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Age-Related Changes in Information Processing on Tasks of Perceptual Speed

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AGE-RELATED CHANGES IN INFORMATION PROCESSING ON TASKS OF PERCEPTUAL SPEED

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Abstract

The general slowing theory of cognitive aging claims that age-related decline in cognitive performance results from the global slowing of processing functions. This theory derives from evidence showing how tests of perceptual speed account for virtually all the age-related variance in many tasks. However, these tasks may reflect more than individual differences in general speediness, such as different strategies resulting from the different possible ways of understanding the task, differential memory abilities, or a speed-accuracy trade-off. Using verbal protocol analysis and eye tracking, different models for common tests of perceptual speed were evaluated. Participants completed the number comparison, digit-symbol, and backward digit span tasks in either a “think-aloud” or a silent control condition. In both conditions, participants’ eye movements were recorded for number comparison and digit-symbol, and each participant was given one of three types of instructions for these two tests, one focusing the participant on speed, accuracy, or both. Overall, results show that the number of fixations during encoding potentially mediates age-related decline on these tasks, whereas other variables, such as fixation duration and switches between interest regions, did not correlate with age. The results have implications for theories of aging, as only one model, based on encoding delay, fully accounted for the observed results.

Introduction

Theories of age-related cognitive decline account for age-related variance by using either general constructs, such as inhibition, working memory, or perceptual speed, or by using task-specific processes. Currently, the general slowing hypothesis (Salthouse, 1996) is one of the most successful, because most of the cross-sectional age-related variance on many different psychometric tasks is eliminated after controlling for tasks assumed to measure the perceptual speed construct. Moreover, perceptual speed is distinguished from psychomotor speed and decision speed, because tasks measuring perceptual speed do not depend on motor control and could be solved with perfect accuracy by all individuals given sufficient time (Salthouse, 2000). Typical studies tend to use specific tasks for measuring perceptual speed, namely digit-symbol substitution (Wechsler, 1981) or number comparison (Ekstrom et al., 1976). However, evidence exists that such tests may reflect more than merely speed of processing, such as memory performance or task strategies. If this is true, general slowing may not be the only construct available to explain why digit-symbol or number comparison may mediate the age-related variance in different cognitive tasks. This study will examine perceptual speed tasks with process tracing methods, namely eye tracking and verbal protocols, to investigate whether older adults approach these tasks similarly to younger adults and to test whether memory processes are reflected by age-related decline in performance.

Theories of aging and cognition

Older adults exhibit impoverished performance on a large variety of perceptual and cognitive tasks relative to younger adults, both in longitudinal and in cross-sectional samples. The principle age effects include age-related decline in Type A cognition (Hebb, 1942), fluid cognition, such as reasoning, memory, and spatial ability (Cattell, 1943; Horn, 1982; Horn & Cattell, 1963), and neurological tests (Salthouse, 1991). Most hypotheses attempting to explain these age effects rely on a small set of general factors to account for the age-related variance, such as processing resources (Craik & Byrd, 1982), attentional inhibition (Hasher & Zacks, 1988), or impoverished perceptual acuity reflecting a generalized decline (Baltes & Lindenberger, 1997). Processing speed decline or the slowing with which cognitive operations are carried out has been considered highly relevant to aging in several influential studies (Birren, 1965; Cerella, 1985; Myerson et al., 1990). However, Salthouse (1996) proposed processing speed as the central construct to explain age decline for most cognitive tasks.

General slowing theory

Originally conceptualized by Birren (1965), the theory of general slowing proposes that age-related decline in cognitive functioning results from reductions in the speed with which cognitive operations are executed. Salthouse (1996) established the processing speed theory of aging, describing two primary mechanisms causing the diminished performance, limited time and simultaneity, which are caused by slow processing. The limited time mechanism refers to how the required sequence of processes for a task may not all be completed in a constrained amount of time, because each process requires a specific amount of time to execute. Therefore, if age increases the time required to execute specific processes, the respective sequence required for a task may not fall within imposed time constraints. In contrast, the simultaneity mechanism refers to how the products from early processing fade over time and may not be available when needed by subsequent processes. Hence, if processes in older adults have longer execution times, subsequent processes may not be executed in time to use results from earlier cognitive operations. Salthouse distinguishes the processing speed account of the simultaneity mechanism from the accounts based on memory decay or displacement, stating that the time to activate a process is diminished in older adults, rather than the rate of information loss (see Salthouse & Babcock, 1991).

As evidence of general slowing, Salthouse reviews several studies showing that tests of perceptual speed share large portions of the age-related variance on a wide variety of tasks including free recall (Salthouse, 1993), paired associates (Salthouse, 1993), long-term memory for activities (Earles & Coon, 1994), associative learning (Salthouse & Kersten, 1993), continuous associative memory (Salthouse, 1995b), working memory (Salthouse & Babcock, 1991; Salthouse, 1991; Salthouse & Meinz, 1995), matrix memory (Salthouse, 1995a), backward digit span (Salthouse, 1988), Stroop inhibition (Salthouse & Meinz, 1995; Salthouse, 1995b), geometric analogies

(Salthouse, 1987), series completion (Salthouse & Prill, 1987), and arithmetic tasks (Salthouse & Coon, 1993). Moreover, Salthouse estimates the proportion of age-related variance shared between a criterion (e.g., free recall) and a controlled variable (e.g., digit-symbol) by calculating the shared over simple effects, namely by dividing the portion of the criterion variance shared by age and the control variable by the portion age explains alone. The portion of criterion variance shared between age and the control variable is found by subtracting the criterion variance that age accounts for above and beyond the control variable—thereby "controlling for" the control variable, yielding the criterion variance unique to age—from the variance age accounts for alone. However, although the previously mentioned criterion variables all share a large proportion of the age-related variance with digit-symbol substitution and other perceptual speed and reaction time measures, this may not imply a causal relationship between age-decline in these variables and perceptual slowing. Lindenberger and Pötter (1998) argue that these hierarchical linear regression analyses cannot yield causal information in such quasi-experimental designs without *a priori* theoretical justification. In fact, these authors show how a nonzero partial correlation between the criterion and the control variable while controlling for age can strongly influence the magnitude of the shared over simple effects parameter. Therefore, variance components in variables orthogonal to age affect the amount of age-related variance shared between a criterion and a control variable. According to this argument, without theoretical reasons for a causal relationship between slowing and criterion measures of memory and problem solving, Salthouse's (1996) shared over simple effects may be difficult to interpret, especially because many of the partial correlations between these variables controlling for age are moderate to large (Czaja et al., submitted). Nonetheless, the general slowing hypothesis remains an influential theory of cognitive aging, and its foundations rest on the specific constructs reflected by these control variables, particularly digit-symbol substitution and other tasks of perceptual speed.

Digit-symbol substitution

Substitution tasks, typically involving the replacement of digits with symbols or vice versa, have long been used to study individual differences (e.g., Ryans, 1939). The digit-symbol substitution task commonly used today originated as a subtest in the

WAIS intelligence battery (Wechsler, 1955/1981). The original paper and pencil task presents a code table showing nine pairs of digits and symbols followed by a series of empty boxes below digits, requiring the participant to write the matching symbol below each digit as quickly as possible for 90 seconds. Subsequently, participants receive a surprise memory test for the digit-symbol pairs, although the most common variable of interest for scoring the test is the number of symbols completed during the 90 seconds. Moreover, a computerized version of the test, where participants rapidly identify if individual digit-symbol pairs are valid in relation to the code table, was shown to correlate substantially with the original version. The median response time for the computerized version was strongly and significantly correlated with both the paper and pencil test, $r = -.73$, and with age, $r = .75$ (Salthouse, 1992). The author found that the computerized version shares 98% of the age-related variance with the paper and pencil test.

Observing that digit-symbol substitution is highly negatively correlated with increasing age, Salthouse (1992) argued for an explanation of age-related cognitive decline related to general slowing. As previously discussed, many studies by Salthouse and colleagues in the early 1990s demonstrated that the effects of age on performance for many problem solving and memory tasks are mediated by performance on the digit-symbol task, leading to Salthouse's (1996) processing-speed theory of aging. Similarly, in a recent meta-analysis Hoyer et al. (2004) supported the strong relationship of digit-symbol and age across 141 studies, showing that only age contributed significantly to a regression model accounting for 86% of the digit-symbol variance, using age, education, and year as predictors. Overall, the digit-symbol substitution task has been hailed as “A potentially fruitful research agenda” as the test's large correlations with memory and fluid abilities imply it is “measuring processes important to the relation between age and cognition” (Salthouse, 1992). Other studies have used the digit-symbol task as a dependent processing-speed variable showing interactions of age with education, gender, and morningness-eveningness (Salthouse, Atkinson, & Berish, 2003). However, the interpretation of all these effects depends on what set of constructs is reflected by digit-symbol performance.

Salthouse (1992) concluded that processing speed best accounts for age-decline in the digit-symbol task, arguing against explanations based on peripheral motor speed or memory. Despite the finding that writing speed declines with age (e.g., Birren & Botwinick, 1951; Dixon, et al., 1993), Salthouse argued that older and younger adults devote approximately the same relative amount of time writing symbols relative to their overall performance (Erber, 1986; Erber et al., 1981; Salthouse, 1988; Storandt, 1976). Additionally, the large amount of age-related variance in the computerized version of digit-symbol shows how writing speed cannot account for the digit-symbol age effects.

An early study of younger adults by Burik (1950) indicated that incidental memory for the digit-symbol pairs did not correlate with task performance, although recent data suggests a strong correlation when older adults are included, $r(649) = .49$, $p < .001$ (Czaja et al., submitted). And although older adults consistently show age-related memory declines, Erber et al. (1981) found that digit-symbol strongly predicted age even after older and younger adults had memorized the pairs to perfect recall. The data showed that memorizing the pairs prior to completing the task only helped younger adults. Moreover, the relationship between practice and age effects typically shows that age differences remain constant or even increase after multiple trials (Erber, 1976), even if both age groups receive monetary incentives (Grant, Storandt, & Botwinick, 1978). Salthouse argued that practice should enhance memory for the pairs, and if memory decline affects performance, the age relationship should be attenuated after training. Moreover, Salthouse (1978) argued that when the number of digit-symbol pairs was reduced from nine to one, the age effects remained, indicating the unimportance of memory to explaining age differences in this task. Finally, Salthouse (1992) claimed that strategies do not differentiate older and younger adults after analyzing the serial position curves in median response times for the computerized version of the task, although it is possible that different strategies may lead to similar serial position curves.

Salthouse (1992) primarily linked digit-symbol performance to the processing-speed construct by showing that virtually all the age-related variance of digit-symbol is explained by controlling for perceptual speed tasks such as number comparison; however, this conclusion rests on the assumption that these comparison tasks are pure measures of speed. The test involves matching symbols corresponding to digits; participants who can better remember these pairing and consequently refer back to the key less often may show different performance from individuals who more frequently reference the key. The memory loss associated with advancing age may force older adults to reference the digit-symbol key more frequently than younger adults. Moreover, older adults may tend to perform the task more carefully than younger adults by using more elaborative and strategic encodings of the digit-symbol pairs, resulting in different task performance; this is similar to older adults' careful tendency to emphasize accuracy over speed in completing rapid laboratory tasks (Salthouse, 1979). In short, increased memory transience and differential strategies on the task may contribute to the age-effects on the digit-symbol task.

The contribution of memory to digit-symbol performance has been subject to debate, and some researchers claim that memory processes are relevant to digit-symbol performance. For example, when Salthouse (1978) reduced the number of pairings in the key from nine to one and found that older adults showed a larger absolute increase in performance than younger adults, he discovered partial evidence for the role of memory, because fewer pairs require less memory load. However, Salthouse argued that after dividing these differences by the standard scores, no interaction with age could be detected, concluding that memory plays a small role in digit-symbol, if any. In contrast, Piccinin and Rabbitt (1999) contest that dividing by the standard scores is mathematically invalid, and that the results still suggest an important role of memory. Similarly, the argument that, after practice, age effects on digit-symbol are not reduced implies memory is not relevant to task performance rests on the assumption that practice necessarily improves the memory representations of the digit-symbol pairs. However, if these pairs were never sufficiently encoded, this assumption would prove incorrect. Other researchers have used factor analytic techniques to account for digit-symbol variance (Salthouse, Atkinson, & Berish, 2003). These studies have shown mixed results; for example, Davis (1956) argued that digit-symbol loaded on perceptual speed and numerical ability, whereas Wechsler (1955) claimed it loaded on perceptual speed, memory, and freedom from distractibility. Using older subjects, Berger et al. (1994) showed the highest loadings on perceptual speed and memory. A modification of the digit-symbol task called symbol copy has been considered a more pure test of perceptual speed (Kaplan, Fein, Morris, & Delis, 1991). Symbol copy is essentially the same as digit-symbol without a coding element—symbols are presented above empty boxes and participants copy the symbols into the boxes, eliminating the potential memory component. Moreover, a recent meta-analysis of four studies comparing digit-symbol to symbol copy (Joy & Fein, 2001) shows the average correlation to be r = .74, meaning that roughly 55% of the digit-symbol variance is accounted for by speed alone. These authors also showed that symbol copy strongly relates to age, r = -.58, although significantly less well than digit-symbol, r = -.68, supporting the idea that perceptual speed alone cannot account for all the age-related variance attributed to digit-symbol. In a large-scale study over a wide age range, Joy, Kaplan, and Fein (2004) showed that after regressing symbol copy out of digit-symbol, the incidental recall tests accounted for roughly 5% of the residual variance. While this also advances the idea that memory processes account for some variance above and beyond speed, the remaining variance is still unexplained. Furthermore, the incidental memory on digit-symbol may not precisely reflect older-adult memory deficiencies, as some older adults may be slower to encode the pairings in the beginning of the task when compared to younger adults, but may still show good recall by the end of the task. These older individuals would be recorded as having very good, if not perfect pair recall, but may still have had memory trouble earlier in the task. Finally, Laux and Lane (1985) found a significant contribution of memory processes to digit-symbol performance for only older adults using componential analysis of the symbol-digit task (similar to digit-symbol, but participants write digits below symbols). Thus, it is possible that a superior assessment of memory encoding could explain more of the age-related variance.

Additionally, research has shown how older adults sometimes use different strategies than younger adults on cognitive tasks, often switching to retrieval strategies later than younger adults (Rogers, Hertzog, & Fisk, 2000), which can affect skill acquisition (Bosman & Charness, 1996). Differential strategy use could also account for variance in digit-symbol. For example, Erber (1976) found that younger adults were more likely than older adults to report using a mnemonic after several trials of digit-symbol training. Moreover, older adults may deliberately spend more time searching the code table for the relevant digit-symbol pair than younger adults. Notably, additional time in the code table could also reflect unintentional effects—older adults typically have more difficulty searching for a target among distractors, for instance.

A recent longitudinal study (MacDonald et al., 2003) found that the decline in older adult digit-symbol performance over time is not substantially mediated by perceptual speed (see Wielgos & Cunningham, 1999 for a contrary finding). These authors used hierarchical linear models to examine longitudinal change over six years in performance of digit-symbol, number comparison, and other perceptual speed and working memory measures. After replicating the typical cross-sectional findings, these authors demonstrated how longitudinal change was not consistent with the processing speed theory of aging. This finding is consistent with other previous longitudinal studies. For example, Hultsch et al. (1992) also examined cross-sectional and longitudinal age-related change in cognition and found that a measure of verbal processing speed reduced the cross-sectional but not longitudinal change in verbal fluency and working memory, although the processing speed measure was not typical. Similarly, Sliwinski and Buschke (1999) found that perceptual speed accounts for only small amounts of the longitudinal age-related variance, even when it accounts for large portions of the cross-sectional variance. For example, these authors found that speed attenuated 5% of the longitudinal decline in FAS performance, a measure closely linked to working memory, as opposed to 100% of the cross-sectional. However, longitudinal aging research cannot escape the caveat that selective attrition (Schaie, Labouvie, & Barrett, 1973; Siegler & Botwinick, 1979), restriction of range, and possibly even practice effects (Schaie, 1996) could attenuate the age-declines in different cognitive tasks, making the comparison of longitudinal and cross-sectional data a challenging task. On the other hand, some of these difficulties, such as attrition, are partially attenuated by the use of multilevel modeling.

If digit-symbol and other tests of perceptual speed cannot mediate age-related declines in measures of problem solving and memory in longitudinal samples, but do share most of the age-related variance in cross-sectional samples, the larger cross-sectional effects may result from the differing age-group cohorts. In this case, the cohort differences in these tasks may be related to the Flynn effect (Flynn, 1984), namely that average scores on tests of fluid intelligence have increased over a relatively short period of historical time. Notably, Hoyer et al. (2004) found no evidence for secular increases in digit-symbol performance; however, these authors conducted a meta-analysis from articles between 1986 and 2002, which may not be an appropriate time span to observe large increases. The Flynn effect could explain why cross-sectional and longitudinal analyses differ on many fluid tests, but it cannot explain all the age-declines in fluid abilities, because many longitudinal studies have documented age-decline within individuals on fluid measures (Botwinick & Siegler, 1980; McCarty, Siegler, & Logue, 1982; Schwartzman et al., 1987; Hertzog & Schaie, 1988; Colsher & Wallace, 1991; Elias, Robbins, & Elias, 1996; Zelinski & Burnight, 1997; for a review of the earlier literature see Schaie, 1983).

Number comparison

Comparison tasks such as number, letter, and pattern comparison are sometimes considered pure measures of processing speed (Salthouse, 1992). However, whether comparison tasks are also subject to differential strategy use has not been examined. Moreover, Salthouse (1992) and MacDonald et al. (2003) both used the number comparison task as a primary perceptual speed measure to examine digit-symbol. Despite its established history as a test of perceptual speed, no studies have investigated whether the differential strategy use impacts the number comparison test. The task requires participants to simultaneously compare two strings of numbers, such as 462372 to 461372, and indicate if they are the same or different. However, participants may differentially group the numbers during the comparison process, potentially leading to improved performance. If strategies (possibly related to memory) significantly impact performance on number comparison or other similar tasks, then whether such measures reflect “pure” perceptual speed is questionable.

Verbal reports

Eliciting strategies used on cognitive tasks is sometimes done inferentially from patterns of results. However, these methods may fail to identify different strategies when both strategies have similar patterns and also yield little information to the precise nature of the processes involved. One of the most detailed methods for strategy elicitation is verbal protocol analysis (Ericsson & Simon, 1993). The method of concurrently “thinking-aloud” while completing a task involves a brief warm-up period followed by tape-recorded (or video-recorded) trials. The warm-up is used to instruct participants not to explain how they complete the task, but rather to think-aloud as if they are alone, vocalizing thoughts as they naturally occur. The experimenter then gives several types of practice problems, including finding the fourth letter after ‘H’, counting dots, and basic multiplication problems. Additionally, researchers specify a number of process models for how the task could be completed. Once the protocols are recorded, transcribed, and coded, these *a priori* models can be checked against that data and supported or rejected, much like hypothesis tests.

Ericsson and Simon reviewed a large number of studies and concluded that if verbal protocols are correctly elicited, they do not react with task accuracy or change the method for task completion. However, protocols do tend to increase latencies, because of the time required to verbalize. Therefore, studies investigating tasks with time-based dependent variables should consider this additional verbalization time when analyzing latency data.

Eye tracking

In additional to the other patterns of results, eye tracking is an additional method of validating that thinking aloud does not change the underlying processes involved in completing the task. For example, in this experiment if the general relationship between eye movements and relevant variables (namely age and task performance) does not change in the think-aloud relative to the control conditions, the hypothesis that no processing differences occurred cannot be rejected. Using such results in combination with other converging evidence supports the assertion that the processing elicited from verbal reports is no different than in the silent controls. Eye tracking methodology offers a large number of variables for such analyses, including fixation duration, number of fixations, saccade amplitude, as well as more global analyses of eye movements, such as the number of switches between different portions of a task stimulus, which we will employ in our later analyses.

Previous research with eye tracking and digit-symbol has focused exclusively on younger adults. Stephens (2001) monitored the eye movements of a single participant on a computerized digit-symbol task, finding that the latency for code table fixation and the average number of fixations predicted overall latency on individual items, *r* = .78, *p* < .05, and *r* = .56, *p* < .05, respectively. Stephens concluded that concentration plays a major role on item performance, because the participant would occasionally deviate from the typical pattern of eye movements in sub-optimal ways, such as focusing on the item in the code table, rather than the target, directly after a response. However, given that the sole participant was a psychologist, it is unclear whether these results suffer from an expectancy bias. In a follow up study, Stephens and Sreenivasan (2002) used a larger sample (n=7) on the written digit-symbol task and found that the time to search the code table per item and the number of fixations on the code table per item predicted overall performance performance, *r* = -.68, *p* <. 05, and *r* = -.75, *p* < .05, but the time to write individual symbols did not, *r* = -.19, *p* > .05. The authors argue that efficiency of search and encoding time lead to the observed individual differences in digit-symbol. Schultetus and Charness (1998) found that older adult performance on digit-symbol could be mediated by the number of total fixations, but not by fixation duration. However, this study did not examine where these additional fixations took place and could not reject the possibility that older adults may be more distracted by irrelevant aspects of the code table or may simply search the key more frequently.

Models for perceptual speed tasks

Table 1. *Model predictions for age correlations with speed tasks*

	DSS: Number of Switches	DSS: Delay on Target	DSS: Delay on Relevant Key	DSS: Delay on Irrelevant Key	NC: Number of Switches	NC: Delay on Numbers
Simultaneity	+	+	+	+	+,0	+
Memory Decay	+	0	0	0	+	0
Encoding Deficit	+	-	-	0	+	-
Encoding Delay	0	+	+	0	0	+
SPAN	+	+	+	0 (No fixations)	NA	NA

To investigate age-related decline in digit-symbol and number comparison performance, we compare the primary models available. See Table 1 for a listing of each model of age-related decline and its key predictions for our perceptual speed tasks. Each model makes predictions based on how it affects processing and/or storage of information, and each task is discussed in terms of the general processes completed and intermediate products of processing stored. If a model predicts "processing delays" for a given process, our primary assumption is that we will observe more fixations, longer fixation durations, or both when older participants' gaze is directed at specific parts of the stimuli. For example, if a model predicts delays in encoding the target in digit-symbol, we would expect to observe older adults having longer fixations, having more fixations, or both when gazing at the target. Therefore, in this example we tacitly assume that individuals cannot process the relevant portion of the key while simultaneously processing the target. As we will later discuss, the correspondence between eye behavior and cognitive processing is not obvious or universally accepted, and our predictions reflect our own assumptions that there is some correspondence based on the position of the eye in the specific task regions at different points in time.

In digit symbol, there are five primary processes: encoding the target pair, encoding the relevant pair in the code table, searching for the target pair, searching for the relevant pair in the code table, and comparing a pair to a memory representation. The intermediate products of processing consist primarily of the temporarily stored representation of the target pair or of the relevant pair in the code table. In number comparison, there are three primary processes: encoding number strings or substrings, searching for the other string, and comparing a string or substring to a memory representation of a string or substring. The intermediate products of processing consist of the temporarily stored string or substring.

First, Salthouse's (1996) simultaneity mechanism is one candidate (note that the limit-time mechanism cannot apply given that response time is the dependent variable, rather than a limiting constraint), which proposes that the time to execute processes is slower in older adults, but that the decay rate of temporary information is equivalent to this rate in younger adults. In this model, older adults will be more likely to lose access to the intermediate products of processing (i.e., the temporarily stored information) because of increased process execution time (rather than increased rate of information decay). According to simultaneity, if longer execution times of the relevant processes cause older adults to lose access to this information, older adults would have to re-encode the information again. In digit-symbol, this would lead to older adults being more likely to re-encode either the target pair or the relevant pair in the key, causing older adults to switch between the code table and target more frequently than younger adults. Below we discuss a possible caveat with this argument. Additionally, this model would also predict that older adults take longer to initiate encoding processes and search processes—thus, we would expect that older adults would have longer fixation durations and/or more fixations on the relevant pairs in the key and target and would also have delays on the irrelevant parts of the code table (as they are taking longer to search). In number comparison, older adults would take longer to encode number strings and would therefore show age-related delays during the encoding of the strings. However, the predictions for switches are less clear and will be discussed below.

Importantly, it can be argued that simultaneity might not predict more switches on these tasks. For instance, in digit-symbol older adults might be slowed during encoding of the target and search of the key, but the additional time for the memory trace to decay might not be large enough for older adults to lose access to the representation of the target. Thus, older adults might be slower during all processing steps, but never require extra switches back to the target because the memory trace is still accessible. Whether or not additional switches are predicted depends on assumptions regarding both younger and older adults' rates of memory decay. However, in digit-symbol if *younger adults* require more than one switch on average, we can tentatively claim that the time duration in question must be of a magnitude large enough to cause decay. If even younger adults can lose access to a temporarily stored trace during this short duration, older adults taking even more time would be even more likely (on average) to lose access to this trace and consequently require additional switches. But similar arguments are less plausible for number comparison because *a priori* it is unclear how many switches would occur for individuals with perfect memory, i.e., that never lose access to the temporary representations. This is because we do not specify how many digits are grouped during a single encoding. Consider the case of a match trial with each digit string containing 9 digits. If an individual switched five times, it could mean that temporary information was lost if the participant encoded 4-digit chunks at a time. But if this hypothetical participant encoded 2-digit chunks, five switches would imply no memory loss. Therefore, for digit-symbol, simultaneity may predict more switching, but for number comparison, it only predicts the absence of a negative relationship.

An important alternative model is a memory decay model, where older adults' rate of information decay is greater than that of younger adults, but that there are no differences in the time to activate processes. Further, we will assume in this model that there are no differences in encoding ability between age groups. This model predicts that in both digit-symbol and number comparison older adults will switch back and forth more than younger adults, because they lose access to temporarily stored information. This is because the model does not predict age differences in search or encoding, yet an age effect remains and can only be explained by more switching. Thus, we would predict no age-related delays (i.e., delays referring to more fixations or longer fixation durations) in the processing of the target or the code table. In number comparison, we would not predict age-related delays in the processing of each number string, but like digit-symbol more switches between the digit strings based on loss of intermediate products of information processing.

A similar memory model is an encoding-deficit model. This model posits an age difference in the ability to encode to be memorized stimuli, where the representation of younger adults is more robust than that of older adults. This model predicts differences at encoding, namely that younger adults will make superior encodings and will consequently require more fixations or longer fixations during encoding processes on both tasks. Hence, we would predict younger adults to have more fixations on the target and on relevant parts of the code table. Given that older adults will have worse representations, they will also be more likely to experience retrieval failure during the comparison process and will consequently make more switches in digit-symbol, again under the assumption of younger adults making multiple switches. In number comparison, older adults must take more switches than younger adults; otherwise, the age-effect on this task would be reversed! However, this model does not predict an age difference on search, and would not predict an effect on the number of irrelevant code table fixations in digit-symbol.

However, another memory-based model is an encoding-delay model. Under this model, older adults have more delays during encoding processes of the target stimuli, but after a stimulus is encoded, the representation is equally robust to decay as in younger adults. This model predicts more difficulty encoding for both tasks, but *does not* predict differences in the number of switches for either task. Moreover, this model would not predict differences in search and would not predict an age effect on the number of irrelevant fixations in digit-symbol.

Another model that has been computationally modeled is Byrne’s (1998) SPAN (speed, parallelism, activation, and noise) computational model of working memory, and is also similar to the model for the symbol-digit task of Laux and Lane (1985). SPAN uses a production system architecture similar to ACT-R (Anderson, 1993) and also borrows concepts and parameter values from EPIC (Meyer & Kieres, 1997) and MHP (Card, Moran, & Newell, 1983). SPAN fixes parameter values for a production cycle (50 ms), eye movement (200 ms), retrieving information from a visual buffer (250 ms), executing motor commands (70 ms), and hitting keys (100 ms). Moreover, SPAN assigns each element of declarative memory i activation values at a given time t according to a novel formula:

$$a(i,t) = a(i,t-1) - \delta(t) + (\gamma/\Omega(t))\beta(i)\Sigma p(i)$$

Here, 'a' represents the activation level of the memory element, δ refers to time-based decay, Ω refers to workload and is a function of the activations of other memory elements, β is a bias for memory elements, p derives from the inputs of productions matching the memory element, and the parameter used to model individual differences in age, γ, which is termed a "propagation rate" parameter. According to Byrne, the γ parameter reflects most closely the construct of processing speed, and the author shows how a similar 20% reduction in this parameter models the age-related change in older adults' performance on both the digit-symbol and the computation span tasks as compared with behavioral data from Salthouse and Coon (1994).

SPAN performs the computer-based digit-symbol task in a few simple steps of processing on the code table and the presented target. First, the model encodes the target symbol, and uses the digit to make an eye movement to the appropriate entry in the code table (it directs its eye movement based on the digit in the target) and compares its memory representation of the symbol to the symbol in this location of the code table, if and only if the memory representation of the target symbol has not decayed from a retrieval threshold. If the target symbol has decayed, the model encodes symbol in the key and rehearses it as it directs its eye movement back to the target. The target symbol is then compared with the rehearsed memory representation. Reductions in the γ parameter cause performance impairments in three ways, based on the target fading more often (resulting in the second eye movement), additional rehearsed elements from previous trials (from a still-active but no longer necessary rehearsal sub-goal), and more cycles to create a memory representation for the target as all processing is slowed.

The SPAN model makes several clear predictions for digit-symbol. First, older adults should switch between the target and the code table more than younger adults (approximately one extra switch). Likewise, because they take more cycles to encode target symbols, they should fixate longer or have more fixations on the target before looking at the code table. And because they are more likely to have to re-encode the digit to make the switch, we would predict greater delays on the relevant pair in the code table as well. But the model never fixates on the irrelevant parts of the code table so we would expect neither an age relationship nor any fixations on the irrelevant parts of the key. Finally, this model applies primarily to digit-symbol and makes no clear predictions for number comparison.

Method

Design

The design of this study is a 2 (age: younger/older) x 2 (protocol: silent/think-aloud) x 3 (instruction: normal/accuracy/speed) mixed factorial. Our primary dependent variables of interest include mean response times for digit-symbol and number comparison. Other important criteria include accuracy on these two tasks, minimum and maximum trial response times, variance in response times, incidental memory performance on digit-symbol, and recall performance on backward digit-span (Wechsler, 1981). Relevant other variables for digit-symbol performance include number of target fixations, number of fixations on the relevant digit in the code table, number of fixations on the relevant symbol in the code table (when different from the digit, viz. on mismatch trials), number of fixations on irrelevant parts of the code table, average fixation duration, average saccade amplitude, the number of switches between the target and the code table, whether the symbol was encoded with a specific label, whether the symbol was encoded multi-syllabically, and the amount verbalized concurrently during a trial, where these latter three only being measurable in the think-aloud condition. Relevant other variables for number comparison performance include the total number of fixations on the two numbers, number of switches between the two numbers, mean fixation duration, mean saccade amplitude, and number of digits verbalized concurrently. Finally, relevant other variables for backward digit span performance include the number of forward repetitions and verbal groupings of numbers. Additionally, intra-individual differences in task performance will be analyzed. Further explanation of these variables will follow below.

Participants

Thirty younger (*M* = 21) and thirty older (*M* = 71) adults participated in a one-hour experiment for payment of 10 dollars per hour. Subjects were recruited from newspaper advertisements or from undergraduate psychology courses at Florida State University, and each was contacted by phone prior to scheduling to conduct pre-screening for eye problems, for non-native English speakers, and for dementia using the Short Portable Mental Status Questionnaire (SPMSQ) and the Wechsler Memory Scale III (WMS-III) (see Czaja et al., in preparation for further explanation of this pre-screening procedure). No subjects were excluded based on these criteria. Each subject was randomly assigned to one of six conditions, where each condition was a combination of a protocol condition (silent or think-aloud) and an instruction condition (normal instructions, accuracy-focused instructions, or speed-focused instructions). For instance, five older adults were in the silent condition and the speed-focused instruction condition.

Apparatus

The number comparison, digit-symbol, and backward digit span tasks were each administered on a 19-inch CRT monitor, although the digit-symbol incidental memory test was paper and pencil. Subjects sat approximately 65 cm away from the monitor. Subjects' eye movements (right eye only) were recorded using an EyeLink II tracking system at a sampling rate of 250 Hz with relative mean visual resolution calibrated to 0.15 degrees for number comparison and 0.38 degrees for digit symbol. The screen resolution was set to 1024 x 768 pixels. Notably, this tracking system has less than 5 degrees of gaze position accuracy. We determined fixations from default eye tracker settings. The size of the digit-symbol target centered in the screen was 5.6 cm in height or roughly 2.5 degrees visual angle.

Procedure

First, subjects signed an informed consent form, and subjects in the think-aloud condition were then instructed on how to give verbal reports (see Ericsson & Simon, 1993 for further details of this procedure). Next, subjects were fitted with a headset mounting a camera to capture eye movements. The first task administered was number comparison, where two digit strings varying from 6 to 12 digits are presented on the left and right hand sides of the screen. We used a three-point calibration for this task, asking subjects to respond after focusing on a dot in three locations of the screen. Once subjects were acceptably calibrated (mean degrees of visual resolution = .15), subjects began the number comparison task. After this, subjects were re-calibrated for digit-symbol using a nine-point calibration procedure. Again, after subjects were acceptably calibrated (mean degrees of visual resolution = .38), subjects began the digit-symbol task. On only these two tasks were eye movements tracked. Immediately after digit-symbol, subjects filled out the incidental recall test. Finally, subjects completed backward digit span and were paid and debriefed.

Number Comparison. The number comparison task consisted of 24 trials asking subjects to decide whether two digit strings were the same. For instance,

3965701746 3665701746

would require a mismatch response. These strings were taken directly from part of the number comparison test (Ekstrom et al., 1976). After each response, subjects were asked to "hit any button to continue" or to "please give a retrospective report" for the think-aloud condition. Notably, each subject received five practice trials prior to beginning the task, after receiving one of three possible instructions. Subjects receiving instructions in the normal condition read "Please respond as quickly as possible without sacrificing accuracy. You will be scored on both speed and accuracy." Subjects receiving instructions in the accuracy condition read "Please respond as accurately as possible. Only accurate responses will be counted toward your score." Finally, subjects receiving instructions in the speed condition read "Please respond as quickly as possible. Only trials completed within 1 second will be counted toward your score."

Digit-Symbol. The digit-symbol task consisted of 50 trials asking subjects to indicate whether a target pairing of a digit and a symbol matched a pairing in the code table (Wechsler, 1981) at the top of the screen, which remained constant and visible on all trials. After each response, subjects were asked either to "hit any button to continue" or to also to first "please give a retrospective report" for the think-aloud condition. Notably, each subject received two practice trials with feedback prior to the task, and after receiving one of three possible instructions. The instructions in each condition were identical to those from number comparison, emphasizing either speed, accuracy, or both.

Backward Span. This task normally consists of orally presented digits, requiring participants to recite the reverse orderings of the digits after hearing all of them (Wechsler, 1981). However, we presented the digits visually, at a rate one digit per second, to obtain verbal reports from participants. For instance, a subject could see 7—8—2—3 show up one digit at a time and afterwards would be asked to recite "3,2,8,7" as a response. The first two trials consisted of three digits, the next two of four digits, and so on. Participants continued to the next pair of trials as long as at least one of the two digits at a given length was correctly recalled backward. Score on this task consisted of the total number of correctly recalled trials.

Coding scheme for verbal reports

For number comparison raters scored verbal concurrent and retrospective protocols for each trial. Virtually all of the protocols consisted primarily of verbalized digits corresponding to the digits presented on each trial; however, the order in which these digits were verbalized contained the primary information we extracted. For example, if the trial was 8041638—8041438, one verbal report was "Eight o four one six three eight, different." In such a report, we presume that the participant reads the entire left hand side, stores the digits in memory, and only then reads the right hand side to determine match or mismatch. On the other hand, if the participant had said "Eight o four, eight o four, one six three, different" we presume that the participant reads only the first three digits, stores them in memory, then compares them to the first three digits on the right string, looks back to the left string and reads the next three digits, stores these in memory, looks back to the right and finally determines that this is a mismatch. These were the two different strategies we examined, each leading to a different number of looks back and forth between the two digits. The first strategy would lead to only one switch from the left to the right string, whereas the second strategy would lead to three switches. Moreover, according to this idea the more digits in each string, the more discrepant these two strategies would become if small (e.g., three digit) groupings are consistently employed. Notably, almost no participants grouped digits such as 16 as "sixteen," despite our expectancy that such groupings would lead to a performance advantage. Finally, we counted how many digits each participant verbalized during the trial because we expected this to explain protocol reactivity on reaction time (longer times in the protocol condition occur primarily because participants are verbalizing a number of digits) and because some participants using the same strategy may differ in the amount of verbalization (e.g., a participant using the first strategy might say "Eight o four one six three eight, eight o four one four, different"). Although most of this information was contained in concurrent reports, some "less verbal" participants said almost nothing concurrently, but their retrospective reports allowed us to obtain similar strategic information.

For digit-symbol substitution raters scored verbal concurrent and retrospective protocols for each trial. First, we were interested in what words participants used to encode the symbols. Pilot experiments indicated that some participants would call a symbol “equals” and others would call it “symbol.” We coded for whether participants used a specific word to encode the symbol or whether they didn’t refer to it at all or called it a ‘symbol’ or a ‘thing.’ Second, we thought using multi-syllabic encodings of symbols might slow response times, so we coded for this as well. Third, retrospective reports helped us assess how many times participants switched between the target and the code table, as indicated by the participant saying “The first thought I had was looking at the five, checking the top and saw it was a ‘U’ which was different.” Here we determine that the participant looked up from the target to the key one time. Finally, we coded whether the participant verbalized the target digit, symbol, or both during concurrent reports to assess whether some participants might be verbalizing more than others, but still using similar strategies.

In backward digit span, the primary variable of interest was how many times the participant rehearsed the digit string in its forward order before attempting to recite it backward. Notably, we found almost no participants grouping the digits into larger number (e.g., 16 as ‘sixteen’) or referring to semantic information, such as phone numbers or dates.

Results

Generally, we set the alpha level for significance in these experiments to the .05 level. All data presented here, including eye tracking data, are from accurate trials only. We analyze mean response time (RT) from both digit-symbol and number comparison, and although other studies have examined median response times, median and mean RT were correlated r (42) > .99 for both tasks and none of the results change when using median RT instead of mean RT. Importantly, we exclude participants from the analyses when either the score on the dependent variable was greater than four standard deviations above the mean (outliers) or when the accuracy levels on either digit-symbol or number comparison were less than 85%. Sixteen out of sixty individuals were excluded based on these criteria. Consequently, our final sample included 17 protocol subjects remaining (9 younger/8 older) and 27 silent subjects (13 younger/14 older). Our final sample contained 11 males and 33 females.

After inspection of means and standard deviations for the two protocol conditions, we found that the variance of the think-aloud subjects was greater than that of silent subjects for both the digit-symbol, F (16, 26) = 2.66, p = .013, and number comparison, F (16, 26) = 3.98, p < .001, with the Levene's test for heterogeneity of variance being reliable for both, p < .05. Consequently, we will analyze the results for the two protocol groups separately.

Primary analyses: Silent participants

We conducted a 2 (age group) x 3 (instruction) univariate ANOVA predicting digit-symbol mean RT revealed reliable main effects of age group, F (1, 21) = 9.143, p = .006, MSE = 245943, η_p^2 = .303, though neither instruction, nor the higher order interactions were reliable, p > .05. Note that Levene's test for heterogeneity of variances between age groups was not reliable, p > .05, and none of our results change if we use log response times. See Table 2 for means and standard deviations, showing how older subjects had slower response times as predicted. Note also that our digit-symbol response times correspond well with normative data (younger adults tend to score around 65 digits in the 90 second written version, and 65*1498 = 97 seconds, and older adults tend to score around 45, and 45*2076 = 93 seconds). For accuracy, the same univariate analysis reveals no reliable effects, and accuracy did not reliably correlate with response time, *p* > .05.

Table 2. *Descriptive statistics for perceptual speed tasks*

				Mean	**Standard Deviation**
Digit-Symbol	Response Time	Younger	Silent	1498	227
		Older	Silent	2076	618
		Younger	Protocol	2323	932
		Older	Protocol	3066	623
	Accuracy	Younger	Silent	0.96	0.02
		Older	Silent	0.97	0.02
		Younger	Protocol	0.96	0.02
		Older	Protocol	0.96	0.03
Number Comparison	Response Time	Younger	Silent	3333	719
		Older	Silent	4402	1678
		Younger	Protocol	5894	2677
		Older	Protocol	7467	2824
	Accuracy	Younger	Silent	0.96	0.05
		Older	Silent	0.94	0.05
		Younger	Protocol	0.94	0.05
		Older	Protocol	0.95	0.05

Number comparison and digit-symbol mean response times were highly correlated, *r* (25) = .82, *p* < .00001 in this sample. A similar correlation was found within older adults, *r* (12) = .84, *p* < .001, but not within younger adults, *r* (11) = .41, *p* = .16. A univariate ANOVA analysis of number comparison mean response time indicated an effect of age-group, *F* (1, 21) = 5.053, *MSE* = 1395396, *p* = .035, η_p^2 =.194. Also, neither instruction, nor any higher order interactions were reliable. A Levene's test for heterogeneity of variance was not reliable, $p > .05$, and none of our results change if we use log response times. Importantly, the univariate ANOVA on number comparison accuracy yielded no reliable effects, and accuracy was unrelated to response time, $p > .05$. Given that instruction had no effects on any of our primary dependent variables, we remove instructions (speed versus accuracy) as a factor from later analyses.

We also found that chronological age of participants predicted backward digit span performance, $r\,(25) = -.44$, $p = .021$. Salthouse (1996) found that digit-symbol performance shares the age-related variance with a large number of other cognitive tasks. We replicate this finding with our results, showing that this effect of age group on backward digit span is no longer significant in a linear regression after controlling digit-symbol mean RT, $p = .415$. This indicates that digit-symbol accounts for the age-related variance in backward span. Similarly, this age effect on backward span is no longer significant when using number comparison mean RT as a covariate, $p = .107$. Hence, both our perceptual speed tasks account for the age-related variance in backward span, replicating the general findings of Salthouse (1996). Likewise, the age effect on number comparison response time is not significant in the linear regression after controlling digit-symbol, $p = .588$, although the age effect on digit-symbol remains reliable after controlling number comparison, $p = .013$, and number comparison contributed significant additional variance, $F\,(1, 21) = 34.535$, $p < .001$. Hence, digit-symbol explains the age-related variance in number comparison, but number comparison does not explain all the age-related variance in digit-symbol.

Finally, incidental recall performance on digit-symbol correlated with chronological age, $r\,(25) = -.55$, $p = .003$, and with digit-symbol RT, $r\,(25) = -.41$, $p = .034$, but age remains a reliable predictor of digit-symbol performance after controlling for recall in a linear regression, and recall does not contribute significant additional variance, $p > .05$. We also examined the effects of age on minimum digit-symbol RT, $r\,(24) = .74$, $p < .001$, maximum digit-symbol RT, $r\,(24) = .45$, $p = .021$, and standard deviation in digit-symbol RT, which was not reliable, $p = .057$. Lastly, we examined the effects of age on number comparison minimum RT, $r\,(25) = .49$, $p = .009$, maximum RT, $r\,(25) = .52$, $p = .006$, and standard deviation in RT, $r\,(25) = .49$, $p = .009$.

Between groups results for digit-symbol

We examined the bivariate correlations between age group (note that we also verified that using chronological age produces equivalent results), digit-symbol, and our eye tracking variables, namely the number of switches between the key and target (switches), the number of fixations on the target (target fixations), the number of fixations on the relevant digit in the key (digit fixations), the number of fixations on the relevant symbol in the key when different than the digit (symbol fixations), the number of fixations on irrelevant parts of the key (irrelevant fixations), the overall mean fixation duration, and the mean saccade amplitude. Notably, one participant's eye tracking data was lost due to calibration errors (this must have occurred after the task had started as all subjects were appropriately calibrated before the task). First, for better understanding of how our findings apply to our models, we first report the average number of switches for younger (M = 1.9, S = .46) and older (M = 2.0, S = .55) adults, indicating that this variable is relevant as previously discussed. Bivariate analyses revealed reliable correlations between digit-symbol performance and target fixations, r (24) = .64, p < .001, digit fixations, r (24) = .53, p = .006, and number of fixations on irrelevant parts of the key, r (24) = .50, p = .009. None of the other variables reliably correlated with performance, though switches showed a trend, r (24) = .38, p = .056. However, only two of these variables correlated with age group, namely target fixations, r (24) = .59, p = .002, and digit fixations, r (24) = .61, p = .001.

Additionally, we examined the correlations between these relevant eye tracking variables. We found that target fixations correlated with digit fixations, r (24) = .46, p = .017, and surprisingly with fixation duration, r (24) = -.61, p = .001. Digit fixations also correlated with irrelevant fixations, r (24) = .64, p < .001, and irrelevant fixations correlated with fixation duration, r (24) = -.40, p = .041.

Finally, age group remains a reliable predictor of digit-symbol RT when both target fixations and digit fixations are added to the model, and these do not contribute additional reliable variance, p > .05. However, the semi-partial correlation for age group is reduced from sr = .708 to sr = .330, indicating that number of target and digit fixations can potentially partially mediate the age-related variance in digit-symbol performance. Z-scored fisher transformations indicate this difference is reliable, although this must be cautiously interpreted given that using this method for hypothesis testing assumes independent samples for each parameter, an assumption that is violated in this case.

Within groups results for digit-symbol

Restricting our analyses to just younger adults, we found no reliable correlations with age and digit-symbol performance, *r* (11) = .46, *p* = .114, possibly due to range restriction. However, restricting our analyses to older adults, we found a reliable relationship, *r* (12) = .61, *p* = .021. Examining correlations with the same set of eye tracking variables, we found only one reliable correlation with digit-symbol RT, namely irrelevant fixations, *r* (11) = .73, *p* = .005. Notably, we found no reliable correlations with age.

Intra-individual differences on digit-symbol

To supplement and provide additional support for our between subjects findings, we conducted analyses within participants. For each individual, we examined the within-person correlations between different variables (all for accurate trials only), then applied Fisher's Z-transformation to get a normally-distributed variable. We then run one-sample t-tests for each Z-scored correlation coefficient to test whether it is different from 0. Our goal was twofold: to determine which effects are between subjects, rather than within subjects, particularly the correlations between RT and target, digit, and irrelevant fixations, as well as the intercorrelations between these variables, and secondly to examine the effects of practice via correlations of these five variables with trial number. See Appendix G for the complete set of correlations.

We found that Fisher transformed correlations with RT were reliably different than zero for target fixations, digit fixations, irrelevant fixations, symbol fixations, switches, saccade amplitudes, but not fixation durations. Hence, this lends support to our earlier assertions for a relationship between RT and these variables, and provides a more sensitive analysis showing how switches, saccade amplitudes, and symbol fixations related to performance. Additionally, we support our between subjects intercorrelations, finding that target fixations correlated with fixation duration, but not with digit fixations. This indicates a between subjects factor accounted for the aforementioned relationship of target to digit fixations. Also, we found that irrelevant fixations correlated with both digit fixation and again with fixation duration. However, earlier irrelevant fixations correlated *positively* with digit fixations, indicating a between subjects factor overrides the within-subjects trend.

We investigated the effects of age group on these within-person correlations of RT. We found only one reliable age group effect on the above mentioned correlations, namely that age correlates with the relationship of RT to irrelevant fixations, r (24) = .42, p = .035, indicating that older adults showed larger correlations of RT and irrelevant fixations within subjects. This fits well with our earlier finding that irrelevant fixations correlated with performance within the older adult group.

Finally, we examined the correlation between trial and RT, which was strong and reliable. Thus, individuals tended to improve over the course of the experiment. Additionally, a similar univariate ANOVA as used above revealed no reliable effects of age on this practice variable. We examined improvement over time with other RT variables. We found negative correlations with trial number for target fixations, digit fixations, and irrelevant fixations, but not for fixation duration. Thus, individuals tended to make fewer fixations on the target, the relevant digit, and irrelevant parts of the code table over time. However, none of these relationships correlated with age, showing that both age groups tended to improve over trials at the same rate and that both groups tended to reduce their frequency of fixations. But we also found that individuals showing stronger practice effects (*Zr* for trial and RT) had stronger reductions in the number of target fixations across trials (*Zr* for trial and target fixations), r (24) = .45, p = .021. Therefore, we tentatively conclude that improvement within subjects was mediated by their making fewer target fixations. This also supports our findings for a relationship between performance and the number of target fixations. Finally, we examined correlations with overall digit-symbol mean RT performance with the practice effect (Zr for trial and RT), finding that slower individuals showed stronger improvement effects, r (24) = .40, p = .043.

Notably, we have conducted many statistical tests and some of these results may be capitalizing on chance. However, most of these results are not relevant for comparison of our models and we believe that they are merely suggestive. The two most important findings are the relationship between age and fixations on the target and relevant digit, and both of these strong correlations were highly significant, $p < .002$.

Between groups results on number comparison

We examined bivariate correlations between age group, number comparison RT, and our eye tracking variables. Notably, one participant's data could not be analyzed due to calibration failure (this must have occurred after the task had started as all subjects were appropriately calibrated before the task). Response time on number comparison almost perfectly correlates with the mean number of total fixations on both numbers (fixations), *r* (24) = .963, *p* < .00001, and strongly correlates with number of switches (switches), *r* (24) = .512, *p* = .008, but not with fixation duration or saccade amplitude, *p* > .05. Fixations correlates well with switches, *r* (24) = .607, *p* = .001, but not with fixation duration or saccade amplitude, *p* > .05. None of the other eye tracking variables reliably correlated. Age group does not reliably correlate with any of the variables, though shows a trend with fixations, *r* (24) = .333, *p* = .096, but chronological age is reliably correlated with fixations, *r* (24) = .393, *p* = .047. Therefore, we can cautiously conclude that older adults fixated more frequently. Finally, adding fixations to a linear regression predicting number comparison RT with age group leaves age group non-significant, *p* = .305. Hence, we have evidence that the total number of fixations mediates the age-related variance in number comparison.

Within groups results for number comparison

Restricting our analyses to younger adults, we found no reliable correlation with age and number comparison performance, *r* (11) = .486, *p* = .093. Similarly, restricting our analyses to older adults also resulted in no age effect, *r* (12) = .425, *p* = .130. As we did not find age effects within these groups, we do not conduct further within-group analyses, though trends are clearly emerging and are possibly not reliable due to decreased power and range restriction.

Intra-individual differences on number comparison

Similar to our analyses with digit-symbol, we calculated within-subject Fisher transformed correlations and conducted one-sample t-tests on these values to lend support and re-examine our between-subjects findings. See Appendix H for a full listing of one-sample t-test findings. We found that RT correlates with fixations, with switches, and with fixation duration, but not with saccade amplitude. Also, we support our earlier between subject finding that fixations correlates with switches. Notably, positive age group correlations with the relationship between RT and fixations, *r* (24) = .43, *p* = .028, as well as between RT and switches, *r* (26) = .39, *p* = .047, illustrates that older adults showed stronger relations of RT with these two variables.

We also examined effects of trial number, finding that trial correlates with RT, with fixations, with switches, and with fixation duration, but not with saccade amplitude. Thus, we found a practice effect on number comparison, and we also found that older adults show weaker practice effects, age group being negatively correlated with the RT-trial relationship, *r* (24) = -.44, *p* = .025. We also found that slower individuals showed weaker practice effects, mean RT being negatively correlated with the RT-trial relationship, *r* (24) = -.48, *p* = .013. A linear regression shows that this latter effect is mediated by age as neither variable is reliable when both are predictors. Notably, this practice-performance relationship was the opposite from that of digit-symbol. However, these findings are not contradictory. Digit-symbol improvement was unrelated to age group and showed initially worse performers improving the most. In contrast, number comparison improvement was slower for older adults, and as older adults have worse performance, we found that individuals with worse performance improvement more slowly. Finally, this practice effect strongly related to decreases in the number of fixations across trials, *r* (24) = .82, *p* < .001, but not to trial effects on any of the other eye tracking variables. Therefore, improvement occurred when individuals made fewer fixations over time. However, as previously mentioned many of these results may be capitalizing on chance, and we argue that they should be cautiously interpreted and require replication in future studies.

Primary analyses: Think-aloud participants

We conducted 2 (age) x 3 (instruction) univariate ANOVA analyses for accuracies and response times for digit-symbol and number comparison within the think-aloud group. For number comparison, we found a trend, but no age group effect on number comparison, *p* = .07. Given the possibility that verbalizing contributed to our missing age effect, we covaried the number of digits verbalized per trial, though age group remains non-significant, *p* = .136. For digit-symbol, we also found a trend, but no reliable age effect, *p* = .06, and this remained true even after covarying the number syllables concurrently verbalized on average. Hence, we did not pursue further age analyses for protocol subjects, although we probably would find these effects given more power. However, one think-aloud variable that holds promise is the frequency of encoding symbols with more than one syllable during digit-symbol, which *negatively* correlates with response time, $r\,(15) = -.544$, $p = .024$, and shows a potential trend with chronological age, $r\,(15) = -.473$, $p = .055$. After increasing the numbers of participants, we expect to find the expected age-related decline on digit-symbol and that such variables, related to encoding, might partially mediate decline.

Interestingly, the number of rehearsals per trial from verbal protocols correlated with backward digit span performance, $r\,(15) = .62$, $p < .01$, including when we exclude individuals with spans less than 4 digits, $r\,(7) = .79$, $p = .012$ (we must consider this because it is possible that individuals only need to rehearse when they reach higher digit spans). Rehearsals did not correlate with age, however.

Discussion

Overall, we replicate previous literature finding effects of age on perceptual speed tasks as well as Salthouse's (1996) finding that controlling for these tasks accounts for the age-related variance in other cognitive measures. Our instruction manipulation (to examine a potential speed-accuracy trade-off) appears to have no reliable effects on performance, but as accuracy and response time never correlated, we did not find evidence for a speed-accuracy trade-off. For unclear reasons, verbal think-aloud subjects showed reliably more variability than silent subjects, and we had difficulty finding the primary age effects on task performance, most likely due to reduced power in the protocol condition.

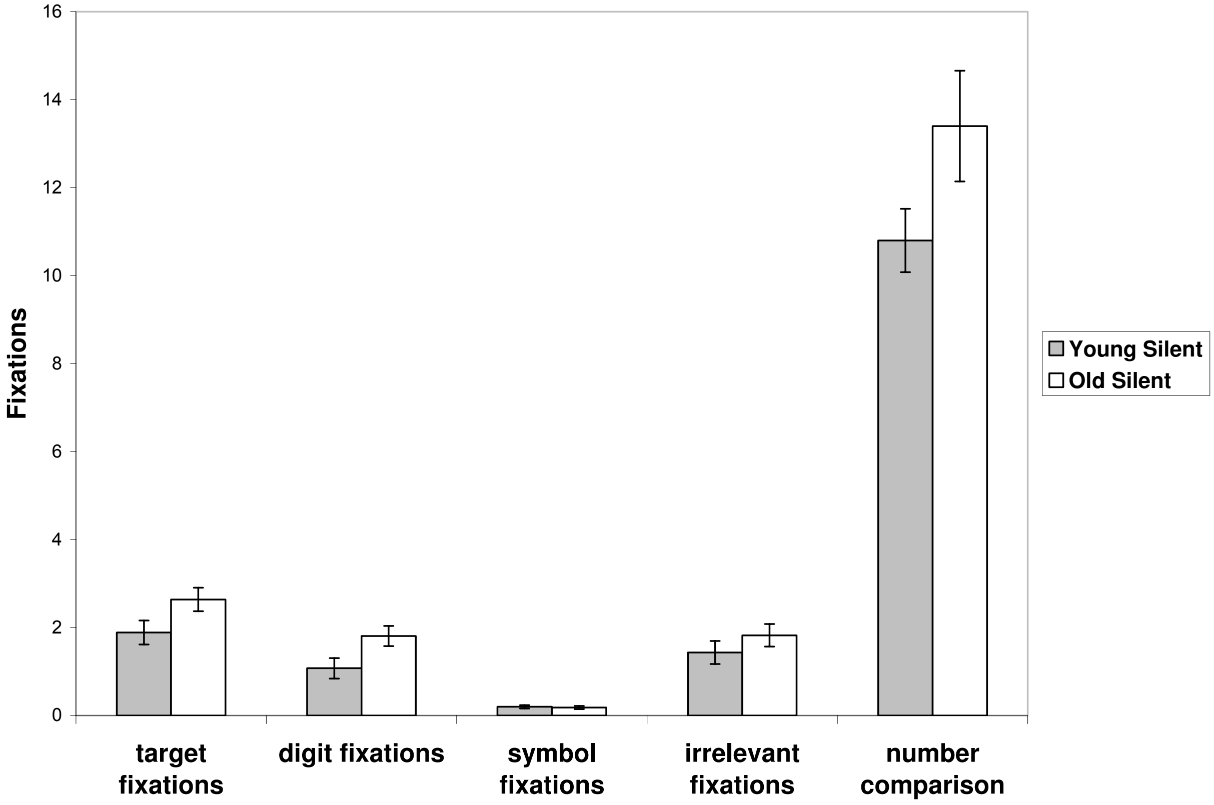


Figure 1: *Age effects on the number of fixations*

From our findings, we argue that many elements of processing in digit-symbol and number comparison appear consistent across both age groups. In digit-symbol both younger and older adults, after encoding the target, tend to search for the corresponding digit in the code table, as opposed to the corresponding symbol, as illustrated by the magnitude of the symbol fixations variable in Figure 1. Thus, during mismatch trials, virtually all participants searched for the target digit, rather than the target symbol. All silent participants appeared to use between one and two extra fixations to search the key, and on average silent participants made roughly 2 switches, looking first at the target, then at the key, then back to the target. Using these data along with our age effects, we can construct process models for younger and older adult digit-symbol performance (see Appendix C and D). In these models, the primary digit-symbol age effects are in the encoding steps (where extra fixations occur). But as this did not fully mediate the age effect on digit-symbol, we also believe the step involving the comparison of target to the code table pair also incurs an age cost. In number comparison, all participants made roughly three switches on average (on average, strings were 9.7 digits long), indicating that participants encoded between four and five digits at a time. In this task, fixations fully mediated the age effect (younger adults averaging around 10 total fixations, older adults around 13 fixations), so we suspect that encoding processes account for age-differences and that no age-differences exist during the comparison phase. We found that older adults take about 1 extra fixation during encoding (see Appendix E and F). However, given the post-hoc nature of these models, they must be validated by further experimentation.

Additionally, we confirmed that our most relevant between subject correlations also occur within subjects. We found several interesting practice effects as well, namely that on digit-symbol age did not relate to improvement although poorer performers tended to improve the most. However, in number comparison increased age did negatively relate to improvement, and worse performers (namely older adults as shown by our regressions) tended to show the *least* improvement. In number comparison, improvement was mediated by decreasing numbers of fixations, and individuals tended to reduce their fixations over time. This is intriguing as a reduction in the number of fixations also explains the practice effects in digit-symbol, though we found no age effects in this case. One possible explanation is that differences between the tasks account for the discrepancy. In number comparison, there are fewer search processes than in digit-symbol, where the code table must be searched.

Implications for general slowing and theories of aging

Our results have not supported the simultaneity mechanism of Salthouse's (1996) theory of general slowing. As illustrated in Table 3, encoding delay was the only one of the *a priori* theories proposed that consistently predicted our findings.

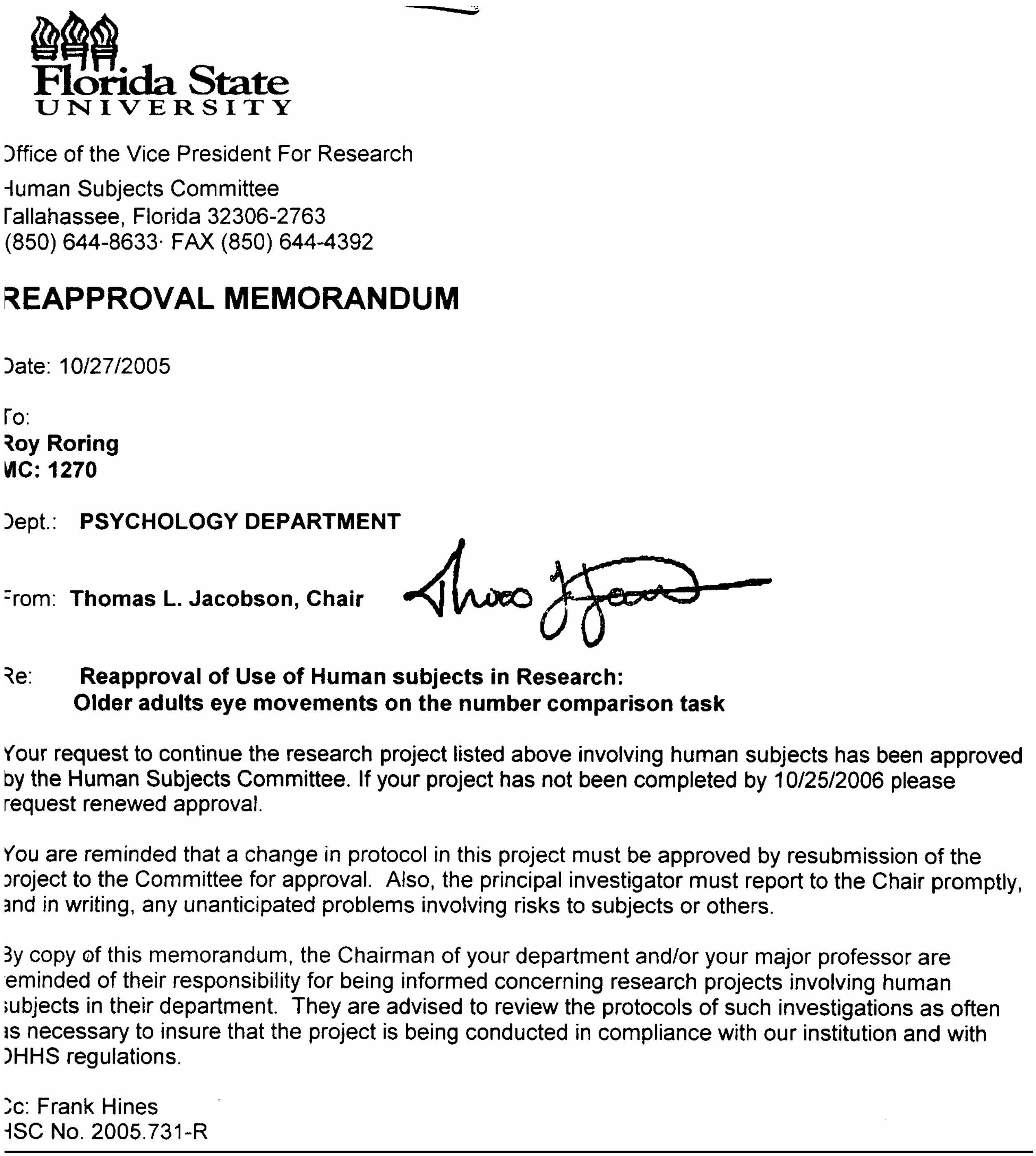
Table 3. *Comparing model predictions with observations*

	DSS: Switches (0)	DSS: Target Fixations (+)	DSS: Relevant Key Fixations (+)	DSS: Irrelevant Key Fixations (0)	NC: Switches (0)	NC: Fixations (+)
Simultaneity	No	Yes	Yes	No	Yes	Yes
Memory Decay	No	No	No	Yes	No	No
Encoding Deficit	No	No	No	Yes	No	No
Encoding Delay	Yes	Yes	Yes	Yes	Yes	Yes
SPAN	No	Yes	Yes	No		

But this may not be incompatible with theories based on slowing, and may specify that the slowing is specific to encoding processes, rather than general to all processes. Moreover, the simultaneity mechanism was not contradicted by any statistically significant result. Our use of null results here is an important caveat to our findings, although all other rejected models were contradicted by at least one non-null correlation. But in defense of simultaneity, one possible additional argument is that the slowing during search might be small relative to the slowing in encoding, as these processes are fundamentally different. Hence, effects of switches and of slowed search may require more power to detect. Additionally, this theory does not specify exactly why encoding is delayed. Aside from strictly neurological explanations, it is possible that older adults take more time for other reasons, perhaps related to subjective perceptions of their cognitive abilities. Thus, older adults take longer because they assume they must, though such a theory would predict that older individuals who believe their abilities are perfectly intact would show no performance decline during encoding. Another possibility is that older adults' encoding strategies are different; however, this theory leaves unspecified exactly what these strategic differences are and consequently is difficult to falsify. Finally, encoding processes may be generally impaired in older adults due to more implicit or automatic aspects of encoding being distinct from those aspects in younger adults. But any theory based on encoding delay will not predict age-related decline during non-encoding portions of task processing.

More generally, we do not dispute that older adults' performance is slower than that of younger adults on most cognitive tasks. However, *slowing* is a description of the phenomena, not an explanation. We tested the predictions of many specific mechanisms, with only one mechanism accurately reflecting our results. Our data provide evidence that processes related to encoding may partially account for the age-related variance in performance on perceptual speed tasks. However, additional age-related variance remains unexplained and future research is necessary to test theories that can fully account for the age-related changes in these tasks to better understand what causes age-related reductions in performance on the broader range of cognitive tasks.

Appendix A: IRB Approval



Florida State
UNIVERSITY

Office of the Vice President For Research
Human Subjects Committee
Tallahassee, Florida 32306-2763
(850) 644-8633· FAX (850) 644-4392

REAPPROVAL MEMORANDUM

Date: 10/27/2005

To:
Roy Roring
MC: 1270

Dept.: **PSYCHOLOGY DEPARTMENT**

From: **Thomas L. Jacobson, Chair**

Re: **Reapproval of Use of Human subjects in Research:**
Older adults eye movements on the number comparison task

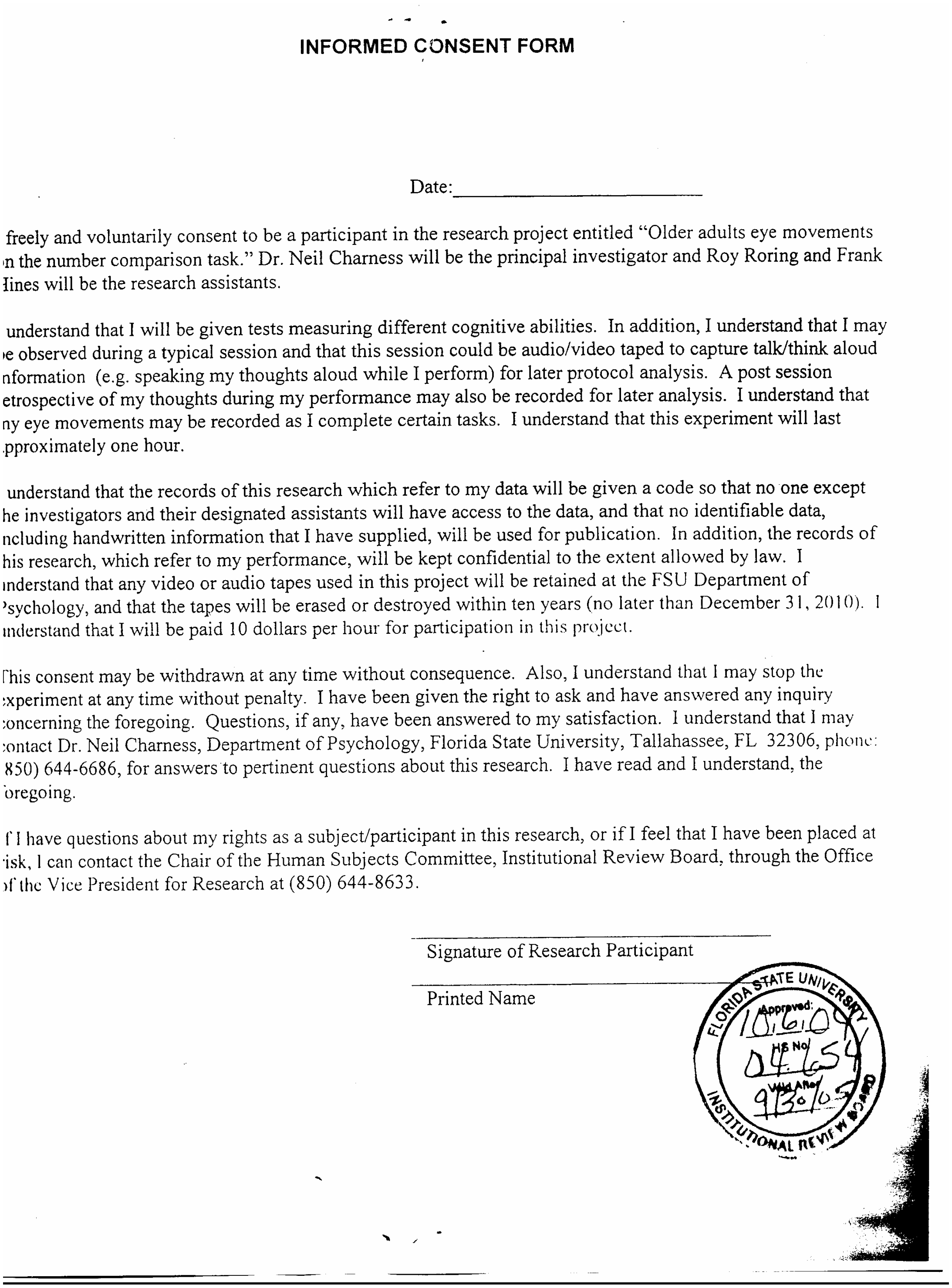
Your request to continue the research project listed above involving human subjects has been approved by the Human Subjects Committee. If your project has not been completed by 10/25/2006 please request renewed approval.

You are reminded that a change in protocol in this project must be approved by resubmission of the project to the Committee for approval. Also, the principal investigator must report to the Chair promptly, and in writing, any unanticipated problems involving risks to subjects or others.

By copy of this memorandum, the Chairman of your department and/or your major professor are eminded of their responsibility for being informed concerning research projects involving human subjects in their department. They are advised to review the protocols of such investigations as often as necessary to insure that the project is being conducted in compliance with our institution and with DHHS regulations.

Cc: Frank Hines
HSC No. 2005.731-R

Appendix B: Informed consent form



INFORMED CONSENT FORM

Date:________________________

freely and voluntarily consent to be a participant in the research project entitled "Older adults eye movements n the number comparison task." Dr. Neil Charness will be the principal investigator and Roy Roring and Frank ines will be the research assistants.

understand that I will be given tests measuring different cognitive abilities. In addition, I understand that I may e observed during a typical session and that this session could be audio/video taped to capture talk/think aloud nformation (e.g. speaking my thoughts aloud while I perform) for later protocol analysis. A post session etrospective of my thoughts during my performance may also be recorded for later analysis. I understand that ny eye movements may be recorded as I complete certain tasks. I understand that this experiment will last pproximately one hour.

understand that the records of this research which refer to my data will be given a code so that no one except he investigators and their designated assistants will have access to the data, and that no identifiable data, ncluding handwritten information that I have supplied, will be used for publication. In addition, the records of his research, which refer to my performance, will be kept confidential to the extent allowed by law. I nderstand that any video or audio tapes used in this project will be retained at the FSU Department of sychology, and that the tapes will be erased or destroyed within ten years (no later than December 31, 2010). I nderstand that I will be paid 10 dollars per hour for participation in this project.

his consent may be withdrawn at any time without consequence. Also, I understand that I may stop the xperiment at any time without penalty. I have been given the right to ask and have answered any inquiry oncerning the foregoing. Questions, if any, have been answered to my satisfaction. I understand that I may ontact Dr. Neil Charness, Department of Psychology, Florida State University, Tallahassee, FL 32306, phone: 850) 644-6686, for answers to pertinent questions about this research. I have read and I understand, the oregoing.

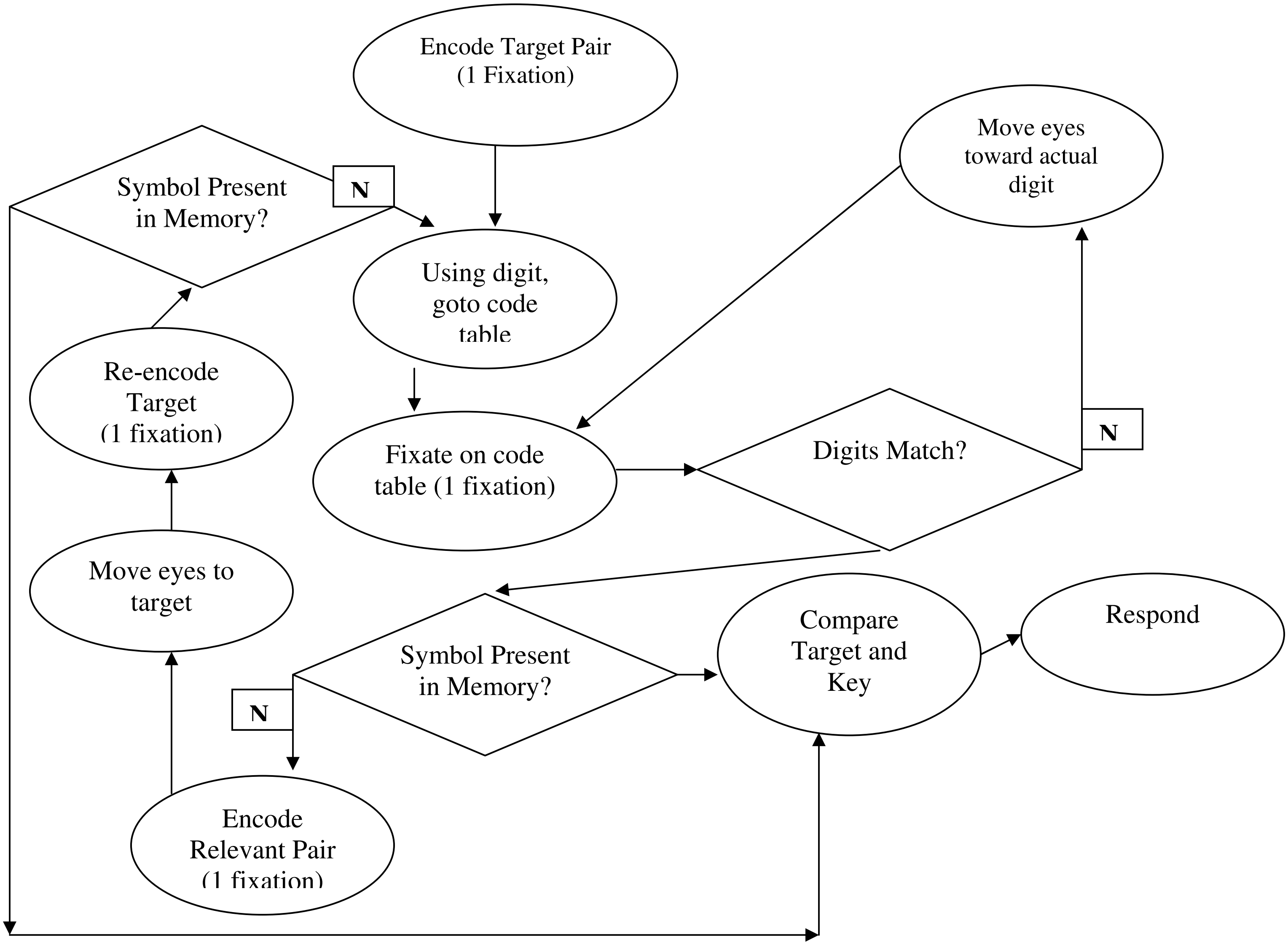
f I have questions about my rights as a subject/participant in this research, or if I feel that I have been placed at isk, I can contact the Chair of the Human Subjects Committee, Institutional Review Board, through the Office f the Vice President for Research at (850) 644-8633.

____
Signature of Research Participant

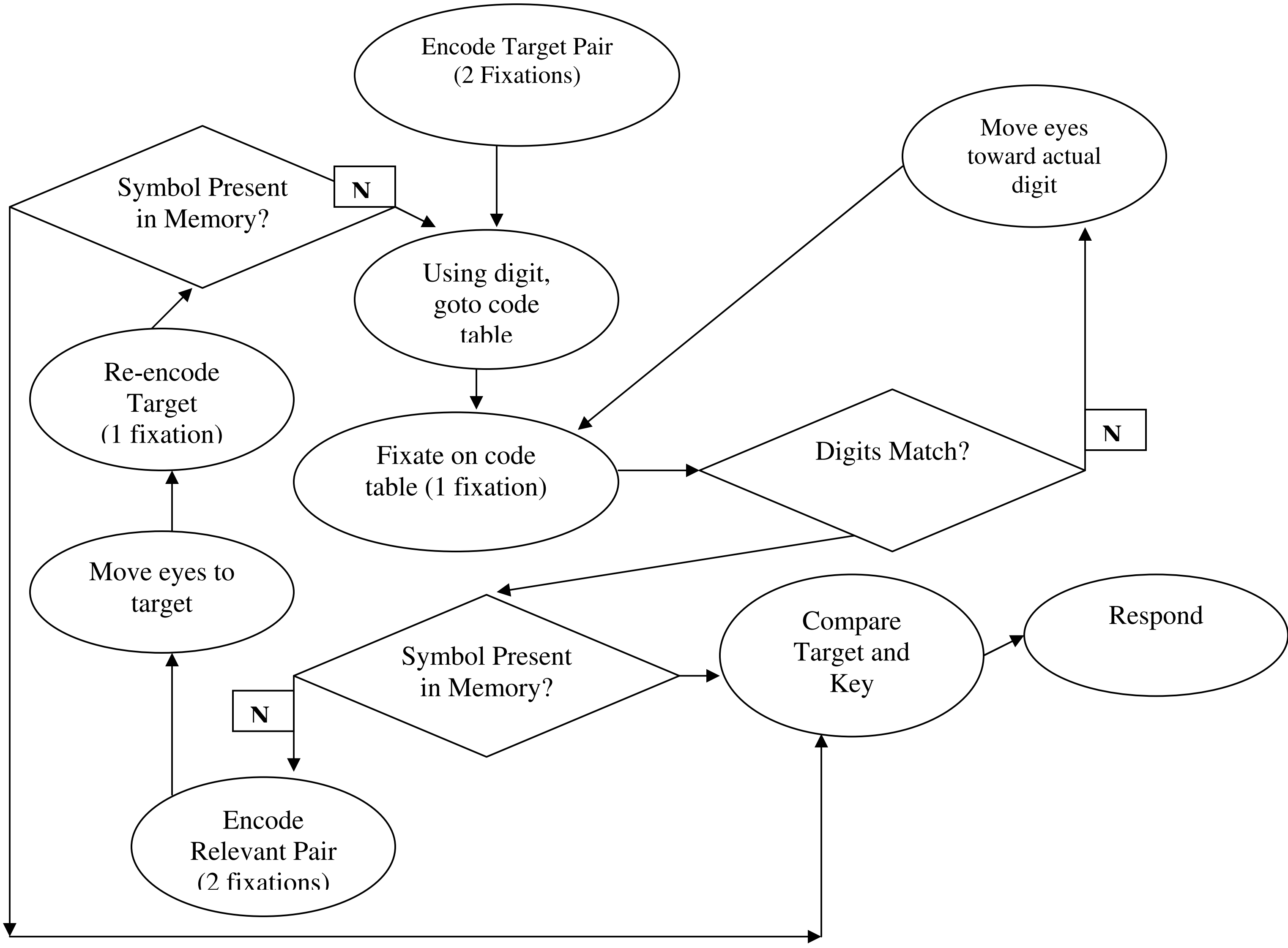
____
Printed Name

Approved: 10.6.04
HS No. 04.654
Void After 9/30/05

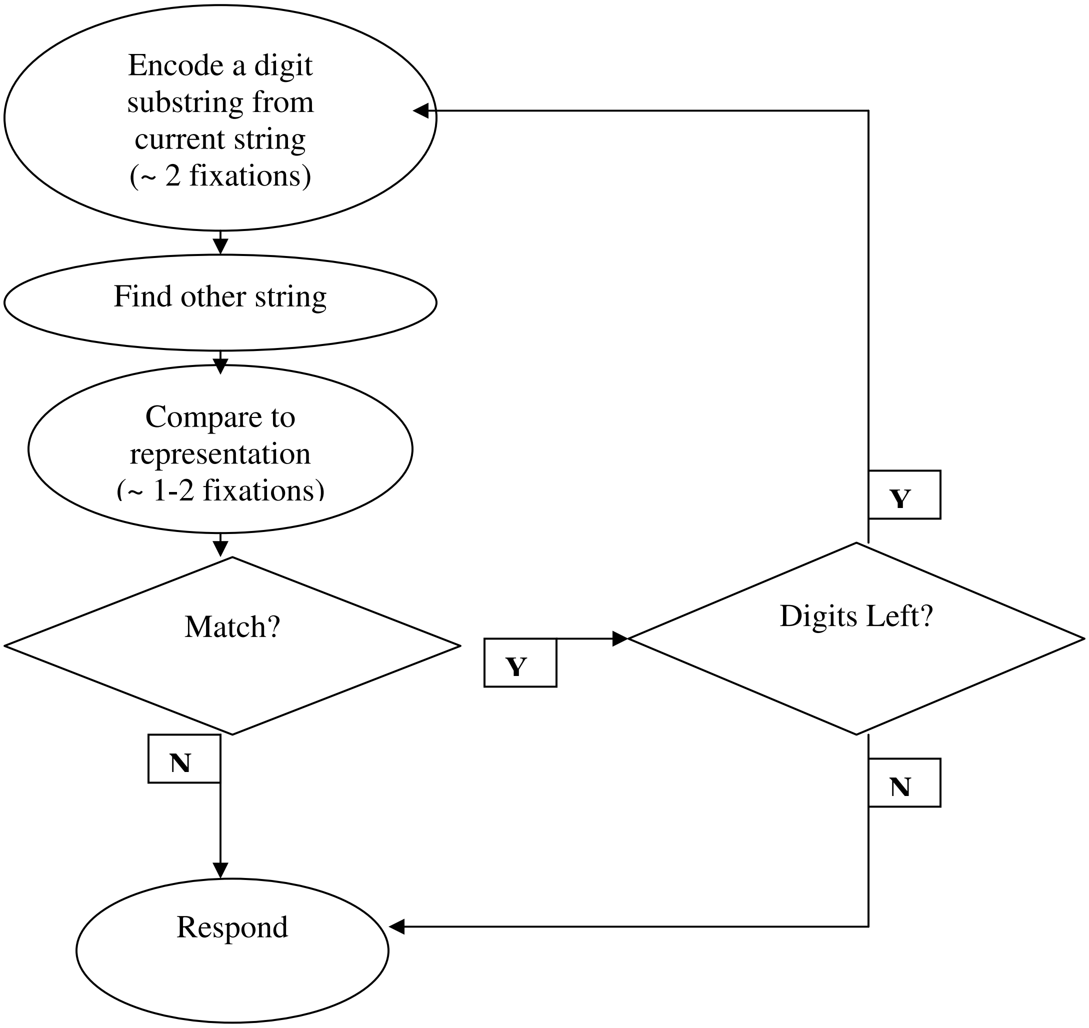
Appendix C: Younger adult process model on digit-symbol



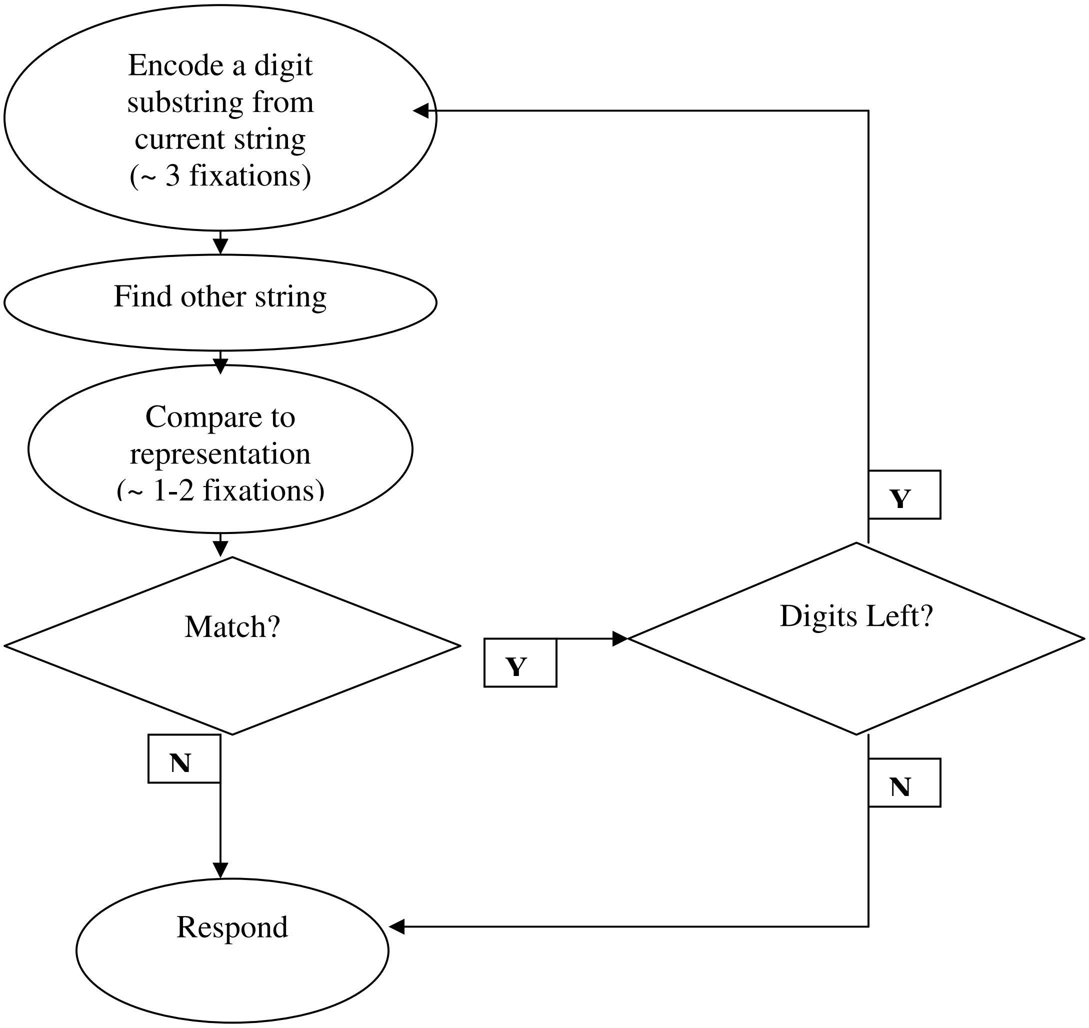
Appendix D: Older adult process model on digit-symbol



Appendix E: Younger adult process model on number comparison



Appendix F: Older adult process model on number comparison



Appendix G: One-sample tests for digit-symbol

	Test Value = 0					
					95% Confidence Interval of the Difference	
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
Zr_RT_FixTarg	9.265	25	.000	.51680	.4019	.6317
Zr_RT_FixKeyDig	5.313	25	.000	.19873	.1217	.2758
Zr_RT_FixKeySym	3.557	24	.002	.15405	.0647	.2434
Zr_RT_FixIrr	11.042	25	.000	.56849	.4625	.6745
Zr_RT_NumSwitch	10.247	25	.000	.58828	.4701	.7065
Zr_RT_FixDur	-.440	25	.663	-.01565	-.0888	.0575
Zr_RT_SaccAmp	-2.696	25	.012	-.09644	-.1701	-.0228
Zr_FixTarg_FixKeyDig	1.750	25	.092	.07920	-.0140	.1724
Zr_FixTarg_FixKeySym	.494	24	.626	.01539	-.0489	.0796
Zr_FixTarg_FixIrr	3.166	25	.004	.12502	.0437	.2064
Zr_FixTarg_NumSwitch	14.437	25	.000	.61835	.5301	.7066
Zr_FixTarg_FixDur	-6.162	25	.000	-.24803	-.3309	-.1651
Zr_FixTarg_SaccAmp	.353	25	.727	.01382	-.0668	.0945
Zr_FixKeyDig_FixKeySym	-2.586	24	.016	-.11204	-.2015	-.0226
Zr_FixKeyDig_FixIrr	-2.286	25	.031	-.12616	-.2398	-.0125
Zr_FixKeyDig_NumSwitch	2.772	25	.010	.09303	.0239	.1621
Zr_FixKeyDig_FixDur	-1.240	25	.227	-.03795	-.1010	.0251
Zr_FixKeyDig_SaccAmp	-10.917	25	.000	-.24445	-.2906	-.1983
Zr_FixKeySym_FixIrr	-.522	24	.607	-.01920	-.0952	.0567
Zr_FixKeySym_NumSwitch	2.772	25	.010	.09303	.0239	.1621
Zr_FixKeySym_FixDur	-1.240	25	.227	-.03795	-.1010	.0251
Zr_FixKeySym_SaccAmp	-10.917	25	.000	-.24445	-.2906	-.1983
Zr_FixIrr_NumSwitch	4.857	25	.000	.21414	.1233	.3049
Zr_FixIrr_FixDur	-6.864	25	.000	-.20069	-.2609	-.1405
Zr_FixIrr_SaccAmp	-2.177	25	.039	-.08195	-.1595	-.0044
Zr_NumSwitch_FixDur	-5.076	25	.000	-.21628	-.3040	-.1285
Zr_NumSwitch_SaccAmp	6.112	25	.000	.26978	.1789	.3607
Zr_FixDur_SaccAmp	1.870	25	.073	.08916	-.0090	.1874
Zr_RT_Trial	-11.392	25	.000	-.47991	-.5667	-.3931
Zr_Trial_TargFix	-7.418	25	.000	-.31725	-.4053	-.2292
Zr_Trial_DigFix	-4.907	25	.000	-.22151	-.3145	-.1285
Zr_Trial_IrrFix	-6.662	25	.000	-.26617	-.3485	-.1839
Zr_Trial_FixDur	.825	25	.417	.03777	-.0565	.1320

Appendix H: One-sample tests for number comparison

	Test Value = 0					
					95% Confidence Interval of the Difference	
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
nc_zr_RT_trial	6.526	25	.000	.27422	.1877	.3608
nc_zr_RT_fix	28.210	25	.000	1.77132	1.6420	1.9006
nc_zr_RT_switch	16.147	25	.000	1.01837	.8885	1.1483
nc_zr_RT_fix_dur	3.000	25	.006	.16861	.0529	.2844
nc_zr_RT_sacc	-1.067	25	.296	-.06735	-.1974	.0627
nc_zr_trial_fix	6.553	25	.000	.22979	.1576	.3020
nc_zr_trial_switch	3.614	25	.001	.15310	.0659	.2403
nc_zr_trial_fix_dur	4.671	25	.000	.27894	.1559	.4019
nc_zr_trial_sacc	.785	25	.440	.05073	-.0823	.1838
nc_zr_fix_switch	16.708	25	.000	1.06139	.9305	1.1922
nc_zr_fix_fix_dur	-.875	25	.390	-.04968	-.1667	.0673
nc_zr_fix_sacc	-1.531	25	.138	-.08572	-.2010	.0296
nc_zr_switch_fix_dur	-2.202	25	.037	-.12453	-.2410	-.0080
nc_zr_switch_sacc	6.628	25	.000	.41929	.2890	.5496
nc_zr_fix_dur_sacc	-.649	25	.522	-.04171	-.1740	.0906

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Biographical Sketch

Roy Winn Roring III was born in Norman, Oklahoma. He earned a B.S. in computer science with minors in mathematics and physics at the University of Oklahoma in 2003. He has authored and coauthored publications published in psychological journals and has presented at international conferences. His current research interests include individual differences in cognitive ability and expertise as well as developmental changes in cognition and its application to technology enhancement.