003$, $\eta^2_p = .74$]. The increase of error rates due to manipulation of the eccentricity was greater within cluttered displays than uncluttered [$F(1,14) = 34.20$, $p < .01$, $MSE = .004$, $\eta^2_p = .71$], and this interaction effect of Clutter by Eccentricity was numerically larger for the older than young adults though the age-related difference was statistically marginal [interaction contrast .09 vs. .16; $F(1,14) = 3.46$, $p = .08$, $MSE = .004$, $\eta^2_p = .19$]. The effect of Eccentricity also tended to be greater for older than young adults, though this effect too reached only marginal significance [$F(1,14) = 3.77$, $p =.07$, $MSE = .004$, $\eta^2_p = .21$]. Error rates were lower in the redundant- than single-target condition [$F(1,14) = 10.282$, $p < .01$, $MSE = .0002$, $\eta^2_p = .42$]. The rest of the effects were not significant [all *p*s > .10].

6.2.3. Analysis of workload capacity coefficients

Figure 11 presents geometric means of workload capacity as a function of the eccentricity for the no-clutter and clutter conditions for young (top) and older (bottom) adults. As shown in the Figure 11, both young and older adults' performance was almost at the level of fixed capacity (*C(t)* = .5). Only the main effect of Clutter reached statistical significance: workload capacity was modestly but significantly greater within cluttered displays than uncluttered (M = .51 vs. .54) [$F(1,14) = 4.79$, $p = .04$, $MSE = .003$, $\eta^2_p = .25$]. The other effects were not reliable [all *p*s > .27].

6.2.4. Mixed-target trials

Data for mixed-target trials were analyzed in the interest of comprehensiveness. In the mixed trials, young adults responded X less frequently than they responded O [40% vs. 60%, one-sample $t(7) = -2.75$, $p = .02$]. Older adults showed the same pattern, but not reliably [44%, one-sample $t(7) = -.90$, $p = .39$]. RTs in the mixed condition were significantly longer than those for the redundant-target condition [M = 273 ms vs. 298 ms for the redundant-target and mixed conditions respectively, paired-sample $t(7) = 4.64$, $p < .01$, for young adults; M = 377 ms vs. 440 ms, paired-sample $t(7) = 7.08$, $p < .01$ for older adults] and longer than those for the single-target conditions [M = 279 ms vs. 298 ms for the single-target and mixed conditions respectively, paired-sample $t(7) = 2.57$, $p =.03$, for young adults; M = 384 ms vs. 440 ms, paired-sample $t(7) = 7.93$, $p < .01$ for older adults].

These results contradict the predictions of a simple first-terminating model in which the attended items were processed independently and the subject's response was determined by the first of the two items to complete processing; such a model predicts statistically equivalent proportions of X and O responses, and predicts statistically similar RTs for the single-target and mixed target trials. Data suggest instead the possibility of response conflict, slowing down response selection on mixed-target items (Fournier & Eriksen, 1990), coupled with a preference for X responses, perhaps reflecting a tendency for subjects to respond with their right hands.

6.3. Discussion

Experiment 2 examined whether it is the intertarget contingencies that older adults took advantage of in order to achieve greater capacity in the difficult conditions, compared with young adults. Results are consistent with the interactive channels model: subjects no longer showed capacity increases in the difficult conditions, nor age-related differences in capacity persist. Interestingly, the effects of clutter and eccentricity were larger for older than young adults in the raw RT data, but not in *C(t)* data. This suggests that the raw effect differences were due to age-related general slowing or sensory losses rather than the attentional losses.

Although the current results accord with the interactive channels model, this conclusion assumes that the task difficulty is relatively similar across Experiment 1 and 2. However, note that response mapping of Experiment 2 differed from that of Experiment 1: Subjects in Experiment 2 pressed any button in the XO trials while subjects in Experiment 1 did not. Experiment 3 examined whether inclusion of less frequent mixed trials, therefore increasing overall task difficulty, confounded the results of Experiment 2.

Chapter 7: Experiment 3

The data in Experiment 2 gave evidence that the age-related capacity gain observed in Experiment 1 does not persist in the absence of biased intertarget contingencies. However, there remains a possibility that inclusion of the XO trials increased the overall difficulty, eliminating the age-related benefit. The task with the mixed trials in Experiment 2 required subjects to press either one of the assigned buttons while the task in Experiment 1 did not include the mixed trials. Older adults might be unable to take advantage of the redundant targets even with a slight change in their response mapping. Experiment 3 tested this possibility by increasing levels of intertarget contingency but still employing the same response mapping of Experiment 2. More specifically, the two colored items are identical for 80% of the trials while different for 20%.

7.1. Methods

Subjects.

Subjects were 8 young adults (4 female; mean age = 19.6 years, SD = .99; mean years of education = 14.0, SD = 1.0; mean corrected far acuity = 20/17.8, SD = 4.5; mean corrected near acuity = 20/22.5, SD = 4.3) and 8 older adults (4 female; mean age = 66.3 years, SD = 5.0; mean years of education = 17.1, SD = 3.1; mean corrected far acuity = 20/24.5, SD = 6.4; mean corrected near acuity = 20/25.6, SD = 4.9) were recruited from the community of the University of Illinois at Urbana-Champaign. All were screened for normal color vision with the Ishihara color blindness test (Ishihara, 1989). All subjects were naive to the purpose of the experiment. All were paid for participation. None of the subjects had participated in either of the earlier experiments.

Apparatus.

Apparatus for Experiment 3 was identical to that of Experiments 1 and 2.

Stimuli.

Stimuli were identical to those of Experiment 2 except that the inter-target correlation was .8 (the two targets were identical for 80% of the trials while different for 20% in the dual-targets condition).

Procedure.

Procedure was identical to that of Experiment 2.

7.2. Results.

Treatment of the data was identical with that in Experiment 2.

7.2.1. RTs.

Figure 12 present mean RTs as a function of the eccentricity for the no-clutter (top) and clutter (bottom) conditions for young adults, and Figure 12 for older adults. Older adults produced longer RTs than young adults [$F(1,14) = 18.75$, $p < .01$, $MSE = 56083.68$, $\eta^2_p = .57$]. RTs were reliably longer in displays with clutter than without [$F(1,14) = 118.48$, $p < .01$, $MSE = 1632.11$, $\eta^2_p = .89$], at the far than near eccentricity condition [$F(1,14) = 141.17$, $p < .01$, $MSE = 1214.94$, $\eta^2_p = .91$], and in the single- than the redundant-target condition [$F(1,14) = 10.31$, $p < .01$, $MSE = 505.63$, $\eta^2_p = .33$]. The effects of the Clutter and Eccentricity manipulations were larger for older than young adults [$F(1,14) = 17.14$, $p < .01$, $MSE = 1632.11$, $\eta^2_p = .55$ for the age X clutter interaction; $F(1,14) = 10.31$, $p < .01$, $MSE = 1214.94$, $\eta^2_p = .42$ for the age X eccentricity interaction]. The effect of eccentricity was larger with clutter than without [$F(1,14) = 139.94$, $p < .01$, $MSE = 505.84$, $\eta^2_p = .90$], and further, this interaction effect was larger for older than young adults [$F(1,14) = 20.72$, $p < .01$, $MSE = 505.84$, $\eta^2_p = .59$].

The redundancy gain tended to be larger in the far than near eccentricity condition, but fell short of the conventional cut-off for statistical significance [$F(1,14) = 4.25$, $p = .058$, $MSE = 158.08$, $\eta^2_p = .14$]. However, the magnitude of the redundancy gain in cluttered displays was larger than in displays without clutter [$F(1,14) = 5.21$, $p = .03$, $MSE = 114.81$, $\eta^2_p = .27$]. Older adults showed a trend toward larger redundancy gains in the presence of clutter than in its absence, but the effect was only marginal [$F(1,14) = 3.80$, $p = .07$, $MSE = 166.26$, $\eta^2_p = .21$]. The remaining effects were not significant [all *p*s > .14].

7.2.2. Error rates.

Figure 14 and 15 present mean error rates as a function of the eccentricity for the no-clutter and clutter conditions for young and older adults, respectively. The far eccentricity condition elevated error rates [$F(1,14) = 26.79$, $p < .01$, $MSE = .003$, $\eta^2_p = .65$]. The presence of clutter increased error rates [$F(1,14) = 25.39$, $p < .01$, $MSE = .004$, $\eta^2_p = .64$], and this increase was greater at the far than at the near eccentricity [$F(1,14) = 22.81$, $p < .01$, $MSE = .003$, $\eta^2_p = .62$].

Redundant targets lowered error rates [$F(1,14) = 21.57$, $p < .01$, $MSE = .0002$, $\eta^2_p = .60$], an effect that was larger in cluttered displays than uncluttered [$F(1,14) = 6.77$, $p = .02$, $MSE = .0001$, $\eta^2_p = .32$] and larger in the far than in the near eccentricity condition [$F(1,14) = 13.22$, $p < .01$, $MSE = .0003$, $\eta^2_p = .48$]. Finally, the four-way interaction reached the statistical significance [$F(1,14) = 4.71$, $p = .04$, $MSE = .0002$, $\eta^2_p = .25$]. The remaining effects were not reliable [all *p*s > .10]. The data thus gave no indication of speed-accuracy tradeoff.

7.2.3. Analysis of workload capacity coefficients

Figure 16 presents geometric mean values of C(t) as a function of the eccentricity for the no-clutter and clutter conditions for young and older adults. The performance was near the level of fixed capacity regardless of the experimental conditions. Targets in the far eccentricity condition elevated levels of workload capacity (.51 vs. .54 for near and far conditions, respectively) [$F(1,14) = 8.14$, $p = .01$, $MSE = .002$, $\eta^2_p = .36$]. Levels of workload capacity trended to be higher in cluttered than uncluttered displays for older than young adults, but the effect was not statistically reliable [$F(1,14) = 3.11$, $p = .09$, $MSE = .005$, $\eta^2_p = .18$]. The remaining effects were not reliable [all *p*s > .16].

7.2.4. Mixed-target trials

Analyses identical to those in Experiment 2 were conducted. In the mixed trials, young adults responded X slightly less often than O, though the bias toward O responses was not reliably different from the chance [48%, one-sample $t(7) = -.28$, $p = .78$]. Older adults exhibited the same pattern, and significantly less often than the chance [37% vs. 63%, one-sample $t(7) = -3.34$, $p = .01$]. RTs in the mixed condition were reliably longer than those in the redundant-target condition [M = 256 ms vs. 308 ms for the redundant-target and mixed conditions respectively, paired-sample $t(7) = 8.85$, $p < .01$, for young adults; M = 442 ms vs. 528 ms, paired-sample $t(7) = 10.80$, $p < .01$ for older adults] and than in the single-target condition [M = 264 ms vs. 308 ms for the single-target and mixed conditions respectively, paired-sample $t(7) = 2.19$, $p = .06$, for young adults; M = 442 ms vs. 537 ms, paired-sample $t(7) = 7.96$, $p = < .01$ for older adults]. The data pattern here are similar with that in Experiment 2, suggesting a response conflict effect in the mixed condition. Older adults responded O more frequently than X, perhaps showing their tendency to respond with the right hand.

7.3. Discussion

Experiment 3 tested whether requiring the more complex response mapping in Experiment 2 than Experiment 1 eliminated the capacity increase effect in more difficult conditions. Experiment 3 increased the level of interstimulus contingency but kept the response mapping identical to that in Experiment 2.

Results show that the age-related effect of the redundancy gain on the RT measure did not reappear even with the higher level of interstimulus contingency. Similarly, the analysis of workload capacity revealed no age-related effects reliable, showing that young and older adults performed similarly in the current task. The results imply that the correlation between the targets may need to be extremely high (larger than .8) in order for older adults to benefit from the multiple targets.

The age-related similarities observed in Experiment 3 support an idea that older adults become unable to benefit from the redundant target information from multiple locations when a response mapping is more complex. Even with high correlation of the two targets, subjects showed capacity levels similar to those without the correlation. In order for older adults to take advantage of the redundancy, less complex response mapping may be necessary.

Chapter 8: Experiment 4

Experiment 1 found the age-related benefit of the redundant-targets condition over the single target condition, producing greater levels of workload capacity. However, Experiment 2 and 3 with manipulation of the correlation between identity of the two targets did not find the age advantage. Experiment 4 aims at a more direct replication of the age-related advantage found in Experiment 1. Experiment 4 was a direct replication of the procedure from Experiment 1, only using one level of eccentricity (middle) with clutter. This specific condition was chosen because the redundant-target benefit was larger at the visual periphery and with clutter.

8.1. Methods

Subjects.

Subjects were 8 young adults (7 female; mean age = 21.5 years, SD = 2.0; mean years of education = 15.0 SD = 1.5; mean corrected far acuity = 20/23.1, SD = 7.0; mean corrected near acuity = 20/21.2, SD = 3.3) and 8 older adults (6 female; mean age = 67.0 years, SD = 8.1; mean years of education = 17, SD = 3.4; mean corrected far acuity = 20/23.7, SD = 9.6; mean corrected near acuity = 20/25, SD = 5.0) were recruited from the community of the University of Illinois at Urbana-Champaign. All were screened for normal color vision with the Ishihara color blindness test (1989). All subjects were naive to the purpose of the experiment. All were paid for participation. None of the subjects had prior exposure to the stimuli.

Apparatus.

Apparatus for Experiment 4 was identical with those used in Experiment 1.

Stimuli.

Stimuli for Experiment 4 were identical to those of Experiment 1 except that retinal eccentricity of the target location was fixed at the middle (6.0°) value and that the target was presented only with clutter.

Procedure.

Procedure for Experiment 4 was identical to that of Experiment 1.

8.2. Results

As in the previous experiments, the analyses of mean RTs and RT distributions excluded data for trials with incorrect responses. RTs and error rates were entered to 2 X 2 ANOVAs with target condition (single vs. dual) as a within-subject factor and age (young vs. older) as a between-subject factor.

8.2.1. RTs.

Figure 17 illustrates mean RTs for young (top) and older (bottom) subjects. Displays with redundant targets produced shorter RTs than those with single targets [F (1, 14) = 22.81, $p < .01$, MSE = 166.19, $\eta^2_p = .62$], but the magnitude of this difference did not differ between young and older adults [$F < 1$, n.s.]. RTs were numerically longer for older than young adults [M = 282 ms vs. 348 ms], but the difference was marginal [F (1, 14) = 4.15, $p = .06$, MSE = 8429.95, η^2_p = . 22].

8.2.2. Error rates

Figure 18 presents mean error rates for young (top) and older (bottom) subjects. Error rates were lower when displays contained redundant targets than a single target [F (1, 14) = 26.71, $p < .01$, MSE = .00008, $\eta^2_p = .65$]. The remaining effects were not reliable [ps > .12]. Data thus gave no evidence for speed-accuracy tradeoffs.

8.2.3. Workload capacity

Levels of workload capacity were similar between young and older adults, indicating similar capacity limits [M = .64 vs. .63], and this difference was not reliable [independent-samples $t < 1$, n.s.].

8.3 Discussion

The purpose of Experiment 4 was to replicate the age-related effect observed in Experiment 1. Contrary to the expectation, data did not give evidence for the age-related benefit in workload capacity. The estimates of workload capacity for Experiment 1 and 4 were similar for older (.61 for Experiment 1 and .63 for Experiment 4) but dissimilar for young adults (.55 for Experiment 1. and .64 for Experiment 4). It is thus possible that the age-related benefit in visual processing efficiency in Experiment 1 was driven by spuriously low levels of workload capacity for young adults. Chapter 9 will examine patterns of workload capacity across the four experiments more closely.

Chapter 9: Meta-Analysis

Meta-analysis is a set of quantitative techniques to combine data from multiple studies on a similar issue (Cumming, 2012), and it can provide strong evidence even when individual data set appear less convincing. Although meta-analysis often combines data from large numbers of published studies from multiple labs, a similar approach has been recommended for integrating data from within a smaller series of experiments. A *forest plot* provides one method of doing this. A forest plot presents the mean and confidence interval for the effects within each of a series of studies, providing information of the variability of the mean values across studies. Studies are called *homogeneous* when sampling variability can reasonably account for variability of the study means while *heterogeneous* when study-to-study variability of the means is larger than sampling variability (Cumming, 2012). Preliminary inspection suggested of forest plots (see Figures 19, 20, and 21) suggested that the studies were homogenous, with CIs tending to overlap. A suggested model for meta-analysis of homogeneous studies is *the fixed effect model* (Cumming, 2012). (*The random effect model* is recommended when the studies are heterogeneous. See Cumming, 2012, for more detail of the random effect model).

9.1 The Fixed Effect Model

The fixed effect model assumes that there is a fixed but unknown population parameter such as population mean, μ (in the current context, it is a difference of means between the cluttered and uncluttered conditions or the far and near eccentricity conditions, and the simple mean capacity scores). The meta-analysis produces a combined statistic of interest from multiple studies with different weights. Weights are calculated based on sampling variability of each study. Standard error of a statistic of interest is

$$SE_i = \frac{s_i}{\sqrt{N_i}},$$

where s_i is a sample standard deviation and N is the number of subjects in a study for Study i, and thus sample variance, V, for Study i is

$$V_i = \frac{s^2{}_i}{N_i}.$$

In the fixed effects model, the weight for a study is defined as the inverse of variability of the study. Therefore,

$$W_i = \frac{1}{V_i},$$

where W is the weight for Study i. It follows that a weighted mean is

$$M = \frac{\sum W_i M_i}{\sum W_i},$$

with variance of

$$V_M = \frac{1}{\sum W_i}.$$

9.2. Mean workload capacity across all the experimental conditions

Figure 21 presents mean workload capacity of young and older adults for each experiment, collapsed across levels of clutter and eccentricity, along with the weighted mean of the four experiments. Raw capacity levels were lower than 1.0 in Experiment 1 and 4 even when the correlation between target identities was perfect, indicating highly limited-capacity processing and an absence of facilitatory interactions between channels (Eidels et al., 2011; Townsend & Wenger, 2004).

9.3. Effect sizes of clutter and eccentricity manipulations

Visual inspection of the weighted mean of effect sizes of the first three experiments indicates that the clutter and eccentricity manipulations increased workload capacity as indicated by the CIs of the weighted means excluding zero. Furthermore, the effects obtained in the same direction for both young and older adults: more difficult conditions produced greater levels of workload capacity, consistent with the inverse effectiveness hypothesis. The manipulation of interstimulus contingency did not influence sizes of the effects, suggesting that the benefit of multiple targets arises maximally at near perfect levels of correlation between the targets (except for the effect of clutter in Experiment 3 for young adults). The effect sizes of the eccentricity manipulation were similar for different age groups, producing overlapping CIs, consistent with the age equivalency hypothesis.

The effect size of the clutter manipulation, however, was reliably greater for older than young adults, as indicated by the finding that the the CIs of the estimated effect sizes for the two age groups do not overlap (CI = [.00484, .04087] for young and [.04196, .09002] for older adults), consistent with the inverse effectiveness hypothesis.

Overall workload capacity levels in Experiment 2, 3, and 4 were similar for young and older adult, but the age-related difference in capacity appeared only in Experiment 1. Since Experiment 4 was a replication study using one of the conditions (the clutter and middle eccentricity condition) in Experiment 1, this difference might have arisen due to a sampling error of young subjects in Experiment 1. As a result, mainly driven by the age-related difference in Experiment 1, meta-analysis of the four experiments revealed that mean workload capacity score was reliably greater for older than young adults [CI = [.54, .56] for young; [.564, .61] for older].

9.4. Discussion

Previous studies have suggested that normal aging accompanies the age-related shrinkage of the AVF. Contrary to such common findings in the AVF research, the meta-analysis of overall means for the all four experiments indicate that visual capacity for older adults reliably exceeds that for young adults. Furthermore, the meta-analysis of effects sizes of eccentricities and clutter indicate the age-related similarities of visual workload capacity at various retinal eccentricities and, strikingly, an age-related capacity gain in cluttered displays. That is, the data here indicate that the ability to process information from multiple concurrent sources sustains with normal aging, and can improve in attention-demanding environments.

Chapter 10: General Discussion

Previous research has found that older adults' visual performance in the retinal periphery is worse than young adults', an effect that has been taken as evidence for an age-related constriction of the AVF (e.g. Sekuler & Ball, 1986; Ball et al., 1988; Scialfa et al., 1987). However, dependent measures chosen in the previous studies have been largely atheoretical, and thus have often not provided clear evidence of process-specific age differences (Wagenmakers et al., 2012; Verhaeghen, 2000). To circumvent these constraints, the current experiments directly gauged workload capacity based on RT distributions at various retinal eccentricities, in the presence or absence of clutter. The workload capacity index, *C(t)*, measures how efficiently a system concurrently processes multiple streams of information, and can be assessed against theory-motivated benchmarks of performance (Townsend & Nozawa, 1995; see Chapter 2 for more details). Furthermore, because *C(t)* is a ratio of performance in single and dual target conditions in the redundant-targets paradigm, it effectively removes the influence of generalized psychomotor slowing and controls for the effects of varying sensory quality across the retina and between age groups.

10.1. Summary of the current findings

Experiment 1 measured visual workload capacity for young and older adults while manipulating levels of display clutter and retinal target eccentricity. Interestingly, capacity increased in the periphery of the visual field and in the presence of display clutter, supporting the inverse effectiveness hypothesis (Stein & Meredith, 1993). Older adults' workload capacity, furthermore, was greater than young adults' in cluttered displays, giving evidence to support the inverse effectiveness hypothesis and refute the tunnel vision and general inefficiency hypotheses.

The results of thus Experiment 1 argue against the suggestion that the AVF shrinks with advancing age. Further, older adults showed the benefit of the redundant targets at the periphery regardless of the presence of clutter, while young adults showed the benefit only with the presence of clutter. Related to this age effect, older adults showed higher capacity than young adults in the uncluttered displays as well, and this age-related benefit was larger in the cluttered displays. Experiment 4 attempted to replicate the age-related benefit obtained in Experiment 1.

Experiments 2 and 3 asked whether the effects observed in Experiment 1—an age-related gain in capacity, and an increase in capacity under conditions of large target eccentricity and high clutter—were the result of a perfect correlation between target identities. In Experiment 1, the identities of the two colored items appearing on a single trial were perfectly correlated. On trials in which two colored items appeared, in other words, the two were always matched in identity. Experiments 2 and 3 introduced trials in which the two colored targets differed in identity (the mixed trials) and subjects were allowed to press either button in response. These trials reduced the strength of correlation between the two targets' identities, producing an intertarget correlation of zero in Experiment 2 and .8 in Experiment 3. In both these experiments, the age-related benefit disappeared, and the mean capacity levels between the two experiments were similar for both age groups.

There are two possible accounts for these data. First, an almost perfect level of correlation between the targets may be necessary for older adults to take advantage of the contingencies to improve their visual performance in the current task. Comparing the results of Experiments 2 and 3 shows that increasing intertarget correlation from chance levels to a value of .8 did not markedly influence effect sizes of manipulations of clutter and eccentricity and the simple mean capacity level between experiments for both young or older adults (Figure 19 and 20). A intertarget correlation of greater than .8 might therefore be necessary to enable substantial capacity gains. Second, response mapping complexity in Experiments 2 and 3 may have interfered with the ability to use intertarget contingencies. In Experiment 1, subjects were asked to press either one of the two assigned buttons for the target X or O. In Experiment 2 and 3, they were asked to press either button of their preference in the mixed condition in addition to the task in Experiment 1. Therefore, the more complex response mapping in Experiment 2 and 3 could have interfered the use of the contingencies for both young and older adults, eliminating the effects of eccentricity and clutter manipulations as well as age-related benefit in capacity and lowering the overall capacity scores.

Experiment 4 attempted to replicate the age-related benefit in Experiment 1, using the display with the middle eccentricity level and cluttered condition. Workload capacity levels were indistinguishable between young and older adults, suggesting that the age-related benefit found in Experiment 1 could have been a Type I error, perhaps due to sampling error producing an unduly low estimate of divided visual capacity for young adults.

These observations are largely consistent with the limited-capacity independent parallel model over the interactive channels model. The interactive channel model predicts super-capacity processing (Eidels, Houpt, Altieri, Pei, & Townsend, 2011) unless capacity is extremely limited. Furthermore, even with high levels of the intertarget contingencies in Experiment 3, capacity remained limited across the conditions for young and older adults. Since Experiment 4 did not replicate the age-benefit and showed similar capacity limits for the both age groups, the data accord with the limited-capacity independent parallel model more than the interactive channel model.

A meta-analysis of the data across the four experiments indicated that older adults possess greater workload capacity in general than young adults (Figure 21), though confidence intervals on the mean *C(t)* values for the two age groups approached the point of overlap. In general, levels of workload capacity in the current task were between .5 and .65, indicating limited-capacity processing regardless of the magnitude of intertarget contingencies for young and older adults. For both age groups, meta-analysis indicated that capacity was higher in the far eccentricity and clutter conditions than in the near and no-clutter conditions. Further, data showed age-related capacity benefits in the cluttered conditions. These age-related attentional similarities and benefits arise because of a strategy of the aging visual system to efficiently process information from different concurrent channels in the attention-demanding environments, serving as a compensatory mechanism.

10.2. Implications of the current findings

The previous research suggested the constriction of the AVF for aging adults, but the experimental paradigms and atheoretical dependent measures used in the research conflate effects of generalized psychomotor slowing and age-related sensory losses and effects of attentional processes. The performance decline in the visual periphery could be due to inefficiencies in individual channels or attentional inefficiencies in parallel processing. The current study measured workload capacity, gauging performance gain in the redundant-target condition relative to the single-target conditions, in order to isolate attentional processes from declines in individual channels due to non-attentional factors such as the general slowing and sensory losses across the visual field. Contrary to the previous suggestions in the AVF literature, the data here indicate that the ability to divide attention over large areas of the visual field and across information sources sustains with normal aging. The current set of evidence thus supports the age equivalence hypothesis and the inverse effectiveness hypothesis while disconfirming the tunnel vision hypothesis and the general inefficiency hypothesis. While several age-related factors including general slowing of perceptual processes or sensory losses degrade older adults' visual performance, increase in attentional load in the current study did not reduce the efficiency of these processes disproportionately for older adults. Thus, the current data suggest that the age differences in AVF performance reported in the previous studies were not specifically due to declines in attentional processes, but were more likely the result of age-related losses in lower-level sensory or perceptual processes (c.f. Scialfa et al., 1994).

10.3. Future study

What neural mechanisms underlie the age-related effects? Future studies may record the brain potential while subjects perform the discrimination task, providing a millisecond resolution of the time course of the visual processing. Specifically, analysis of the visual ERP components may provide further insights on which visual processing stages are involved during processing information from redundant targets and how the neural mechanisms change with normal aging. In the current studies, it is possible that redundant targets modulate the N1 component, which is linked with visual discrimination (Vogel & Luck, 2000; Woodman, 2010), an effect potentially larger for older adults. Additionally, spatial attention may modulate the P1 component, linked with early visual processing (Woodman, 2010; Pratt, 2011), differentially for young and older adults. Studying the age-related similarities and benefit in the current paradigm using the ERPs may be an avenue toward better understanding of the relationship between aging and divided attention across the visual field.

10.4. Conclusion

The previous AVF research suggests age-related constriction of the AVF. Contrary to such common finding, the current data suggest the age-related similarities and benefit in attention-demanding environments, allowing older adults to more efficiently process information from multiple concurrent sources, as a compensatory strategy for age-related perceptual declines. These findings argue against the suggestion that peripheral visual losses in older adults are strictly attentional, and suggest instead that they are sensory or perceptual in basis.

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Appendix: Figures

Figure 1. Illustrations of the stimulus display and time course of a trial. (A) A sample display of redundant targets with no clutter. (B) A sample display of redundant targets with clutter. (C) The sequence of events within a trial.

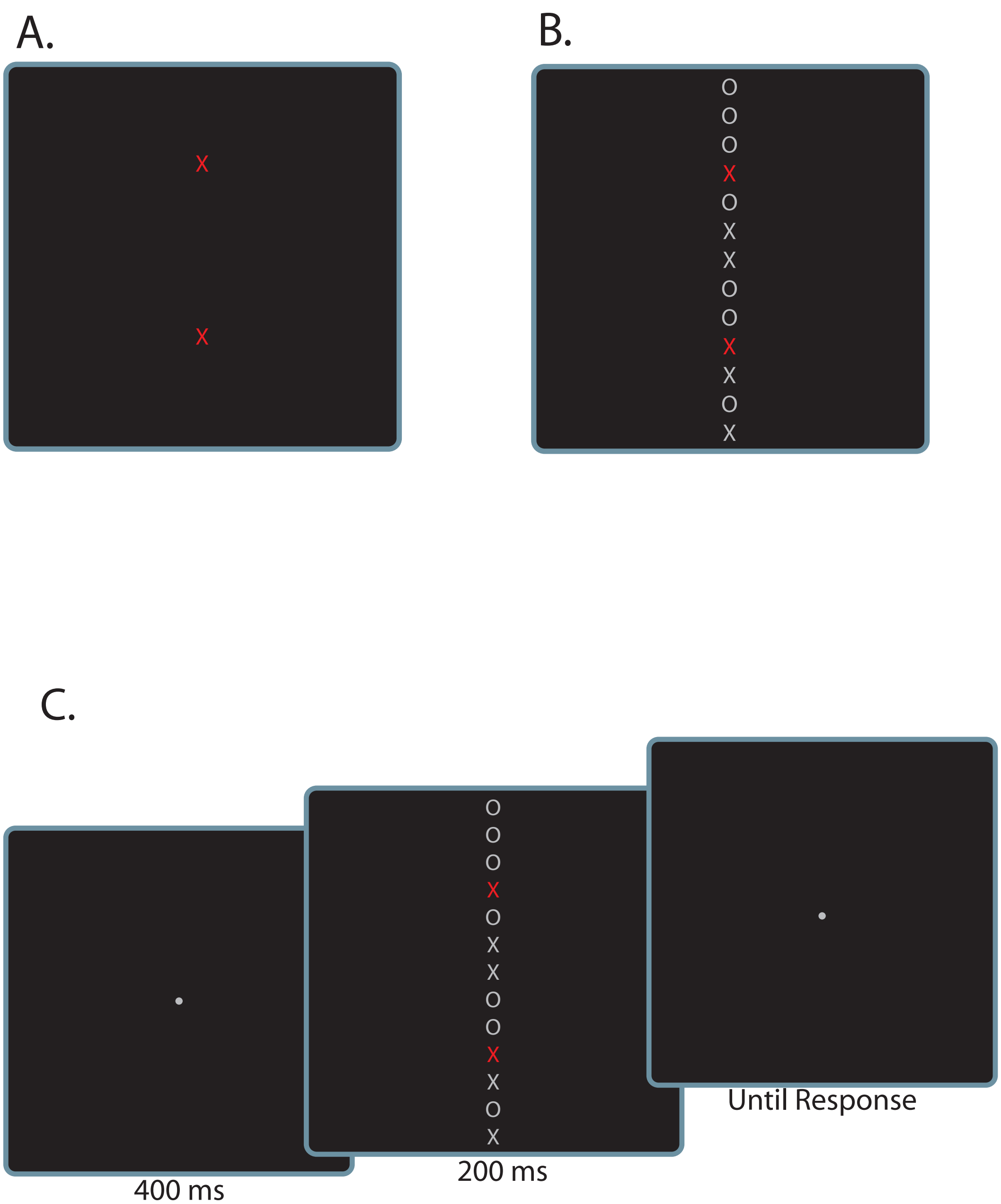


Figure 2. Mean RTs for the target conditions as a function of retinal eccentricity for the no clutter (top) and clutter conditions (bottom) for young adults in Experiment 1. Error bars in all graphs represent within-subject mean standard errors based on the main effect of the target condition (Loftus & Masson, 1995; Baguley, 2012).

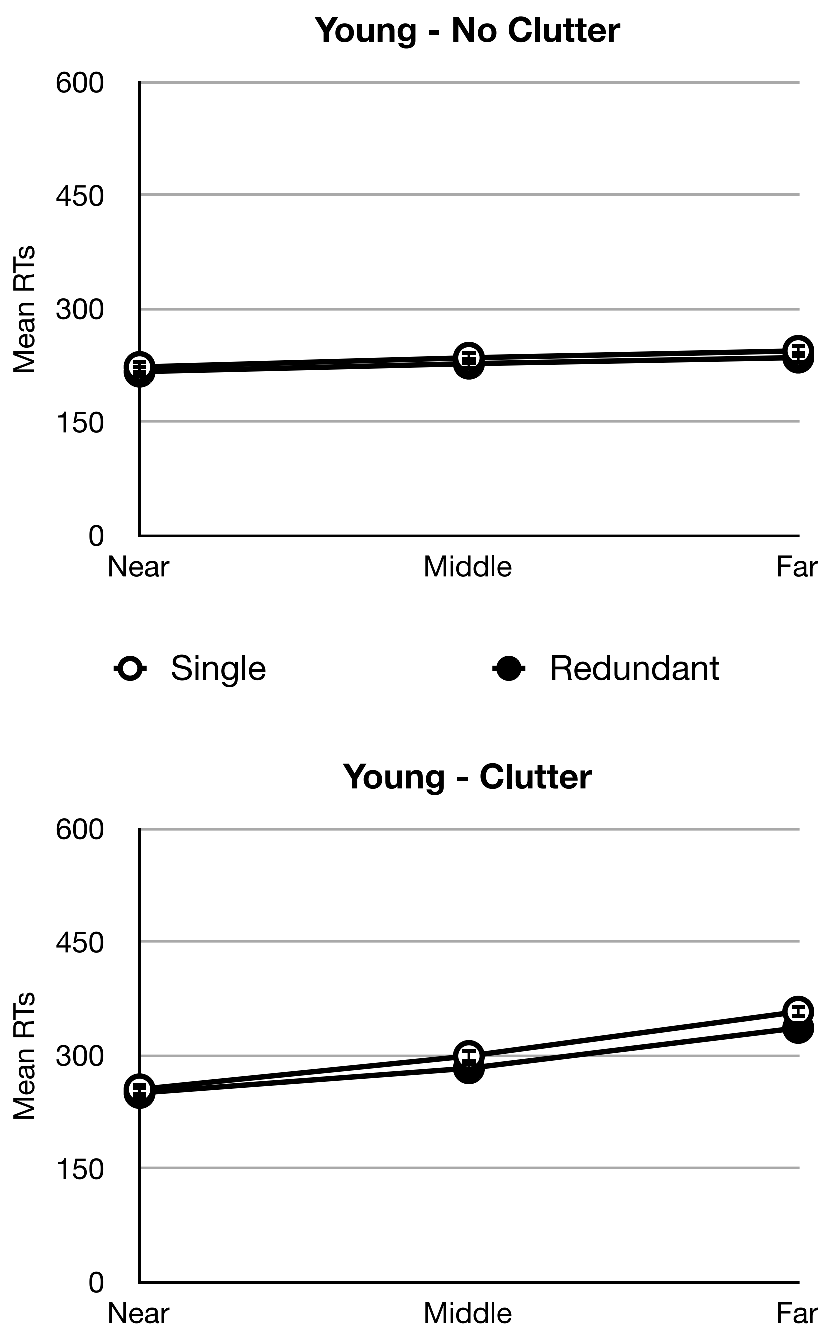
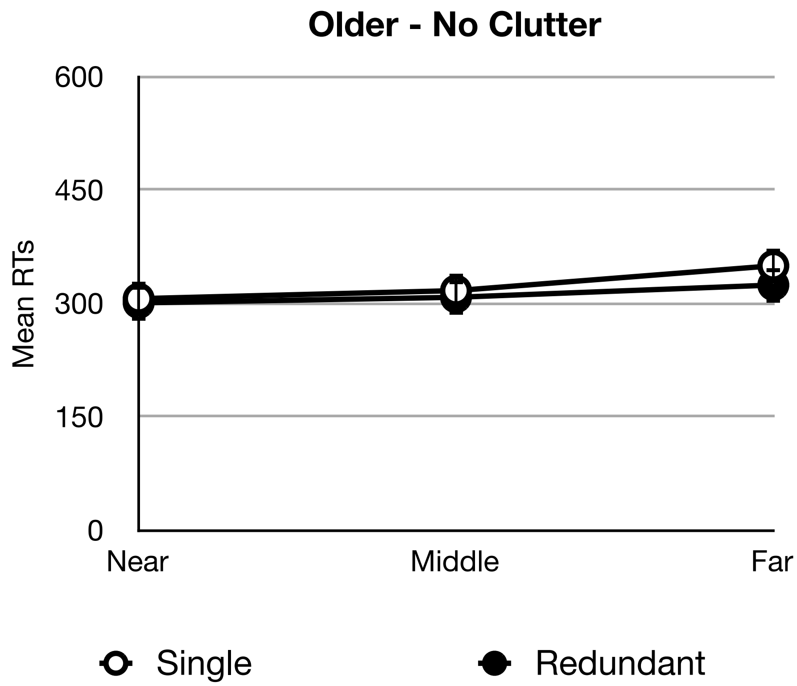


Figure 3. Mean RTs for the three target conditions as a function of retinal eccentricities for the no clutter (top) and clutter conditions (bottom) for older adults in Experiment 1.



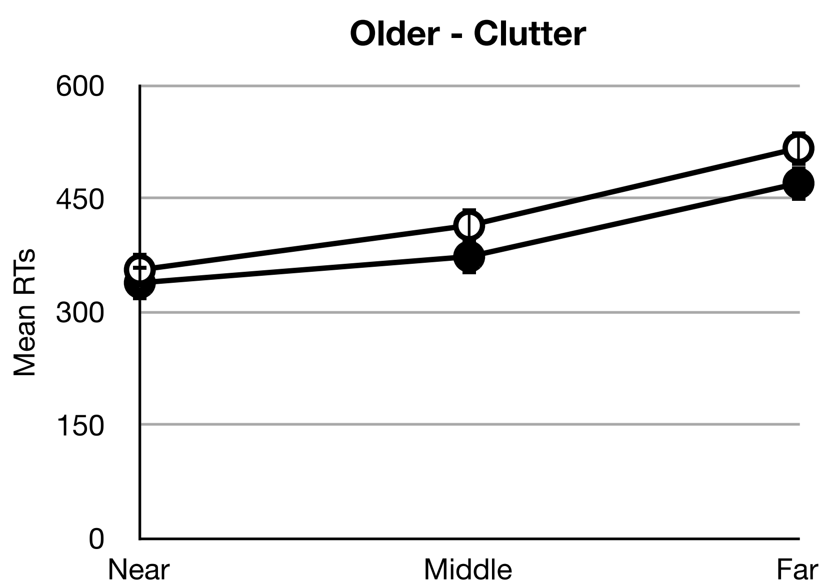


Figure 4. Mean error rates for the three target conditions as a function of retinal eccentricities for the no clutter (top) and clutter conditions (bottom) for young adults in Experiment 1.

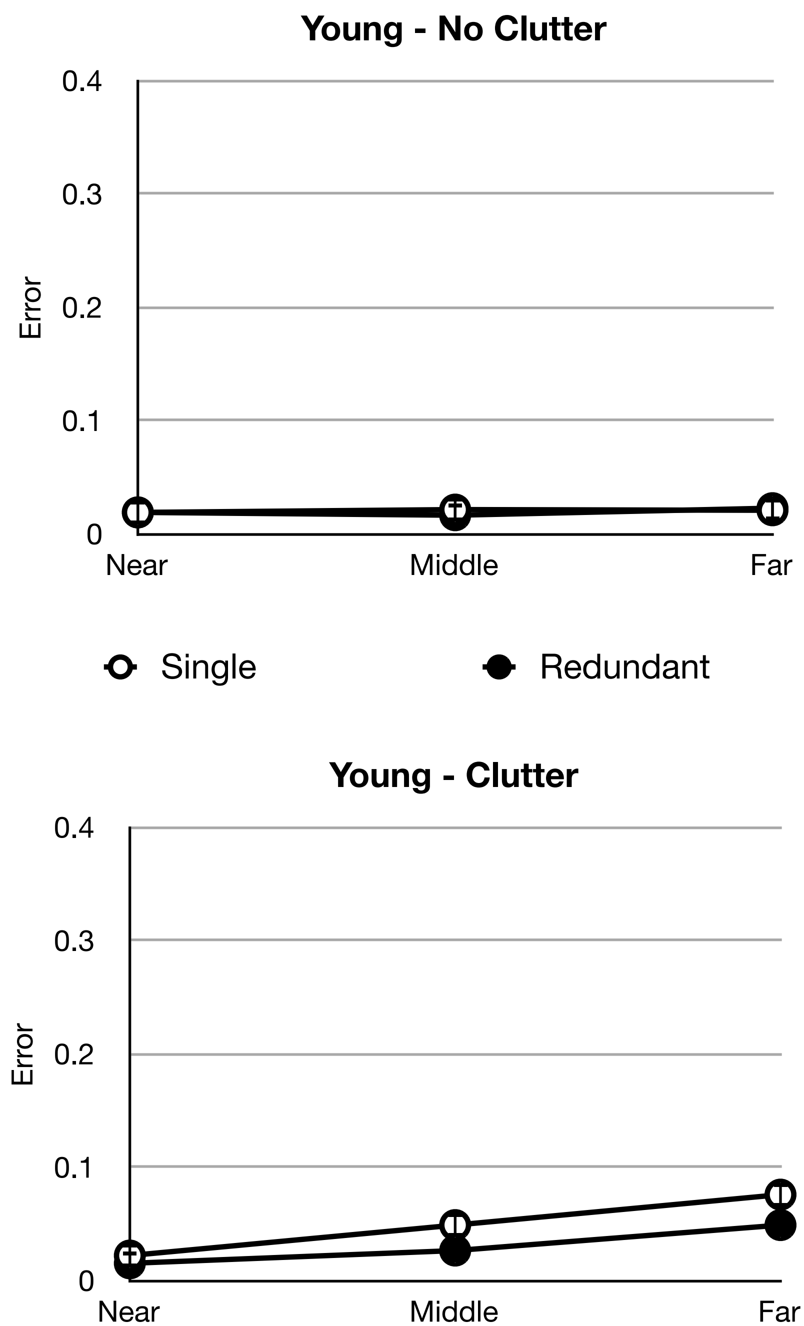


Figure 5. Mean error rates for the three target conditions as a function of retinal eccentricities for the no clutter (top) and clutter conditions (bottom) for older adults in Experiment 1.

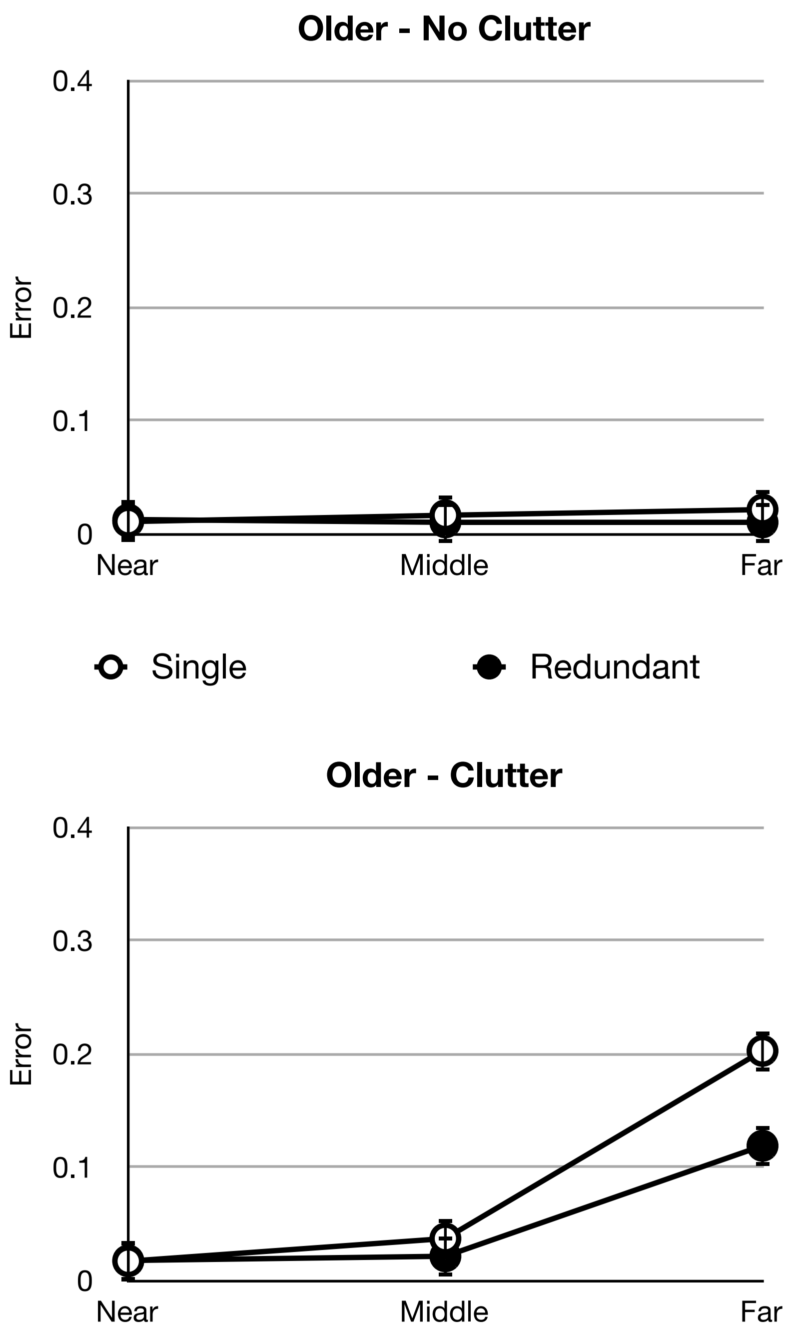


Figure 6. Geometric means for the no-clutter and clutter conditions as a function of eccentricities for young (top) and older subjects (bottom) in Experiment 1. Error bars in all graphs represent within-subject mean standard errors based on the main effect of eccentricity.

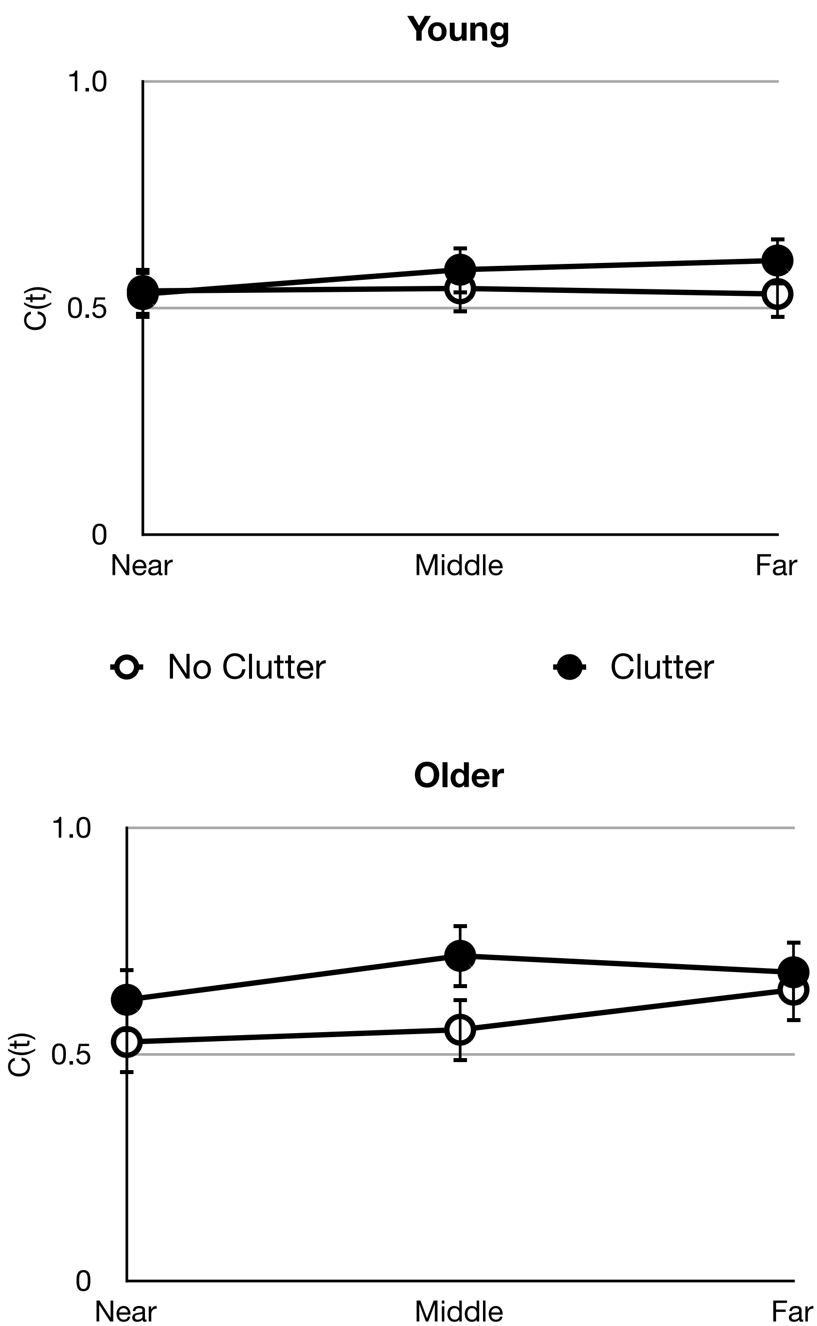


Figure 7. Mean RTs for the target conditions as a function of retinal eccentricity for the no clutter (top) and clutter conditions (bottom) for young adults in Experiment 2.

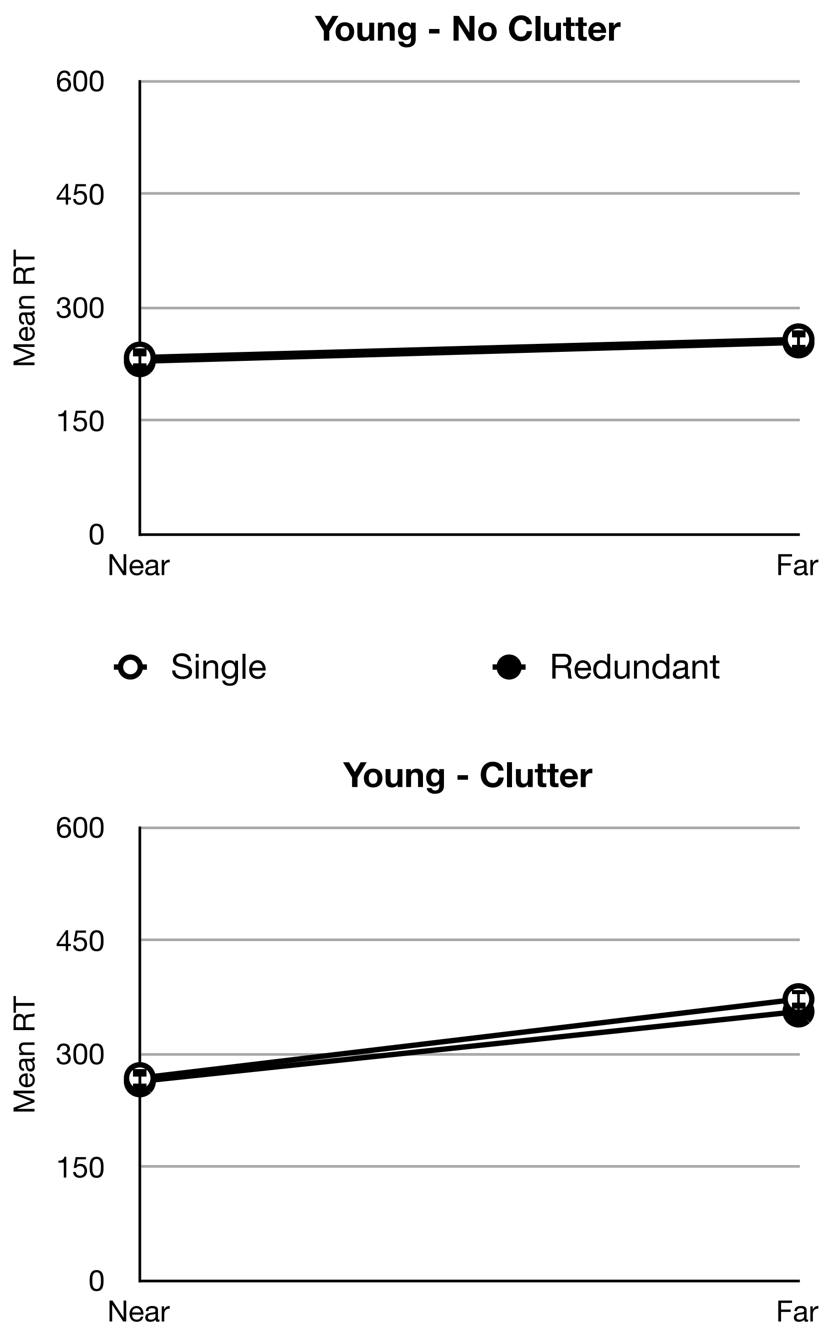


Figure 8. Mean RTs for the three target conditions as a function of retinal eccentricities for the no clutter (top) and clutter conditions (bottom) for older adults in Experiment 2.

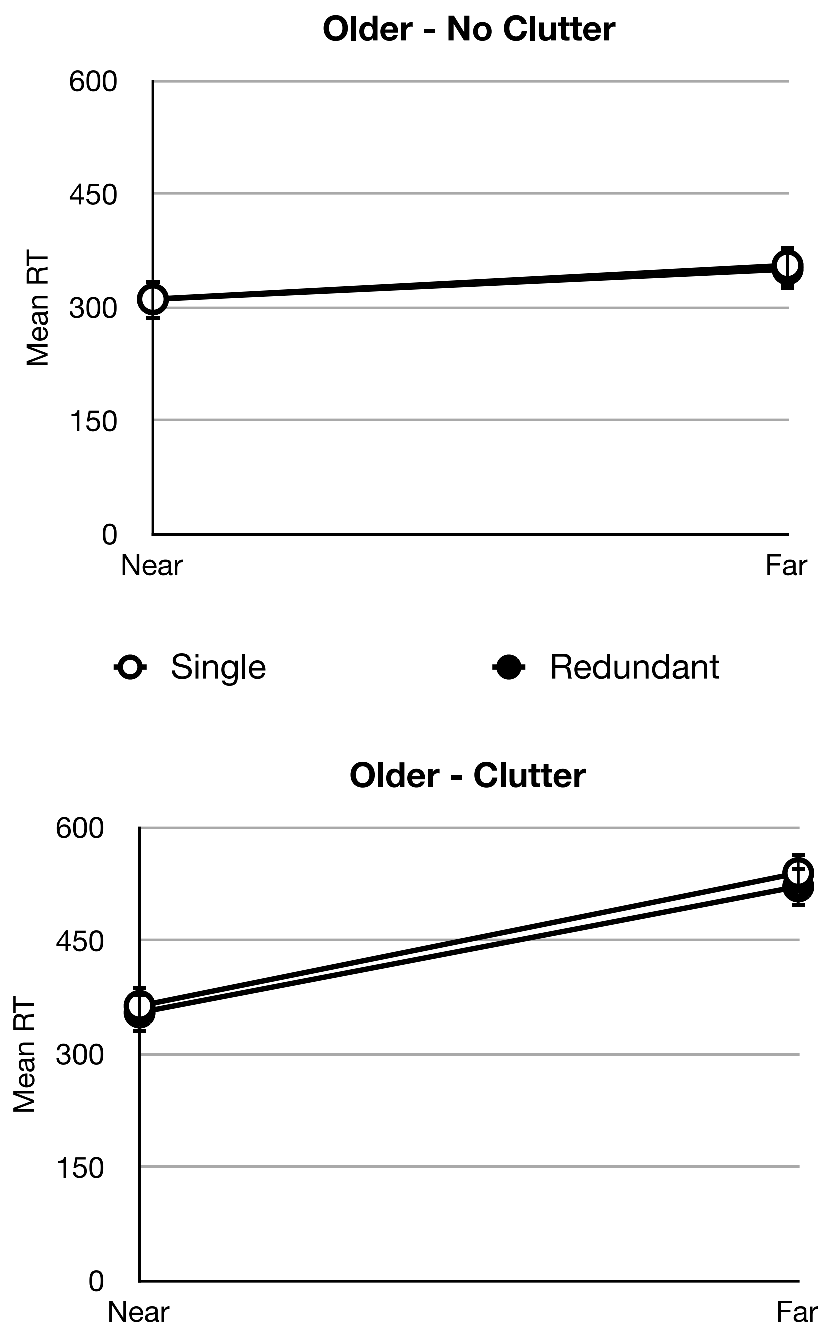


Figure 9. Mean error rates for the three target conditions as a function of retinal eccentricities for the no clutter (top) and clutter conditions (bottom) for young adults in Experiment 2.

Figure 10. Mean error rates for the three target conditions as a function of retinal eccentricities for the no clutter (top) and clutter conditions (bottom) for older adults in Experiment 2.

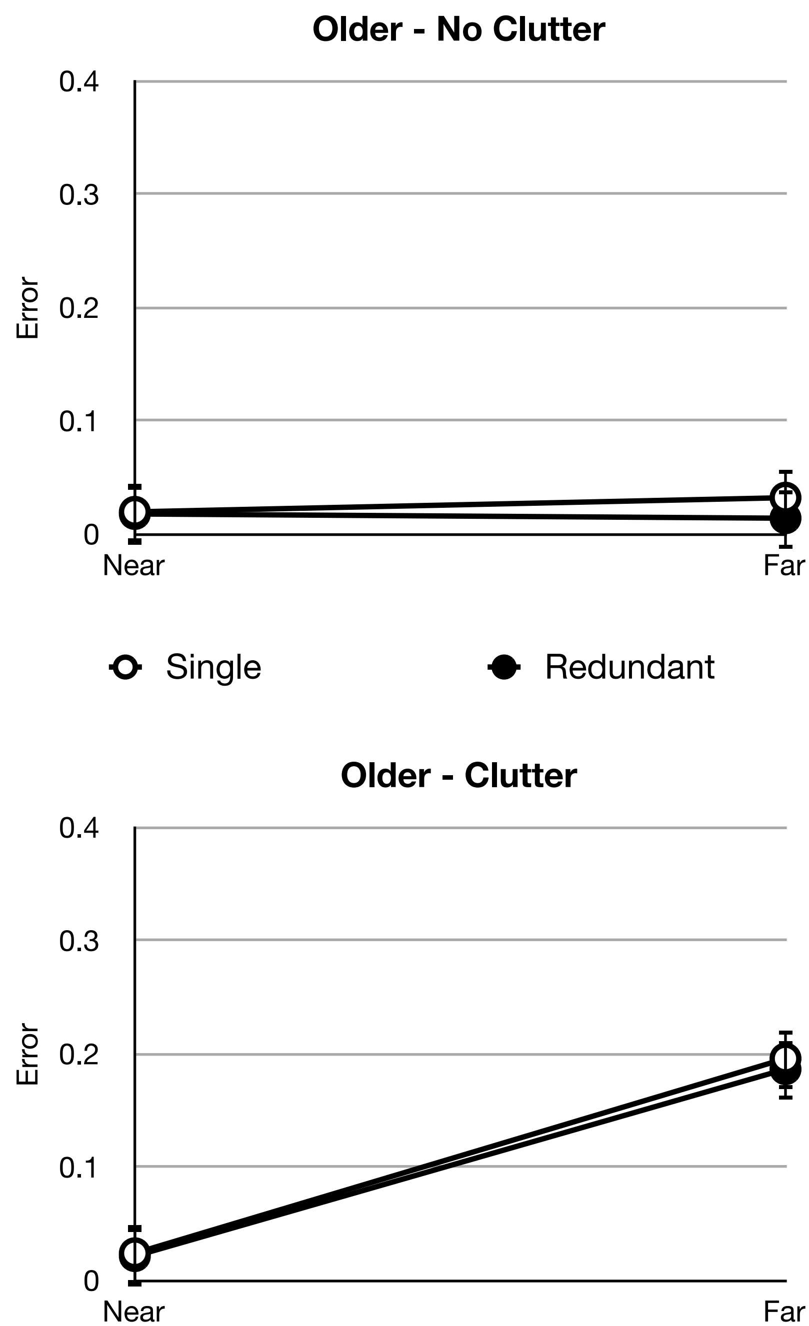


Figure 11. Geometric means for the no-clutter and clutter conditions as a function of eccentricities for young (top) and older subjects (bottom) in Experiment 2.

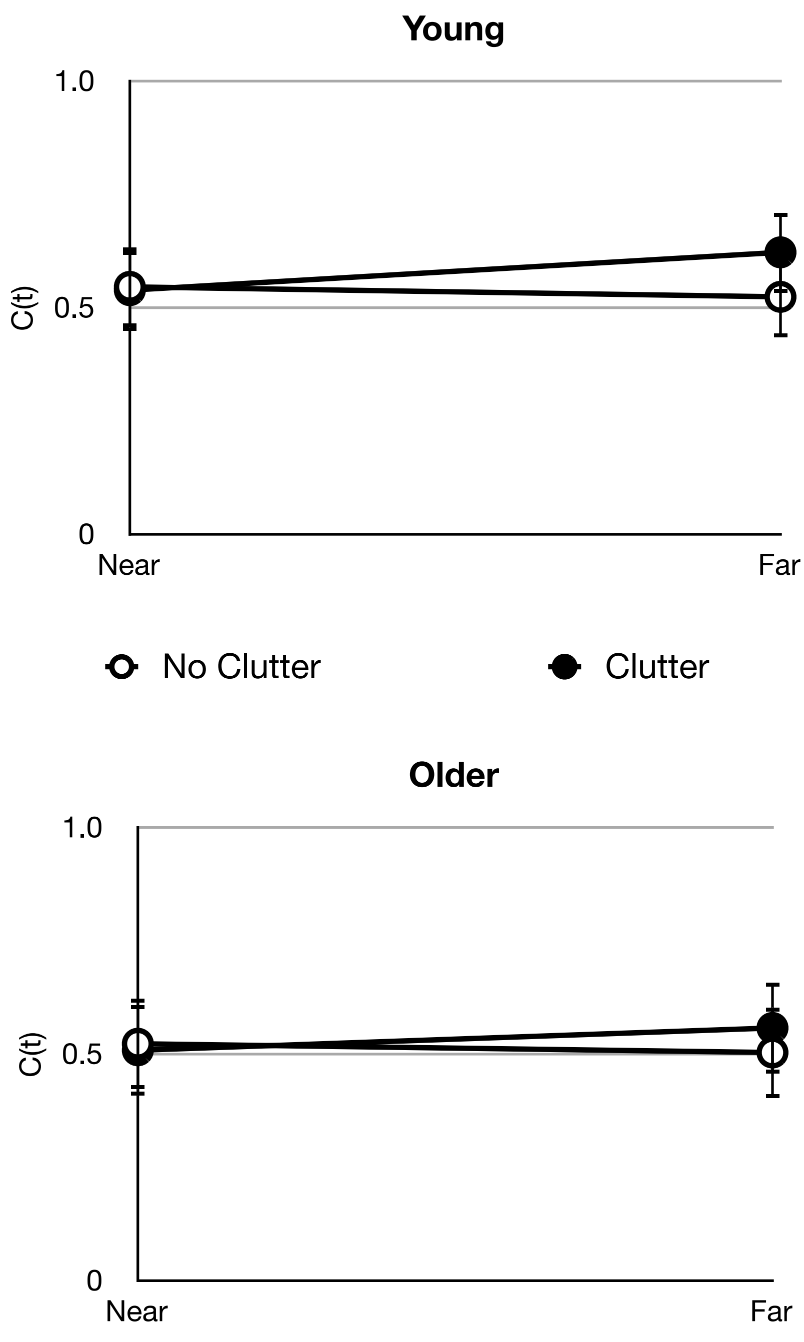


Figure 12. Mean RTs for the target conditions as a function of retinal eccentricity for the no clutter (top) and clutter conditions (bottom) for young adults in Experiment 3.

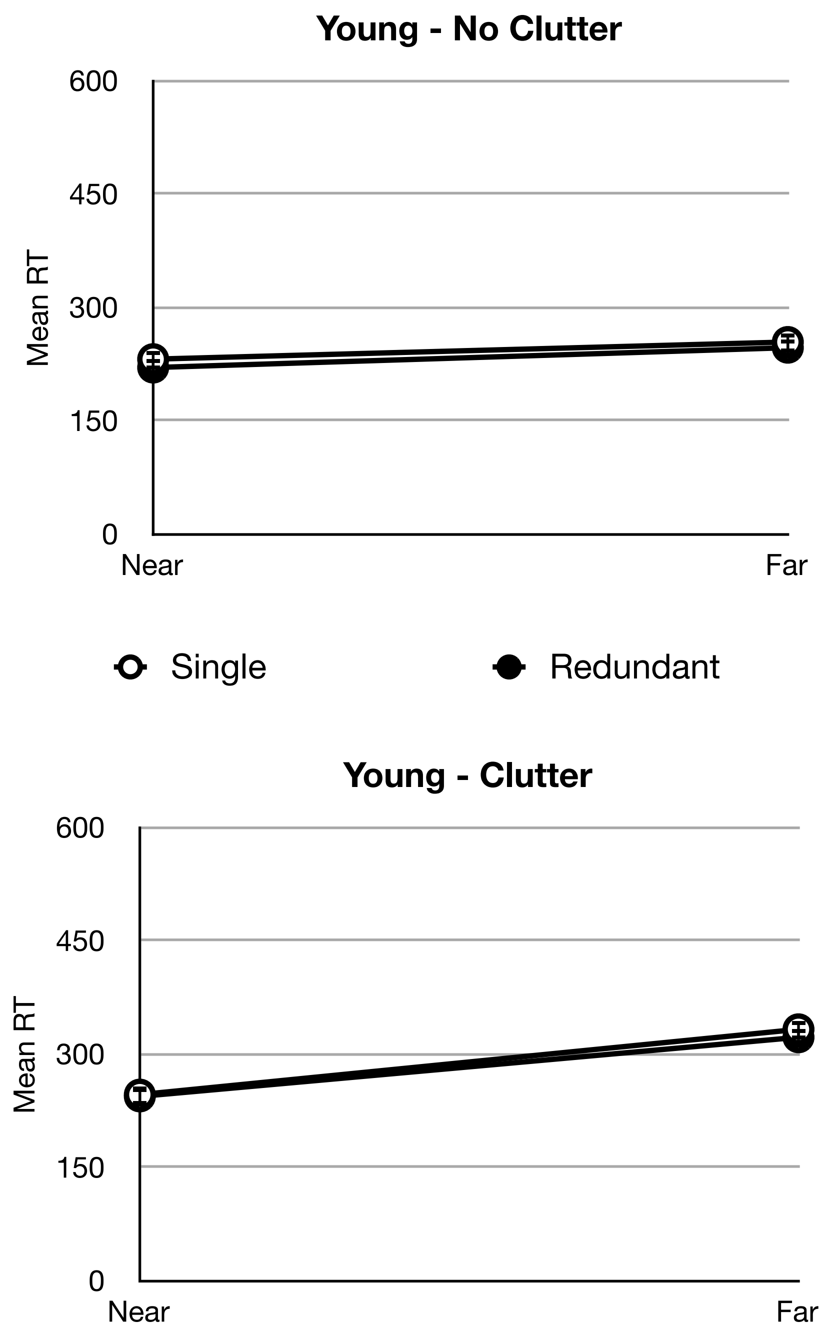


Figure 13. Mean RTs for the three target conditions as a function of retinal eccentricities for the no clutter (top) and clutter conditions (bottom) for older adults in Experiment 3.

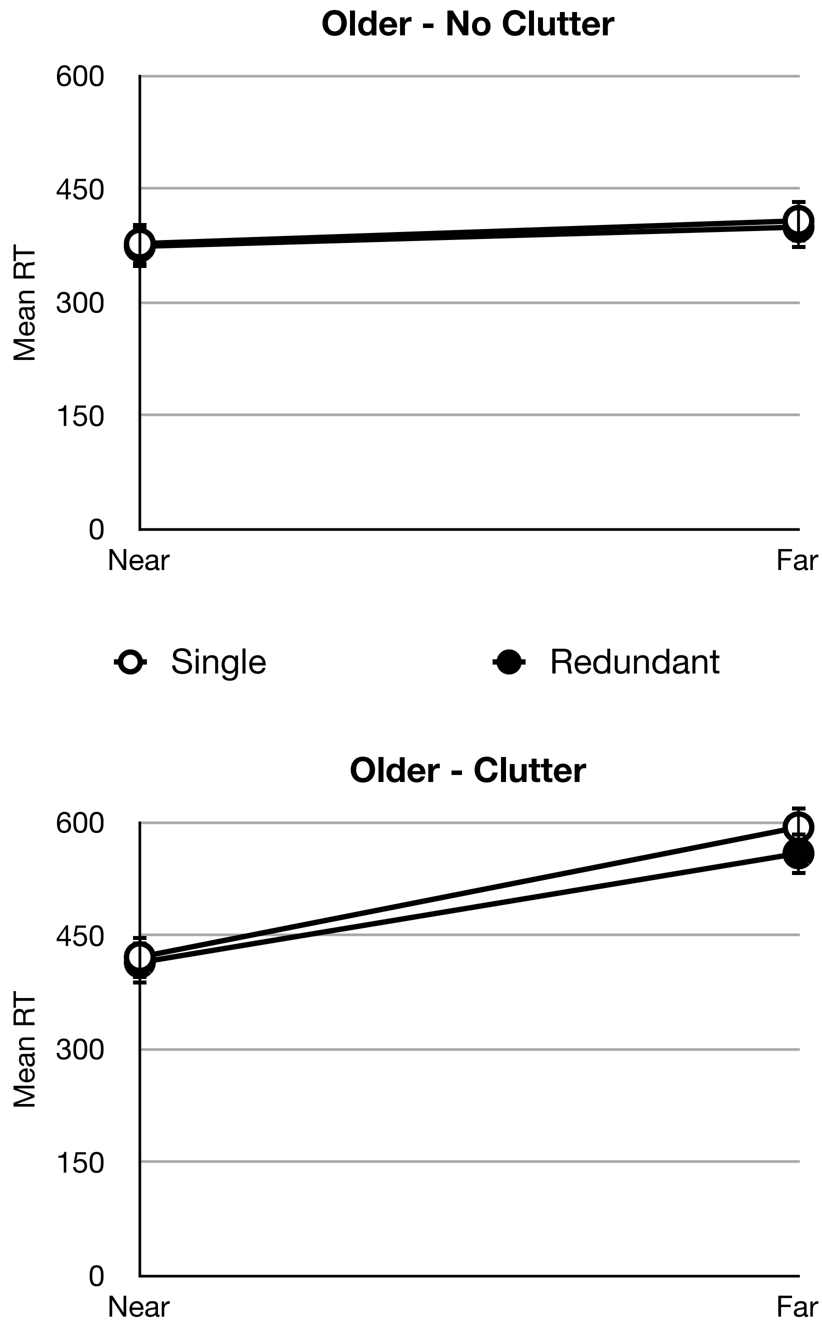


Figure 14. Mean error rates for the three target conditions as a function of retinal eccentricities for the no clutter (top) and clutter conditions (bottom) for young adults in Experiment 3.

Figure 15. Mean error rates for the three target conditions as a function of retinal eccentricities for the no clutter (top) and clutter conditions (bottom) for older adults in Experiment 3.

Figure 16. Geometric means for the no-clutter and clutter conditions as a function of eccentricities for young (top) and older subjects (bottom) in Experiment 3.

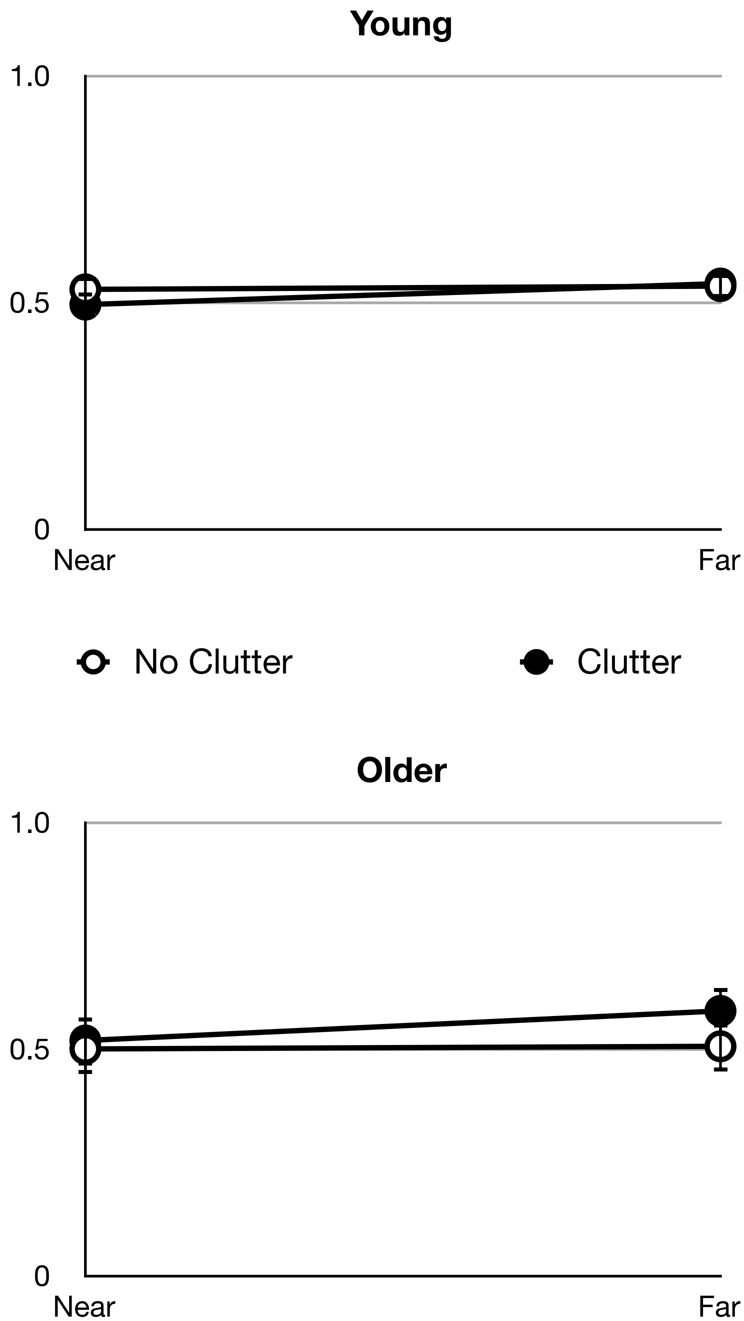
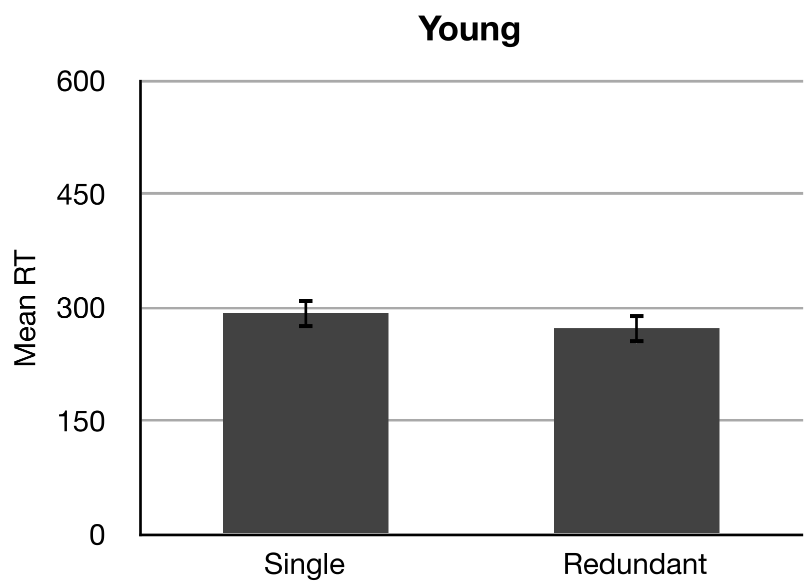


Figure 17. Mean RTs for the single and redundant-target conditions for young (top) and older (bottom) subjects in Experiment 4.



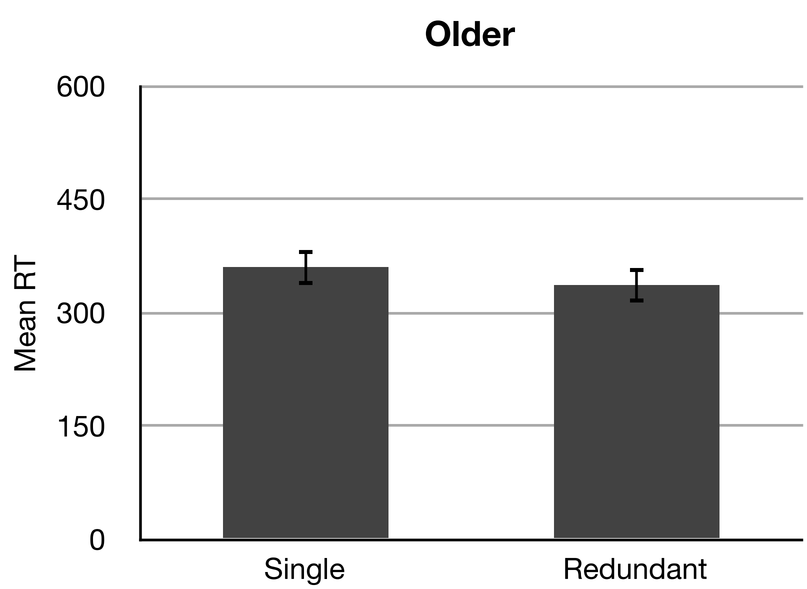


Figure 18. Mean error rates for the single and redundant target conditions for young (top) and older (bottom) subjects in Experiment 4.

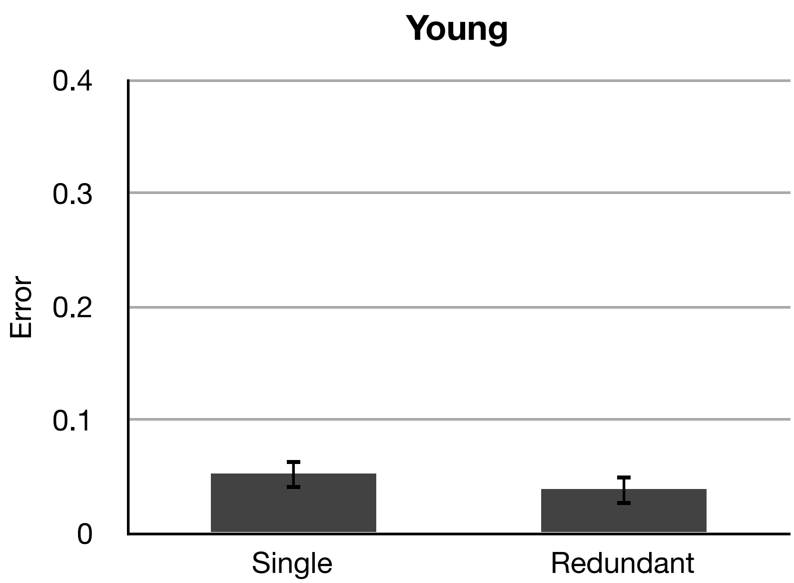


Figure 19. Forest plots of the effect sizes of the clutter manipulation, differences between the no-clutter and clutter conditions, across the three experiments for young (top) and older (bottom) age groups on the workload capacity measure. MA is the result of meta-analysis of the three experiments. Error bars represent 95% CIs.

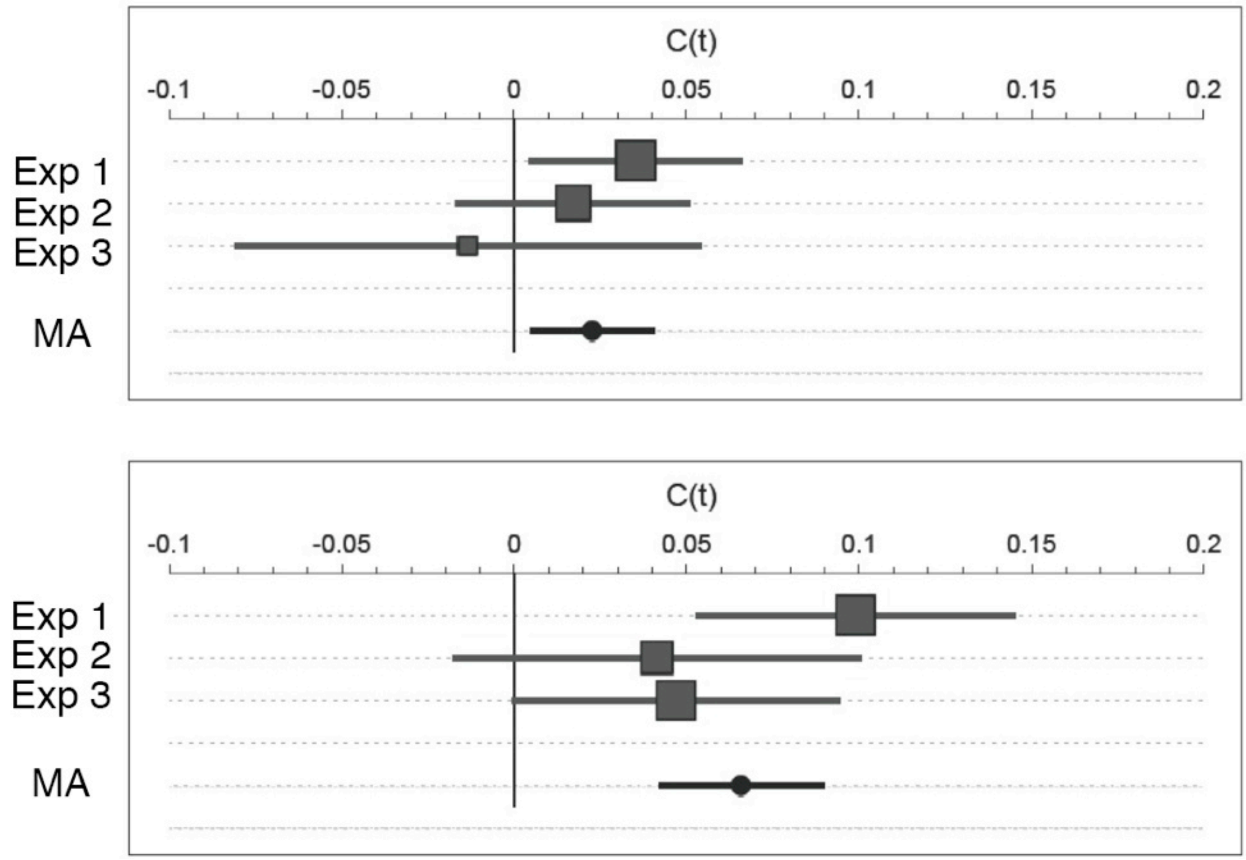


Figure 20. Forest plots of the effect sizes of the eccentricity manipulation, differences between the near and far conditions, across the three experiments for young (top) and older (bottom) age groups.

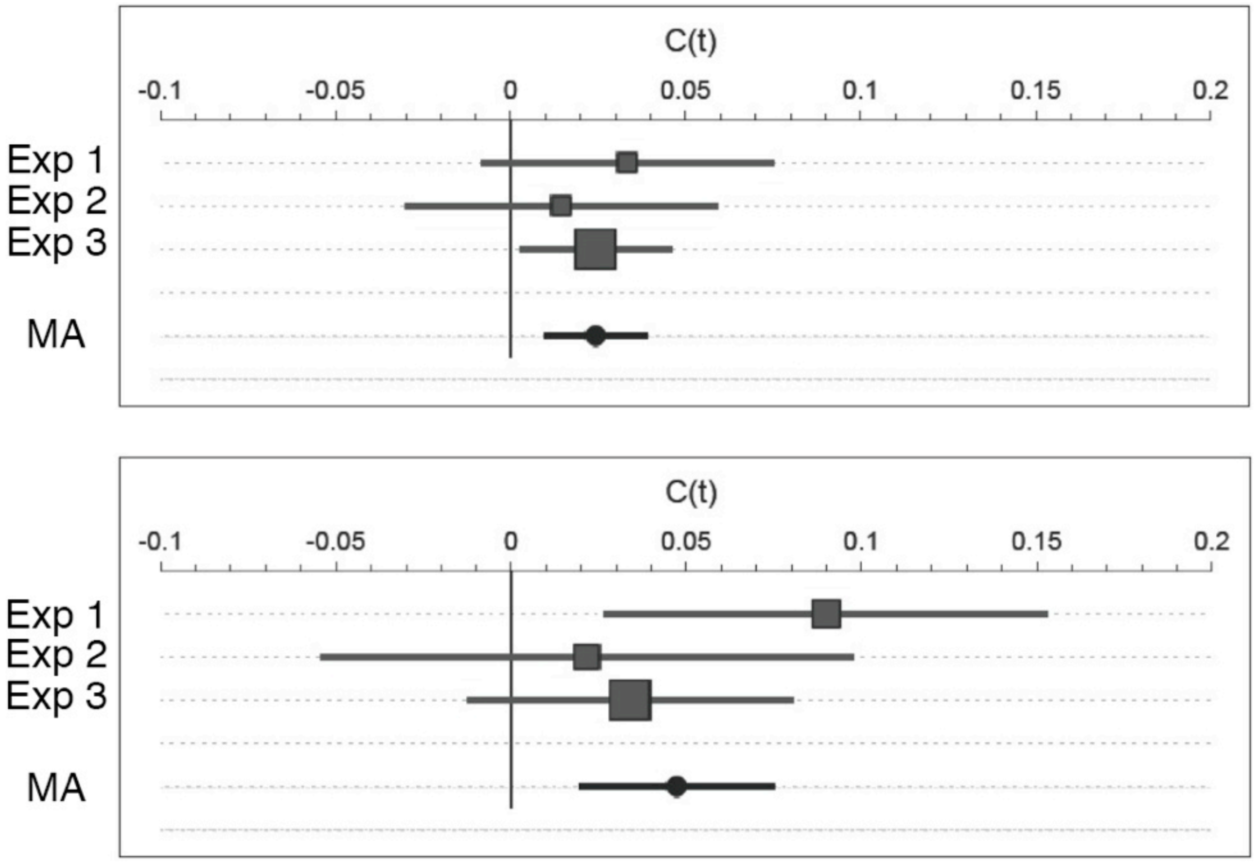


Figure 21. Forest plots of grand means of workload capacity across the three experiments for young (top) and older (bottom) age groups.