Age-related changes in visual temporal order judgment performance: Relation to sensory and cognitive capacities

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ARTICLE INFO

ABSTRACT

Five measures of temporal order judgments were obtained from 261 participants, including 146 elder, 44 middle aged, and 71 young participants. Strong age group differences were observed in all five measures, although the group differences were reduced when letter discriminability was matched for all participants. Significant relations were found between these measures of temporal processing and several cognitive and sensory assays, and structural equation modeling revealed the degree to which temporal order processing can be viewed as a latent factor that depends in part on contributions from sensory and cognitive capacities. The best-fitting model involved two different latent factors representing temporal order processing at same and different locations, and the sensory and cognitive factors were more successful predicting performance in the different location factor than the same-location factor. Processing speed, even measured using high-contrast symbols on a paper-and-pencil test, was a surprisingly strong predictor of variability in both latent factors. However, low-level sensory measures also made significant contributions to the latent factors. The results demonstrate the degree to which temporal order processing relates to other perceptual and cognitive capacities, and address the question of whether age-related declines in these capacities share a common cause.

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1. Introduction

Temporal slowing in the visual system as a result of healthy aging has been documented in a number of different paradigms that range from simple foveal flicker sensitivity (Kim & Mayer, 1994) and impulse response function estimation (Shinomori & Werner, 2003) to more complex stimuli such as temporal continuity judgments (Craig, Rhodes, Busey, Kewley-Port, & Humes, 2010; Kline, Scialfa, Lyman, & Schieber, 1990) and second-order motion (Habak & Faubert, 2000). Other senses have documented similar slowing, including the tactile (Gescheider, Valetutti, Padula, & Verrillo, 1992; Humes, Busey, Craig, & Kewley-Port, 2009) and auditory modalities (Wingfield, Poon, Lombardi, & Lowe, 1985). Cognitive capacities such as speed of processing also have strong age-related declines (Salthouse, 1996), and there is a growing acknowledgment of the relation between lower-level sensory functioning and higher-level cognition. This has become known as the common cause hypothesis (Baltes & Lindenberger, 1997; Lindenberger & Baltes, 1994, 1995, 1997; Lindenberger, Scherer, & Baltes,

2001). A common antecedent or cause could explain slowing seen in different modalities and perhaps cognitive declines as well. The common cause may be a physiological mechanism such as reduced blood flow, or a 'sensory starvation' mechanism in which cognition suffers from poor sensory quality. This view has found somewhat mixed support (Lindenberger & Ghisletta, 2009) and there are suggestions that the nature of the testing affects the degree of relation between cognitive and sensory assays (for review, see Hofer, Berg, & Era, 2003). Complicating such links is the fact that even relatively simple perceptual tasks require a set of operations that include perceiving one or more items, separating them in time, representing them in memory, and reproducing them verbally. Uncompensated declines in any one of these processes could reduce performance, and thus to fully understand a decline with age one must parcel out the various influences that affect visual temporal processing tasks.

Scialfa (2002) recently addressed the role that sensory factors play in cognitive tasks and the changes that result with aging, and suggested ways to separate out sensory factors using an individual differences approach. His primary point was how to reduce the likelihood that sensory factors would affect measures that are designed to tap more cognitive processes. However, vision scientists are primarily interested in perceptual mechanisms, and if

there is an age- or cognitive-related component that is affected by aging, this may help distinguish the various factors that affect performance on the perceptual tasks.

Perceptual speed appears to be a very sensitive marker of cognitive aging (Lindenberger & Ghisletta, 2009; Salthouse, 1996) and therefore temporal processing measures are a reasonable domain to address the relation between sensory declines and cognitive aging. The goal of the present study is to use several variants of temporal order judgments in conjunction with measures of cognitive and basic sensory functioning to address age-related changes in temporal processing and their relation to these other factors. If several dissociable factors combine to determine performance in a perceptual task such as temporal order judgments, these factors may be affected in different ways by the aging processes, and we will use an individual differences approach to distinguish these factors. Although visual information processing tasks have been addressed using psychophysical techniques on typically relatively small numbers of participants, a growing literature has applied individual differences approaches to basic visual processing mechanisms. Examples include contrast sensitivity and spatial frequency channels (Peterzell & Teller, 1995, 1996; Peterzell, Werner, & Kaplan, 1993, 1995; Scialfa, Kline, & Wood, 2002), visual attention (Peterzell, 1993), and higher-level function such as color naming (Lindsey & Brown, 2006).

As noted, even relatively simple judgments such as two-choice categorization tasks can have several components that must be accounted for by models with parameters to capture the different elements (Ratcliff, Thapar, & McKoon, 2006a, 2006b, 2007). Neural elements of the visual system may contribute to slowing, as might memory and response systems. These systems will likely interact since degraded output from the perceptual system may change the functioning of subsequent memory operations. In addition, more complex perceptual tasks seem to show larger effects of aging than simpler tasks such as detection (Faubert & Bellefeuille, 2002; Habak & Faubert, 2000; Haegerstrom-Portnoy, Schneck, & Brabyn, 1999) even when temporal factors do not play a major role in the experiments (Faubert, 2002; Faubert & Bellefeuille, 2002). Thus temporal order tasks may in fact be affected by several different reductions in performance due to aging, each of which may have a separate time course of decline, and these may depend in part on the complexity of the tasks.

In the present study, testing was done using psychophysical procedures, which allows for threshold measurements of a critical stimulus onset asynchrony (SOA) in each task for each subject, as well as estimates of the slope of the psychometric function. Our use of a large number of participants allows for not only group comparisons but also individual difference analyses within age groups (Miller & Schwarz, 2006; Szelag, Kanabus, Kolodziejczyk, Kowalska, & Szuchnik, 2004; Szymaszek, Sereda, Poppel, & Szelag, 2009). This latter point is important, first, because the performance from older subjects often shows considerable variability (Stevens & Cruz, 1996) and second, because correlations across the extremes of the age continuum, which is often done with smaller samples, may lead to inflated correlations (Hofer et al., 2003). In fact, from an individual differences perspective, variability within a group allows for an analysis of covariance that can lead to model testing.

Temporal order judgments (TOJs) have a long tradition in psychophysics (Boring, 1950) and much of the early work focused on issues of attention and prior entry for judgments across modalities. We measured temporal order judgments in four different tasks using sequentially presented letters on an oscilloscope. In three of the tasks subjects had to identify the letters and report them in the correct order, specifically: two letters in the same location, four letters in the same location, and two items in different visual hemifields. In the fourth task, observers simply reported which of two locations appeared first without regard to letter identity, which is similar to the traditional TOJ tasks. In addition we measured basic letter identification in isolation and repeated the two-item task using individual brightness thresholds to control for stimulus visibility on an individual participant basis. These tasks tap a relatively wide range of perceptual and cognitive capacities and differ in their complexity, which may in turn produce larger or smaller aging effects. To further address the issue of the relation between perception and cognition, we include basic measures of flicker sensitivity and gap detection in our analyses, as well as standard intelligence and processing speed measures using the WAIS (WAIS-III; Wechsler (1997)).

2. Method

2.1. Participants

We collected data from three groups of participants, as part of a larger project that measures temporal processing in the visual, tactile and auditory modalities. We tested 146 elders (aged 60–88, with a median of 71 years, with an inter-quartile range of 10 years, 80 were female and 66 were male), along with 71 younger participants (aged 18–30 with a median of 48 years and an inter-quartile range of 4 years; 52 were female and 19 were male) and a smaller number of middle-aged participants (44, aged 40–55 with a median of 48 years and an inter-quartile range of 7 years; 28 were female and 15 were male).

Participants were recruited for the study through advertisements in the local newspaper, flyers in community centers and retirement homes, and postings on the Indiana University campus. Our psychophysical testing is quite demanding, requiring over 40 h of testing for each participant throughout the study. The data presented in the current document required approximately 20 h of testing per subject. Because of the demands of testing we required our participants to be in good health, to pass an eye examination and several other auditory and tactile screenings, and to have 20/40 vision. They also had to be able to make their own way to the testing site. Further details of inclusion and screening are found in (Humes et al., 2009). We excluded conditions such as amblyopia, congenital ocular nystagmus but allowed diabetes, cataract, glaucoma, and macular degeneration.

2.2. Stimuli and procedures

Fig. 1 provides an overview of the stimuli for the different tasks. Testing procedures for the current experiments were done under relatively dim illumination using a scanning oscilloscope (Tektronix model 608 with a P15 phosphor) and a point-plotting display buffer (Finley, 1985). This phosphor has an extremely rapid decay time and allowed for a rectangular 30×30 pixel image to be projected onto the screen with a 1 ms refresh rate. The P15 phosphor is green and projected on a white screen.

The letters were embedded in the background patch at luminance values slightly higher than the background. Display luminance values were computed from contrast using the formula Luminance = $(1 + contrast) * BackgroundLum$. The background patch had a fixed luminance of 40 cd/m^2 and the unilluminated section of the oscilloscope had a luminance of .75 cd/m^2. Viewing conditions were dim but not dark, with indirect lighting provided by three incandescent bulbs illuminating the ceiling in a corner of the room as to avoid reflections on the oscilloscope. When viewed from a distance of 38.1 cm, the image subtended 1.45 degrees horizontally and vertically.

The stimuli chosen for the experiment were the letters M, P, O and T rendered in 12 point Times font. These letters were
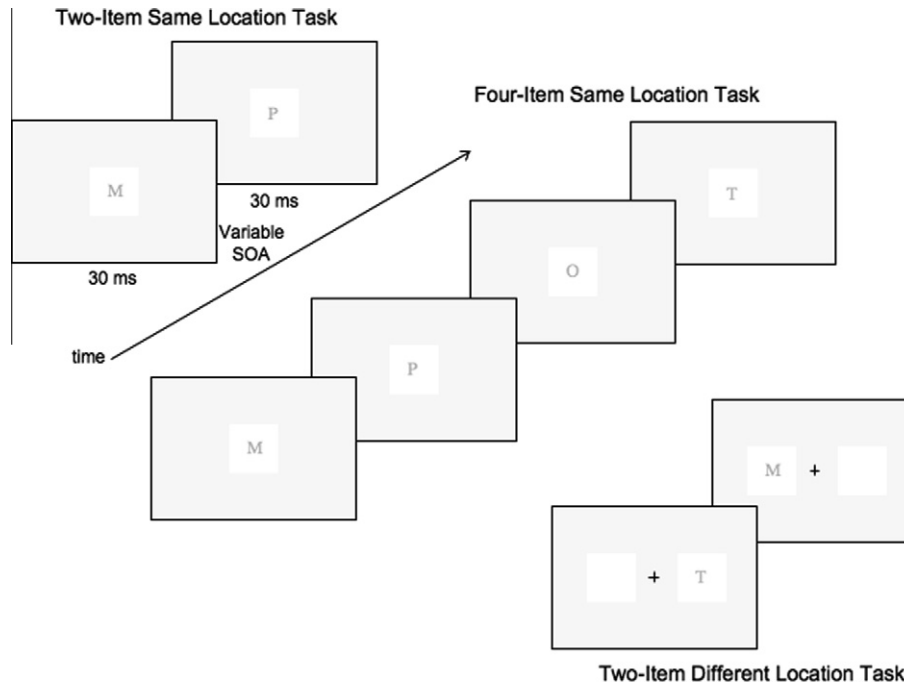
Fig. 1. Example trials with two and four items, in the same and different locations. In most conditions the participant reported the letters, in order. The exception was the two-item, Report Location task in which the participant reported the side of the letter presented first.

embedded in the patches and subtended 1.16 degrees of visual angle at their widest extents. These letters were chosen through a computer search that identified this set as having approximately equal overlap as measured by the number of overlapping and non-overlapping pixels for each pair-wise letter comparison. Fig. 1 illustrates the four stimuli and examples of the different temporal order tasks. For each of the tasks below, the letters were presented for 30 ms and were separated by one of six stimulus onset asynchrony (SOA) values between each letter. Note that the SOA can be less than 30 ms, in which case the two letters will physically overlap on the screen although overlapping pixels from the two letters were not twice as bright as they would be otherwise.

Data for each of the temporal order tasks below was collected using the method of constant stimuli and six fixed SOA values. To established these fixed values, two pilot blocks were run using widely spaced SOA values with the goal to obtain three SOA values with accuracy above the threshold value and three below. The SOA values were adjusted after each run of 72 trials. All participants started off with the same six wide SOA values so as not to discriminate against one particular group.

The final threshold performance for each task was computed by combining the data for the last three runs, each of which used a relatively narrow range of SOA values. We fit a weibull psychometric function to this combined dataset to find a threshold SOA for each subject in each task. The actual accuracy level used to obtain this threshold varies by task, not only because each task has a different chance level, but also the chance level for a particular task depends on whether the subject experiences masking as discussed in a later section.

Each psychometric function was based on 216 trials with the exception of the letter contrast task, which was based on approximately 180 trials. All participants completed the tasks below in the order listed.

2.2.1. Single-item identification task

This task is different than the others, in that we presented a single item in isolation for 30 ms and varied the contrast of the letters using adaptive procedures to find the contrast value that produced 90% correct for each participant. The goal was to determine baseline contrast sensitivity for our stimuli and also to provide a contrast level that could be matched for discriminability across participants.

Unlike the SOA tasks, in this task the letter contrast was continuously adjusted according to tracking procedures (Levitt, 1971) using two interleaved tracks that each used a 3-up, 1-down tracking rule to place contrasts near the 90% threshold value. This task not only gave participants experience with the letters, but also provided a contrast value for our last task (listed below). The tracking procedures were used to place contrast values near the estimated threshold, but the weibull function was fit to all of the data, weighted by the number of trials at each contrast level. The left panel of Fig. 2 provides an example of the psychometric function for this task.

Each run was terminated after seven reversals of each of the two independent tracks. We pooled the data across three blocks of approximately 90 trials per block and fit one psychometric function to find the 90 percent threshold contrast for each subject. This final value measures each participant's ability to recognize letters in isolation, and provides a value for the individual contrast temporal order task describe later.

2.2.2. Two-item identification task

The letter contrast for this task and the next was fixed at .16 for most participants unless they had a very high individual value as assessed by the first task above (greater than .24 in most cases, which were nearly always elders). The letter contrast was increased to .24 (29 elders and two middle aged), .35 (six elders) and .55 (three elders) in order to allow the participants to perform the task.

In this task a fixation point would appear between trials, then disappear for 750 ms upon a subject-initiated key press, and then two letters (selected from the set of four letters) would appear in quick succession. The letters were never the same, and the subject's task was to verbally report the two letters in order to the
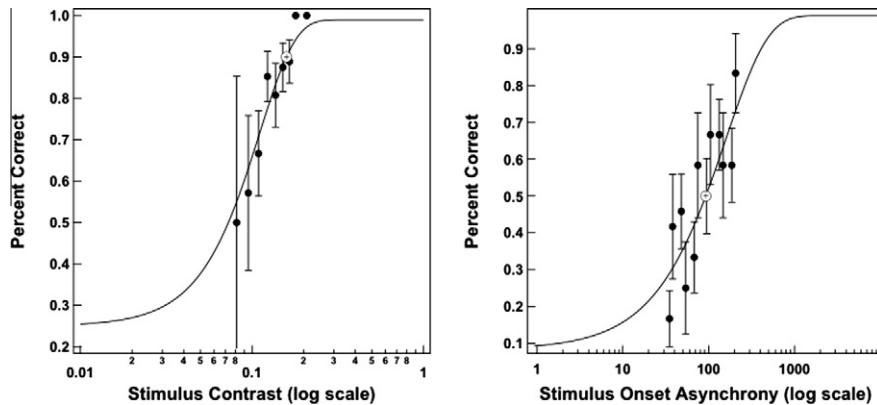
Fig. 2. Psychometric functions for various tasks, with the proportion of correct trials (where all letters were correctly identified in order) plotted for various SOA values used in each experiment. *Left panel*: Example psychometric function from the letter identification condition, fitting 90% thresholds as contrast is manipulated. Letter contrast is presented on a log scale. *Right panel*: Example psychometric function from the two-item, same location task. Error bars represent the standard error of the mean, which is given entirely by binomial variance and the number of trials at that stimulus level. The stimulus onset asynchrony is measured in milliseconds and is presented on a log scale.

experimenter, who typed in the responses. The subject then received auditory feedback from the computer in the form of recorded "correct" and "incorrect" phrases, along with their responses (vertically on the left side of the screen) and the correct responses (vertically on the right side of the screen). The feedback stayed up for 1200 ms, and was replaced by the fixation point, which indicated the availability of the next trial.

There were 12 unique pairs. Chance is therefore 1/12 and we determined 50% thresholds by fitting a weibull function with freely-varying slope and threshold parameters, a lower asymptote of 0.083 and an upper asymptote of 0.99. The right panel of Fig. 2 provides an example psychometric function for this task.

2.2.3. Four-item identification task

This task is similar to the two-item task, with the exception that there were four items presented sequentially. We excluded sequences that had direct repeats (e.g. MMPT), as well as tracks that included double-repeats (e.g. MPMP). However, far repeats were possible (e.g. PMPT). The SOA was identical within a trial for the delay between items 1 and 2, 2 and 3, and 3 and 4. Chance is approximately 1/100 given the allowable sequences, and we used 50% thresholds to find the critical SOA in this task.

2.2.4. Two item, different-location task

We rearranged the display to include two adapting fields to the left and right of fixation. The center of each field was 2.2 degrees from fixation on the horizontal meridian, and each field subtended the same 1.45 degrees in each direction as the previous tasks. The refresh rate for this task and the next was 2 ms due to the fact that we are drawing twice as many pixels each refresh. The stimulus duration for each letter was still 30 ms per item.

The procedures were similar to the two-item task described above, with the exception that the letters always appeared in different hemifields and the participant had to report the identity of the two letters in the order in which they were presented. All other procedures were identical to the two-item task above. The letter contrast for this task and the next was fixed at .35 for all participants. This value was chosen based on preliminary pilot testing on a group of elder participants. For the reasons indicated in Section 3, chance is difficult to determine in this task and we fit both 50% and 75% thresholds.

2.2.5. Two item, Report Location task

This task was designed to reduce the cognitive load of the task. The displays were physically identical to the two-item different-

location task, but the subject merely had to indicate on which side the first letter appeared. Feedback was given, chance is now 50%, and we fit 75% thresholds.

2.2.6. Two item Individual Contrast task

This task was identical to the two-item identification task, in that the two letters were presented in the same location. However, we used the 90% contrast threshold value obtained from the single-item task as the contrast value for the letters. Thus each participant operated at a level in which stimulus visibility was approximately equated across observers. Chance was 1/12 and we fit 50% thresholds.

2.2.7. Two additional measures

In addition to these temporal order judgment tasks, we gathered data on basic temporal processing performance and spatial contrast sensitivity. These methods are briefly described below. Additional details can be found in (Humes et al., 2009), which contains the complete methods and results for the first two tasks before.

2.2.8. Temporal contrast sensitivity functions

We measured the temporal contrast sensitivity function for each participant using a red LED flickering at 2, 4, 8 and 32 Hz around a constant pedestal. Participants performed two-interval forced choice flicker detection and the contrast of the LED was adaptively changed over trials to find a contrast threshold for each frequency.

2.2.9. Gap detection performance

As a measure of low-level temporal processing, we embedded a variable-sized gap in the middle of a 300 ms brightness increment of the LED. Observers indicated which of two intervals contained the gap, which was adaptively varied to find a critical duration of the gap that yielded 75% correct identification.

3. Results

Our general approach to the results will be to (1) document age-related differences across the different tasks, (2) use robust regression techniques to address the magnitude of change across different subgroups and (3) use structural equation modeling to identify elements of the TOJ performance that relate to perceptual and cognitive factors such as contrast sensitivity, low-level temporal processing and memory.

Our use of robust estimation techniques is motivated by the following considerations. Classical least-squares estimation algorithms give equal weight to all observations and are therefore strongly influenced by outliers. Robust estimation procedures, on the other hand, tend to give such observations less weight while still preserving all of the data and the statistical power that the full dataset conveys. The use of non-parametric tests such as median tests also provides similar use of the full dataset without undue influence from extreme values.

For the tasks listed below, we used the following measures to deal with missing data. Manual inspection of all psychometric functions revealed obviously bad fits that were set to missing, although we will still use aspects of this data as described in subsequent sections. We have the following numbers of missing data from the elders: 2 are missing from the Letter Contrast Threshold task, 4 from the Two-item Same Location task, 9 from the Four-Item Same Location task, 26 from the Two-Item Different-Location task for reasons described below, 3 from the Report Location task, and 7 from the Individual Contrast task. This results in about 3.4% of our data that is missing. No data are missing for the young participants, and only 1 subject has missing data from the Individual Contrast task from the middle-aged group. For the modeling work reported in later sections we left these conditions as missing cells to be filled in using linear regression estimation techniques. However, for group comparisons as well as robust regression and robust correlation computations, we set these values to an arbitrarily large value to reflect the fact that our measuring techniques could not assess the poor performance of these subjects, although we do know that they are poor and therefore group at the high end of the measurement scale. The non-parametric and robust algorithms acknowledge the existence of these high values without being overly affected by them as would a parametric technique.

4. Group comparisons of psychometric functions

Table 1 presents the median performance for the different temporal order judgment tasks, along with the letter contrast thresholds and median ages for each participant subgroup. We discuss the data from the same-location and the different-location tasks separately due to the fact that the peripherally-presented different-location items were shown at higher contrasts to compensate for the peri-fovial locations. Group comparisons were done using the non-parametric Kruskal–Wallis, which tests for equality on the medians. Post hoc pair-wise comparisons between each group were conducted using the *kruskalmc* function in the *pgirmess* library in R, which adjusts for multiple comparisons. The critical difference for the comparison between young and elder participants for the tests reported below is 26.1 at an alpha level of 0.05. The critical difference for young vs. middle aged is 35.0, and the critical difference between middle aged and elder is 31.5. As discussed below, virtually all pair-wise comparisons were significant.

4.1. Letter contrast task

The left panel of Fig. 2 presents an example psychometric function, fit with a weibull curve that allows estimation of the 90% percent correct threshold. The weibull function had a slope and threshold estimated freely, chance was fixed at .25 and the upper asymptote was set to .99 to allow for a 1% key press lapse rate. In virtually all cases the psychometric functions were well-fit by the weibull functions.

Panel A of Fig. 3 presents the box plot data for the letter contrast task, which reveals significant group differences ($\chi^2(2, N = 261) = 119.4$, $p < .001$). The young group performed significantly better than the elders (observed difference, OD = 117.9). The middle-aged group fell in between the two groups, with a distribution that has more overlap with the elders. The middle-aged group performs significantly worse than the young group (OD = 59.6) and better than the elder group (OD = 58.3).

Panel A of Fig. 4 plots the scatter plot between participant age and performance in the letter contrast task. The dashed and solid lines plot the median values of age for each group against the median performance for each group. This provides an indication of the degree of change across the two groups. To better quantify the relation between age and performance, we computed the robust regression (lmRob in the R statistical package) between performance and participant age. These results are presented in Table 2 for all subjects (left column) and broken down by subgroup comparisons (young vs. middle aged and middle aged vs. elders) and finally a computed ratio of the two slopes. We interpret these slopes and slope ratios as follows. First, it should be acknowledged that these are not longitudinal data and therefore age-related claims should be made with caution. Cohort differences might drive much or potentially all of the age group differences. Second, with this caution in mind, the literature suggests that some tasks produce an acceleration in deficits in older participants which may be related to increased processing required by some perceptual tasks (Bertone, Habak, & Faubert, 2000; Faubert & Bellefeuille, 2002; Herbert, Overbury, Singh, & Faubert, 2002). This produces an abrupt decrease in performance in elders in some tasks (Herbert et al., 2002; Tang & Zhou, 2009) while relatively stable rates of change over age groups in other tasks (Kennedy, Tripathy, & Barrett, 2009). Within this context, it is of interest to compare the rate of change for younger/middle-aged and middle-aged/elder participants to determine in which decade we see the largest declines.

For the letter contrast task, all three regression slopes were significantly different from zero. The final column of Table 2 presents the ratio of the slopes of the two subgroups. For letter contrast, the slope for older participants is twice as large as that for younger participants, demonstrating a potential acceleration in the deficits with this measure in the latter years.

The significant regression slope seen with all participants demonstrates that letter identification requires higher levels of contrast for older participants. This suggests that some performance differences seen between young and elder participants on the SOA tasks below may result from poorer contrast sensitivity in the elder population. We will address this issue in two ways. First, we have included one task, the two-item same location Individual Contrast task, which equates for letter discriminability for all participants. Additionally, where necessary we can include letter discriminability as part of our structural equation modeling presented in a later section.

Table 1
Median values for each age group for the five temporal order tasks, along with the median participant age in each group and the Letter Contrast Threshold values.

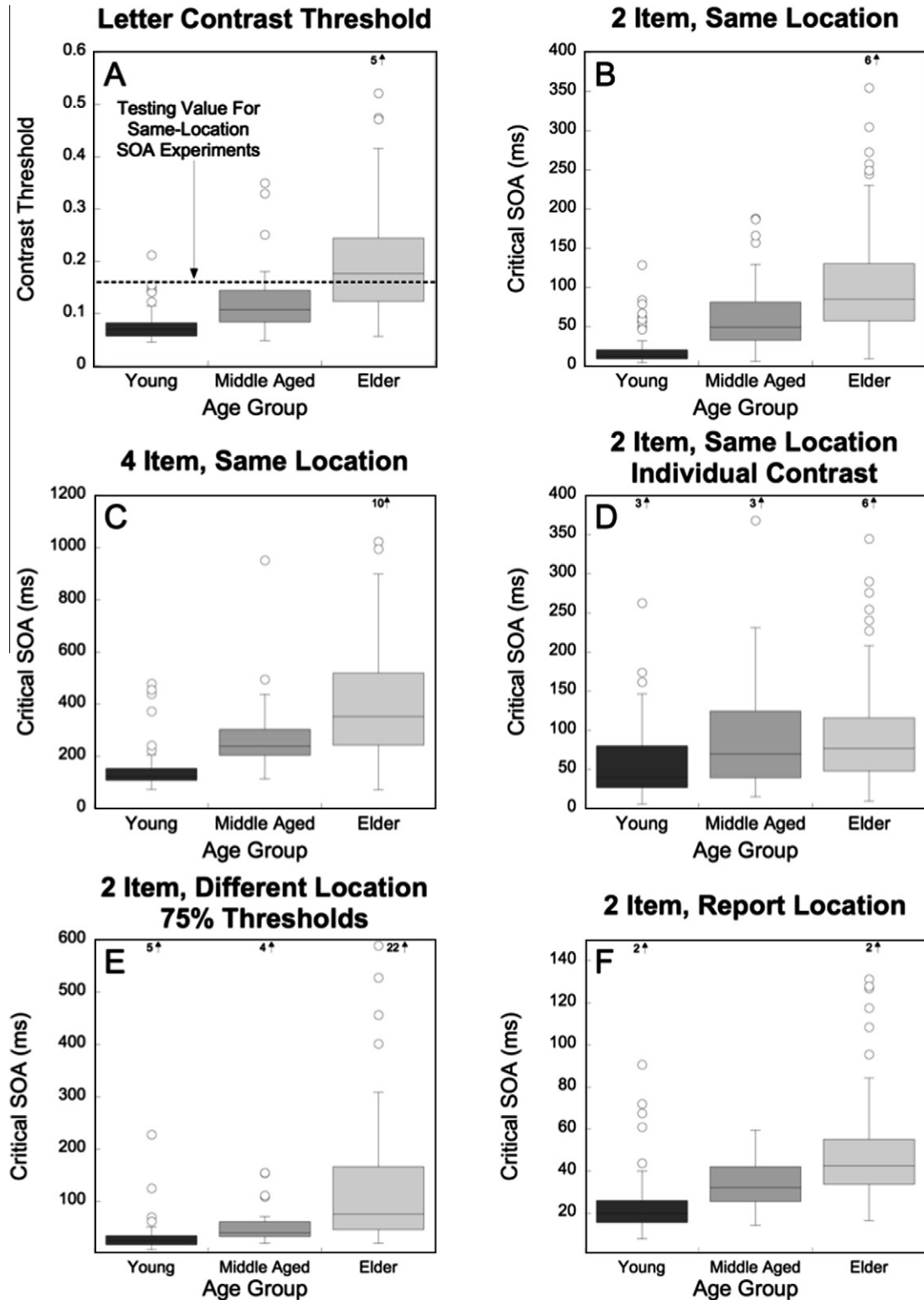| Age group	Age (years)	Letter Contrast Threshold (unitless)	Two Item, Same Location (ms)	Four Item, Same Location (ms)	Two Item, Individual Contrast (ms)	Two Item, Different Location (ms)	Report Location (ms)
Young	21	0.0691	12.7	123.6	40.0	25.5	20.4
Middle aged	48	0.1076	49.2	239.1	70.1	39.6	32.1
Elder	70	0.1768	85.4	352.8	76.8	75.8	42.5

Fig. 3. Box plots of data from the three age groups for letter contrast thresholds and five measures of temporal order judgment performance. The size of the box represents the 25th and 75th percentiles, while the whiskers extend to the minimum value and a value that is 1.5 times the size of the box where there are outliers that exceed this value. Individual outliers are shown as individual points, and those that exceed a reasonable range are illustrated with arrows and the number of extreme outliers (top of each graph).

4.2. Same-location tasks

The right panel in Fig. 2 illustrates an example psychometric function for the two-item, same location temporal order task. Most subjects were well-fit by the weibull function. Panel B of Fig. 3 presents the box plots for this task for each age group, which reveals significant group differences ($\chi^2(2, N = 261) = 121.8$, $p < .001$). Table 1 provides the median values for each age group, and there
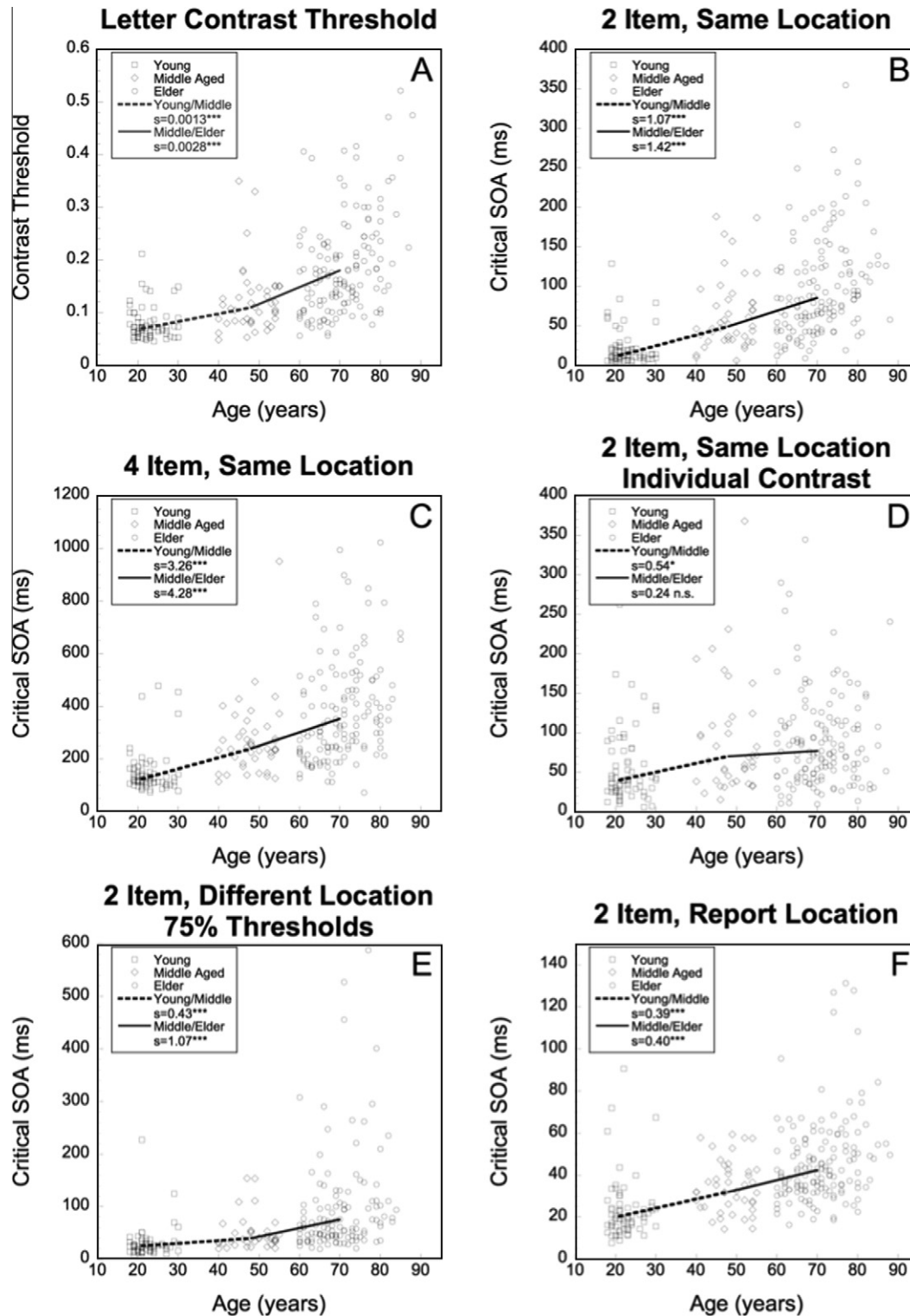
Fig. 4. Scatter plots of Letter Contrast Threshold performance and five measures of temporal order judgment performance, plotted against participant age ($N = 261$). Dashed lines connect the median age and median performance of young and middle-aged participants, while solid lines connect the median age and median performance of middle-aged and elder participants. The figure legend lists the slopes (abbreviated by s) of each of the associated robust regression lines for each group, along with the significance level ($^{***}p < 0.001$; $^{*}p < 0.05$; n.s. = not significantly different from zero).

are strong group differences between young and elder participants (OD = 120.3). The middle-aged group falls in between the two groups, and they are both worse than the younger participants (OD = 78.2) and better than the elders (OD = 42.1).

Panel B of Fig. 4 plots the scatter plot between participant age and performance in the two-item, same location task. The dashed

and solid lines suggest effects of age in both subgroup comparisons, which is borne out by the results Table 2. All three regression slopes were significantly different from zero for this task, demonstrating strong age effects across all ages. The final column of Table 2 presents the ratio of the slopes of the two subgroups, which is close to 1 suggesting consistent age declines across the lifespan.

The data for the four-item, same location task is very similar to the two-item version, with the exception of the change in scale. Panel C of Fig. 3 presents the box plots for the four-item, same-location tasks for each age group, which demonstrates significant group differences ($\chi^2(2, N = 261) = 121.8$, $p < .001$). There are again strong differences between young and elder participants as illustrated by Table 1 (OD = 120.2). The middle-aged group falls in between the two groups, and they are both worse than the younger participants (OD = 75.3) and better than the elders (OD = 45.0).

Panel C of Fig. 4 plots the scatter plot between participant age and performance in the four-item, same location task. The dashed and solid lines suggest effects of age in both subgroup comparisons, which is again borne out by the results Table 2. All three regression slopes were significantly different from zero for this task, demonstrating strong age effects across all ages. The final column of Table 2 presents the ratio of the slopes of the two subgroups, which is again close to 1 suggesting consistent age declines across the lifespan.

4.3. Individual Contrast temporal order task

The results of the two-item, same location, individual contrast task are found in panel D of Fig. 3, which also reveals significant group differences ($\chi^2(2, N = 261) = 22.0$, $p < .001$). The goal of this condition is to reduce the effect of reduced letter discriminability in elders, because each participant is now run at their own individual discrimination contrast value from the Letter Contrast task. Note that our pilot testing procedures were fairly successful in anticipating the median for the elder participants because the median for this task (76.8 ms) is fairly close to that obtained in the two-item, same location task (85.4 ms) as shown by the medians in Table 1. However, the younger participants now demonstrate longer critical SOA values when run at their own contrast values (40.0 ms vs. 12.7 ms in the original task). This increase is not enough to move them all the way to the elder performance, as there is still a significant difference between the two groups (OD = 49.5). Thus the letter contrast sensitivity differences seen between the two groups contributes to differences between young and elder participants on temporal order performance, but it is not the only factor. There appear to be other factors that dictate performance that are unrelated to contrast sensitivity. The middle-aged participants perform significantly worse than the younger participants (OD = 46.8) but they are not significantly different than the elders (OD = 2.7; n.s.).

These results are confirmed by the regression slopes plotted in panel D of Fig. 4. The regression slope for all participants is significant as demonstrated by the left column of Table 2, as is the regression slope for young and middle-aged participants. However, the regression slope for middle-aged and elder participants is not significant. The ratio of the two slopes is 0.441, suggesting that much of the decrease in performance occurs for younger participants.

4.4. Different-location tasks

Panel E of Fig. 3 presents the data for the two-item, Different-Location task. Recall that the different-location tasks were run at a higher contrast value that was determined by pilot testing to be .33 to ensure letter discriminability in the elders. Unfortunately, time constraints did not allow estimation of letter contrast sensitivity in the periphery for all participants, nor do we have an individual contrast Different-Location task as a consequence. Thus all participants were run at a contrast of .33.

There are two complications in analyzing the data from the two-item Different-Location task. First, some of the younger participants never produced accuracy values below 50% for any SOA, even with quite short SOAs (on the order of less than 10 ms). Second, some elders simply could not perform the task at any SOA resulting in missing data (26 out of the 146 elders).

The first issue, common for the young participants produces a problem for the threshold estimation. If the participants could see the letters clearly they would never perform below 50% accuracy, because they could always see the letters and would just have to determine the order of the letters. Estimating a 50% threshold for participants in this category is problematic. To address this, we also fit 75% thresholds, which could be reliably done for virtually all participants. An alternative solution would be to allow the lower asymptote parameter to freely vary, and define the threshold accuracy for each participant at the percent correct mid-way between the lower and upper asymptotes. We attempted this solution, but found that the lower asymptote was not reliability estimated for many participants, in part because we do not have much data at the lowest accuracy levels (our goal was to obtain trials near the middle of the scale, rather than the lower end). Thus the estimates of threshold by this definition were not reliable. Regardless of these complexities, we can still estimate the critical SOAs for each participant using both threshold definitions, with the understanding that the 75% thresholds may be a more accurate representation of performance. In practice, both measures produced similar results, and we present the data only for the 75% threshold.

As shown in the panel E of Fig. 3, the data contains strong group differences ($\chi^2(2, N = 261) = 84.2$, $p < .001$). The young outperform the elders (OD = 99.1) as well as the middle-aged participants (OD = 50.6). The middle-aged participants outperformed the elders (OD = 48.5).

Panel E of Fig. 4 plots the scatter plot of performance on this task against participant age. The robust regression slope for all participants is significant, as illustrated by Table 2. In addition, both the younger group slope and the older group slope are significant, and the middle aged/elder slope is more than twice the younger/middle-aged slope. This suggests that the effects of age accelerate later in life, although of course only longitudinal data can provide definitive evidence of such effects that are free of cohort differences.

The data for the Report Location task are shown in panel F of Fig. 3. This task produced very clean psychometric functions, in part because letter discriminability plays no a role in this task. The critical SOAs are very short for all three groups, as illustrated by the right column of Table 1 and we see significant group differences ($\chi^2(2, N = 261) = 86.4$, $p < .001$). Younger participants outperformed the elders (OD = 100.8). The middle-aged participants are worse than the young subjects (OD = 55.8) and better than the elders (OD = 45.0).

Panel F of Fig. 4 illustrates the correlation between age and the critical SOA in the Report Location task. The slope of the regression line is significant for all participants, as well as for each subgroup, as illustrated by the bottom row of Table 2. However, the ratio of the two slopes is very close to 1.0, suggesting a consistent decline across the lifespan.

4.5. Effects of health conditions

Our optometric exam collected self-reported health conditions from all participants, including high blood pressure (55 elders), arthritis (45), cataracts (41), chronic sinus infections (27), high cholesterol (33), a history of cancer (19), and diabetes (11). We conducted Kruskal–Wallis rank sum tests on each of our five temporal order judgment measures to compare elders who reported these conditions relative to those that did not. Of the different health conditions, only the presence of cataracts produced differences the letter contrast condition. Letter contrast was worse for those with cataracts than those without ($\chi^2(2, N = 140) = 8.95$,

Table 2
Robust regression slopes and significance values for temporal order judgment performance for all participants (left column) and analyses restricted to select subgroups. The final column computes the ratio between the middle aged/elder regression slope and the young/middle aged regression slope. Values greater than 1 suggest an acceleration of the decline at later ages, while values less than 1 suggest an earlier onset of performance declines.

Task	All subjects	Young and middle aged	Middle aged and elder	Ratio of slopes
Letter Contrast Threshold	0.00181***	0.00130***	0.00279***	2.140
Two Item, Same Location	1.211***	1.074***	1.423***	1.324
Four Item, Same Location	3.962***	3.260***	4.284***	1.314
Two Item, Individual Contrast	0.570***	0.545*	0.240 n.s.	0.441
Two Item, Different Location	0.746***	0.435***	1.070***	2.463
Report Location	0.435***	0.395***	0.404***	1.023

n.s. = not significantly different from zero.
* $p < 0.05$.
*** $p < 0.001$.

$p < .01$). We did not see differences in any other measure that exceeded a criterion of $p < 0.01$, which we adopted due to the large number of comparisons in this analysis. Thus the health of our participants did not appear to affect the temporal order judgment measures, although our particular participant group is younger and healthier than those of many other aging studies.

4.6. Summary of group comparisons

All five temporal order judgment tasks show clear group differences, ranging from quite large with the four-item identification task in which there was very little overlap between the distributions of the young and elder age groups, to quite modest in the individual contrast two-item task. These results suggest that sensory variables such as letter discriminability may play a role in temporal order judgment performance, and also that there may be other factors related to the speed of perceptual processing and higher-level cognitive factors such as memory. To decompose these different factors, we next use data from basic sensory assays and the WAIS-III scores to look for relations between these measures and temporal order judgment performance.

5. Individual differences among elders-relation to sensory and cognitive assays

Having established age-related differences in the five different measures of temporal processing, we next turn to a discussion of

what factors might affect performance in elder participants. We chose to restrict our individual differences analyses to just the elder population. The data from younger and elder participants may have a different factor structure, although with only 71 younger participants we probably do not have enough data to test this supposition. However, with 146 elders and a total of 26 dependent measures (including sensory, perceptual and cognitive measures) we will have confidence in the solution for elder participants.

Table 3 illustrates the robust correlations (minimum covariance determinate) between the various tasks, as well as participant age. The correlations are quite high among some tasks, and values that are more extreme than .3 are shown in bold. For comparison, a conservative critical r value with only 122 pairs (we have 146) at the 0.01 level is .232. Thus a "meaningfully significant" threshold of .3 seems appropriate. We find a strong correlation between the 2 and 4 item same-location tasks of .73, and fairly robust correlations for the different-location tasks of .43. We also see evidence of correlations across the same and different-location tasks (.34 and .46 for the Report Location task with the 2 and 4 item same-location tasks, respectively, and a value of .52 for both same-location tasks with the Different-Location task). Thus we see correlations both within locations and across locations.

Somewhat surprisingly, the correlation between age and critical SOA on the individual contrast two-item task is negative when the analysis is restricted to just the elders. This suggests that among elders, when letter discriminability is equated across observers, age is no longer positively associated with performance. Thus equating for letter discriminability appears to be an important control for measures of temporal order judgments.

Of course, real-world conditions rarely offer an opportunity to equate for stimulus discriminability, and cognitive factors such as memory and temporal sequencing may also play a role. To address the factors that affect performance in the temporal order tasks, as well as significant correlations seen among the tasks, we collected both cognitive factors via the WAIS-III assessment and basic sensory measures of temporal processing via temporal flicker and gap detection tasks.

Rather than perform a factor analysis on these data, we have chosen to summarize the relations among the variables using structural equation modeling, which is described in a subsequent section. However, we first describe various cognitive and sensory predictor variables that we will use to determine the various components of the temporal order judgment tasks.

5.1. WAIS measures

We conducted full WAIS-III testing on all participants. The factor analyses revealed strong correlations among the factors scores, which is common during data reduction of these types of data. We used the unstandardized raw scores from the 13 WAIS scores

Table 3
Robust correlations (minimum covariance determinate) between all temporal order judgments, Letter Contrast Threshold and participant age for elder participants ($N = 146$).

	Two Item, Same Location	Four Item, Same Location	Report Location	Two Item, Different Location	Two Item, Individual Contrast	Letter Contrast Threshold	Participant age
Two Item, Same Location	–	**0.726**	**0.344**	**0.518**	−0.004	**0.363**	**0.350**
Four Item, Same Location	**0.726**	–	**0.456**	**0.518**	0.148	0.218	**0.320**
Report Location	**0.344**	**0.456**	–	**0.430**	0.002	0.124	0.253
Two Item, Different Location	**0.518**	**0.518**	**0.430**	–	0.064	**0.304**	0.241
Two Item, Individual Contrast	−0.004	0.148	0.002	0.064	–	**−0.488**	−0.118
Letter Contrast Threshold	**0.363**	0.218	0.124	**0.304**	**−0.488**	–	0.215
Participant age	**0.350**	**0.320**	0.253	0.241	−0.118	0.215	–

because the standardized scores are aged-matched, which tends to remove correlations with age and other factors correlated with age. Our initial analyses suggested very poor relations between some of the WAIS measures and the temporal order judgment tasks, and therefore we only briefly mention some WAIS tasks.

5.2. Temporal contrast sensitivity measures

We included four temporal contrast sensitivity measures and a gap detection task originally reported in Humes et al. (2009). These five measures were obtained in a 2AFC detection task using an LED array, and perception of form was not involved. This assay is designed to provide a baseline measure of temporal acuity.

5.3. Additional sensory and optical factors

In addition to the letter contrast sensitivity previously discussed, we have two additional measures related to sensory quality. As part of the complete optometric examination each participant underwent, we measured pupil diameter under mesopic and photopic lighting conditions. These were measured using a infrared pupillometer (NeurOptics) in a room with a gray-card reading of 0.10 cd/m^2 and 28.28 cd/m^2 for mesopic and photopic conditions respectively. These luminance values were carefully transferred from the same gray-card readings taken in the testing room, which was located in another facility due to personnel constraints. Our optometric exams also provided a measure of Snellen acuity, measured in log-MAR units.

6. Structural equation modeling

Table 4 provides the robust correlations between the five temporal order judgment tasks and the various sensory, perceptual and cognitive measures described above. As a visualization, correlations more extreme than .3 are highlighted in bold. The four fixed-contrast tasks show moderate correlations with the temporal contrast sensitivity measures and fairly strong negative correlations

Table 4
Robust correlations (minimum covariance determinate) between Temporal Order judgments and select sensory and cognitive measures ($N = 146$). Correlates more extreme than .3 are shown in bold.

	Two Item, Same Location	Four Item, Same Location	Report Location, Different Location	Two Item, Different Location	Two Item, Same Location Individual Contrast
2 Hz Flicker Threshold	**0.663**	**0.363**	0.250	**0.342**	**−0.317**
4 Hz Flicker Threshold	0.050	0.179	**−0.325**	0.010	−0.171
8 Hz Flicker Threshold	0.184	0.253	−0.015	−0.103	0.107
32 Hz Flicker Threshold	**0.326**	**0.481**	0.203	0.152	0.074
Gap Detection	0.259	**0.356**	−0.063	**0.376**	−0.217
Symbol Search	**−0.623**	−0.208	**−0.410**	**−0.535**	0.179
Digit/Symbol Coding	**−0.568**	−0.195	**−0.463**	**−0.598**	0.156
Letter–Number Sequencing	−0.040	0.127	−0.228	−0.095	0.182
Arithmetic	−0.103	−0.256	−0.038	−0.150	0.256
Digit Span	**−0.357**	−0.236	−0.279	−0.275	−0.010
Similarities	**−0.502**	−0.216	−0.236	−0.263	0.032
Vocabulary	**−0.329**	−0.056	**−0.310**	0.047	0.134
Information	−0.259	−0.207	0.067	0.125	0.289
Comprehension	−0.212	−0.045	−0.021	−0.114	0.246
Pupil size	−0.104	**−0.327**	−0.152	−0.245	−0.286
Visual Acuity	**0.318**	−0.036	0.142	**0.502**	−0.207

with the speed of processing measures (Symbol Search, Digit/Symbol Coding and to some extent Letter–Number Sequencing). In our tasks, greater numbers represent poorer performance, so negative correlations are expected for these tasks against the WAIS, where higher scores represent better performance. The working memory subtests (Arithmetic and Digit Span) show relatively poor correlations, as do the cognitive measures (Vocabulary, Similarities, Information and Comprehension).

We also see relatively low correlations between the two sensory measures and our five tasks. Neither the pupil size measure nor the Snellen acuity measure show consistently large correlations across the tasks, and the only correlation of note is the fairly large value for the Two Item, Different-Location task and acuity. This might be expected from our design, since our display did not allow us to compensate for cortical magnification for peripherally-presented items, and this is the only Different-Location task in which form identification was required. The small correlations between acuity and performance in most tasks may reflect the relatively high screen we put in place for entry into the study, and the fact that we required 90% identification of letters in isolation. This is important because blurring vision has been shown to affect performance on some non-verbal subscales of the WAIS (Bertone, Bettinelli, & Faubert, 2007). It is possible that under other testing conditions we might see greater effects of acuity on temporal order performance, especially if higher spatial frequencies become task-relevant.

Based on correlations in Table 4, we explored a variety of structural models. The goal of structural equation modeling is to summarize the relation among the various manifest variables by grouping the tasks according to the logic of the design, and then use the parameter values to determine the relations among items. A strength of this approach is that it more accurately estimates the structural correlation between two hypothesized latent factors (say, temporal order processing and speed of information processing) without the unreliability of the manifest variables corrupting the estimate of the underlying structural correlation between latent factors (cf. Blunch, 2008). However, one must first obtain a fitting model before estimates of the parameters can be interpreted. Our modeling will not include age as a predictor variable because we do not have longitudinal data. Instead, we use age to inject variance in the different manifest variables, which provides an opportunity to demonstrate co-variation with the other measures.

The structural equation modeling approach computes the obtained covariance matrix from the elder data and uses the structure of the model as a set of path tracing rules to compute a predicted covariance matrix given a set of estimated regression and correlation parameters. For these analyses we chose to deal with our missing data and extreme values as follows. First, missing data was left blank and estimated using linear techniques in the AMOS program (SPSS Inc.). Second, for the bulk of our modeling we chose to Blom transform the data to reduce the influence of extreme values. The Blom-transform first ranks the data in each measure and then converts the ranks to proportions by dividing by the total number of scores. These proportions are then converted to a normal distribution using an inverse cumulative normal transformation. The subsequent scores are approximately normally distributed with a mean of zero and a standard deviation of 1.0. This transformation is not critical to our results, and we discuss model fits using raw scores in a later section. However, this stabilizes the variances, places all measures on a common scale, which helps with parameter estimation and minimizes the influence of extreme scores.

Fig. 5 illustrates the model that provides the best summary of the significant relations among measures. Given the differences between the tasks, we split the four fixed-contrast temporal order judgment tasks into same-location and Different-Location latent
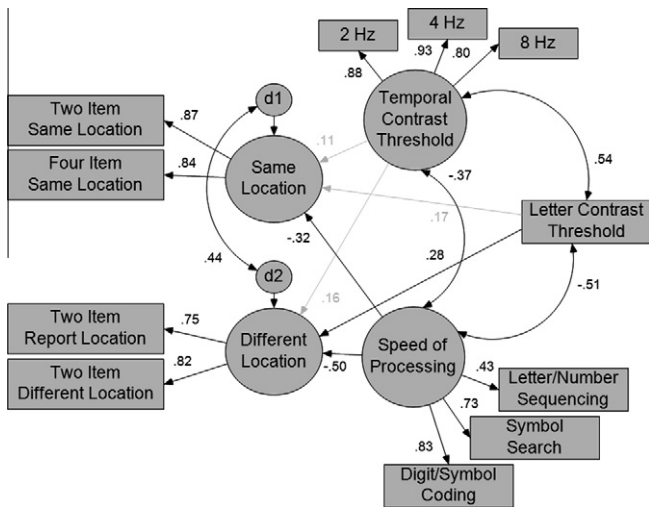
Fig. 5. Structural equation model which uses four of the temporal order tasks as manifest measures to estimate two latent temporal order factors (labeled Same Location and Different Location). These are latent dependent variables which are predicted by the Temporal Contrast Threshold and Speed of Processing latent independent variables, each of which is estimated by several manifest measures. In addition, Letter Contrast Threshold is a manifest variable that is used as a predictor for the latent dependent variables. For clarity, the error terms on each manifest variable are not shown. In addition, the two temporal order latent factors have disturbances which are correlated. Single-headed arrows are regression weights, and double-headed arrows are correlations. Paths that have significant regression weights or correlations at the 0.01 level are shown in black; gray paths are not significant. This model demonstrates a significant contribution of Speed of Processing (as measured by three WAIS subtests) to both temporal order latent factors, while Letter Contrast Threshold has a significant relation with only the Different-Location latent factor. The Temporal Contrast Threshold factor correlated with other measures but did not contribute significantly to either latent temporal factor. See text for more information.

factors, as shown on the left side of Fig. 5 (the Individual Contrast task is discussed in a later section). These provide estimates of the two temporal order latent factors, and the existence of significant regression weights for all four tasks demonstrates that each measures some common element of the latent factors. The lower regression weight for the Report Location task may reflect the fact that pattern identification was not required for this task.

Each temporal order latent factor (labeled Same Location and Different Location) is predicted by additional independent latent factors. The Speed of Processing latent factor is estimated by three WAIS measure (Digit/Symbol Coding, Symbol Search and Letter/Number Sequencing) and has significant regression weights to both latent temporal order factors. Speed of Processing has a standardized regression weight of $-.32$ ($p < 0.01$) with the Same Location latent factor and a standardized regression weight of $-.50$ ($p < 0.001$) with the Different-Location latent factor. Letter/Number Sequencing is sometimes grouped with the working memory subscale, and removing it from the fit in Fig. 5 reduces the model fit slightly but does not otherwise change the results significantly. It is included in the Fig. 5 model because it has a significant, albeit modest, regression term and because elders show some evidence of pattern loadings for this measure with the Speed of Processing factor (Tulsky, 1997).

The Letter Contrast Threshold measure has a significant regression weight with the Different-Location latent factor but not the Same-Location factor. Somewhat surprising was the result that the Temporal Contrast Threshold latent factor did not produce significant regression weights with either latent factor despite the fairly high correlations in Table 4. Based on low regression weights we dropped the 32 Hz and Gap Detection tasks, although the fits are fairly similar if they are included. The Temporal Contrast

Threshold latent factor does have strong and significant correlations with the Speed of Processing ($r(145) = -.37$, $p < 0.001$) and Letter Contrast Threshold ($r(145) = .54$, $p < 0.001$) measures. In addition, the Letter Contrast Threshold correlates with the Speed of Processing latent factor ($r(145) = -.51$, $p < 0.001$), and the disturbances for the two latent temporal order factors correlate($r(145) = .44$, $p < 0.01$), demonstrating some shared variance between the two sets of measures.

The model is fitting surprisingly well as constructed. The χ^2 value is 54.1 with 40 parameters and 37 degrees of freedom. The p-value was 0.034. A standard measure of goodness of fit, the comparative fit index (CFI) was high (0.976) relative to the values (0.90–0.95) that modelers like to see (Hu & Bentler, 1998). The BIC value is 141.5 and the RMSEA value is 0.057. All of these measures suggest that the model is providing a reasonable account of the relations among the observed variables and the latent factors and justifies parameter interpretation.

The interpretation of the parameters of the model in Fig. 5 suggests that both speed of processing and letter contrast sensitivity are both related to temporal order judgment performance. This implicates what might be thought of as both low-level sensory and mid-level information processing factors as mediators of temporal order judgment performance. However, the independent latent factors on the right side of Fig. 5 are accounting for 25% of the variance of the Same Location Temporal Order latent factor and 60% of the variance of the Different Location Temporal Order latent factor. This illustrates that while the dependent latent factors are related to temporal order judgment performance, there remains a substantial amount of unique variance in temporal order performance that is not captured by these measures.

6.1. Alternative models

We explored a wide range of alternative models and data representations to determine that in fact Fig. 5 model was in fact the best representation of the relations among our measures.

6.1.1. Single temporal order factor
The fairly strong correlation between the disturbances of .44 might point toward a model with a single latent factor representing temporal order performance. However, variants of the models that use a single factor to represent temporal order performance fit very poorly, with low loadings on the temporal order judgment manifest variables. Thus there appear to be important differences between same and different-location tasks, and the presence or absence of sequential masking seems like one important criterion.

6.1.2. Individual Contrast
We initially included the Two Item, Same Location Individual Contrast task as part of a measurement model, but it demonstrated a very low and non-significant regression weight relative to the other same-location tasks (.17 vs. .83 and .87 for the two item and four item tasks respectively). As a result, it was dropped from subsequent analyses.

6.1.3. Additional cognitive factors
We added the working memory scores from the WAIS (Arithmetic and Digit Span) as an additional Working Memory latent factor. However, this model, along with one that included scores that estimate a General Cognition factor, produced relatively poor fits (CFI = .928; $p < 0.001$) and low regression weights with the two temporal processing latent factors. Thus neither working memory nor general cognitive abilities seem to be playing a major role in temporal order judgment performance.

6.1.4. Additional sensory factors

We added acuity and pupil size to the model in Fig. 5, and found that while the model fit was good (CFI = 0.978; *p* = 0.067), neither measure of sensory ability produced a significant regression weight with either of our latent temporal order factors. This is consistent with the relatively low correlations seen in Table 4 between these sensory measures and the temporal order tasks. It should be noted, however, that there may be an isolated correlation between the Two-Item, Different Location factor that is important yet does not show up in the aggregate modeling.

6.1.5. Just temporal contrast thresholds

To explore the relation between the flicker contrast thresholds and our latent temporal order judgment factors, we fit a model that included just the Temporal Contrast Threshold latent factor (essentially Fig. 5 without the Speed of Processing and Letter Contrast factors). It produced a reasonably good fit (CFI = .945; *p* = 0.007) and had significant regression weights of .32 and .48 with the same and different location temporal order judgment factors, respectively. Thus, in isolation, the Temporal Sensitivity factors do seem to be related to the temporal order factors, although this relation may be mediated by some third variable such that these regression weights become non-significant when the additional factors are added for the model in Fig. 5.

6.1.6. Fits using raw data

We chose to use Blom-transformed data for the bulk of model fitting in order to minimize the effects of extreme outliers and to stabilize the variances. To test the effects of this choice, we re-ran the modeling using the raw scores as input. Some of the scores are on very different scales, and we attempted a variety of different approaches to obtain good-fitting models. However, we could not obtain reasonable solutions with raw data even when some measures such as Letter Contrast are excluded. Part of these poor fits may result from the extreme values we see in some of the data, which are stabilized using the Blom transform. This reinforces the use of non-parametric and robust measures when working with data with outliers, rather than selectively eliminating extreme values.

6.1.7. Robust correlations as input

As an alternative to the Blom-transformed data used in these models, we exported the results of the minimum covariance determinate robust correlations directly to AMOS as input. This does not allow AMOS to estimate missing data, but does handle extreme values through the robust correlation analyses. Despite trying a wide variety of models including simple measurement models and the full model in Fig. 5, we were unable to obtain model convergence due to matrices that were not positive definite and negative variances. All of the standard techniques used to ameliorate these issues failed.

6.1.8. Summary of modeling

The model shown in Fig. 5 captures the relations among latent factors that are estimated by manifest variables. Each of the two Temporal Order latent factors is estimated by two manifest variables that both had reasonably high regression weights (the lower value for the Report Location task may reflect the fact that the task does not involve letter identification). The speed of processing measures make contributions to both temporal order latent factors, and the Letter Contrast Threshold is related to at least the Different-Location latent factor. We also see correlations among the latent factors and the disturbances of the temporal order factors. This model suggests that both contrast sensitivity and speed of processing play a role in temporal order judgments.

One way to determine the degree to which the sensory and cognitive assays are related to the two temporal order judgment factors revealed by structural equation modeling is to address the percent variance accounted for in the two latent factors by the predictor variables (those on the right side of Fig. 5). For the Different-Location latent factor, the WAIS and sensory predictors account for 60% of the variance, while these same predictors account for only 25% of the variance for the Same Location latent factor. Part of this may result from the fact that we were able to adjust the letter contrast for some participants in the same-location tasks but could not do so for the different-location tasks. However, the same-location tasks also are affected by masking from the temporally-adjacent letters, and this analysis did not include masking predictors.

7. General discussion

This study addressed the degree to which variability across observers on various temporal order judgment tasks could be represented by two underlying latent factors representing performance on same and different locations, and whether this variability could be predicted in part from other sensory and perceptual tasks. We found performance differences between age groups on all measures of temporal processing and significant correlations with age were found for all measures. These age differences were reduced, but not eliminated, when letter discriminability was matched for all participants.

When fitting structural equation models, we found that four of the five temporal order tasks accurately measured the underlying temporal order judgment latent factors. Variability in these factors was accounted for by a combination of cognitive and sensory factors. The conclusions of the structural equation modeling approach suggest that the WAIS processing speed measure contributes to performance in the temporal order tasks, and we also see contributions from letter contrast sensitivity and perhaps temporal contrast sensitivity measures, although not as strongly. The contribution from the processing speed factor is of particular interest since while the WAIS tasks have elements of speeded symbol perception and manipulation, they are done using high-contrast letters and symbols, unlike the present tests that were designed to be near the 90% identification contrast values for most elders. Thus there must be an element of temporal processing that is somewhat independent of stimulus contrast. The fact that we still see a reduced but significant group difference between young and elder participants in the individual contrast two-item task provides converging evidence for this notion of a temporal processing factor that is separate from individual contrast sensitivity.

The relation between sensory and cognitive factors is loosely consistent with the general notion of a common cause (Baltes & Lindenberger, 1997; Lindenberger & Baltes, 1994; Lindenberger et al., 2001). However, the elder population exhibits a great deal of variability in the scatter plots (see Fig. 4) that is not age-related, and apparently not health-related at least with regard to the self-reported conditions in our sample. Whether this variability is simply measurement error or other factors at work will likely have to wait for longitudinal data collected on these same elders. A strength of longitudinal data is that it allows for measurements of rates of change rather than baseline levels, whereas the present study is cross-sectional and limited to more cautious statements about the relation between age and declines in sensory or cognitive functioning.

Further evidence against a unitary common cause comes from the slopes ratios in Table 2, which suggest large differences in early verse late age-related changes across the tasks. In particular, the tasks that are most dependent on letter contrast (the letter contrast task itself and the two-item, Different-Location task) have

the highest slope ratios, suggesting greater changes later in life. However, when letter contrast is controlled in the Individual Contrast condition, we see relatively few changes later in life and a very small slope ratio. The fact that this task has the same cognitive complexity as the Two-Item Same Location task yet a very different slope suggests that cognitive complexity is not the only mediating variable. If a common cause results in correlated declines across tasks, such results are not consistent with a common cause. Instead, both sensory and perceptual variables seem to be making contributions to temporal order judgment performance, despite the fact that we screened our subjects for baseline letter discriminability and insured that all participants could perceive the letters in isolation at at least 90% identification performance.

Scialfa (2002) advised his readers who were interested in cognitive aging research to avoid allowing sensory factors to contaminate their measures. However, perceptual and sensory researchers should also take care to realize that cognitive factors such as processing speed could play a role in perceptual tasks, especially given that the current modeling shows a greater contribution from Processing Speed than from other sensory factors. To the degree that elders show greater age differences in tasks that require increased processing (Bertone et al., 2000; Faubert, 2002; Habak & Faubert, 2000), this may explain group differences on perceptual and sensory-based tasks that may otherwise be attributed to lower-level, modality specific, processes.

Acknowledgement

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