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Predicting eye-movement characteristics across multiple tasks from working memory and executive control

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Abstract

Individual differences in working memory (WM) and executive control are stable, related to cognitive task performance, and clinically predictive. Between-participant differences in eye movements are also highly reliable (Carter & Luke, *Journal of Experimental Psychology: Human Perception and Performance,* 2018; Henderson & Luke, *Journal of Experimental Psychology: Human Perception and Performance, 40*(4), 1390–1400, 2014). However, little is known about how higher order individual differences in cognition are related to these eye-movement characteristics. In the present study, healthy college-age participants performed several individual difference tasks to measure WM span and executive control. Participants also performed three eye-movement tasks: reading, visual search, and scene viewing. Across all tasks, higher WM scores were related to reduced skewness in fixation duration distributions. In reading, higher WM scores predicted longer saccades. In scene viewing, higher WM scores predicted longer fixations. Theoretical and clinical implications of these findings are discussed.

Keywords Eye movements · Individual differences · Reading · Scene perception · Visual · Search

Individuals are known to vary in the speed and efficiency of their eye movements. Clinically, eye movements differ in populations with a variety of neurological conditions, such as schizophrenia (Fukushima et al., 1988; Hutton et al., 2004; Levy, Holzman, Matthysse, & Mendell, 1993; Reuter, Rakusan, & Kathmanna, 2005; Roberts et al., 2013), Alzheimer's disease and other forms of dementia (Burrell, Hornberger, Carpenter, Kiernan, & Hodges, 2012; Heuer et al., 2013; Lueck, Mendez, & Perryman, 2000; Molitor, Ko, & Ally, 2015), traumatic brain injury (Han, Ciuffreda, & Kapoor, 2004; Heitger et al., 2004; Heitger et al., 2009; Samadani et al., 2015; Ting, Schweizer, Topolovec-Vranic, & Cusimano, 2015), and stroke (Dong et al., 2013), compared to healthy controls. These findings suggest that eye-movement-related measures may prove to be a useful tool for diagnosis and for assessment of recovery. Indeed, some researchers have already begun to use them in this way (Dong et al., 2013; Walsh et al., 2016).

Even among healthy individuals, there is a significant degree of variability in how the eyes move (Kuperman & Van Dyke, 2011; Rayner, Abbott, & Plummer, 2015; Staub & Benatar, 2013; Veldre & Andrews, 2014). Furthermore, these individual differences are highly stable over time (Carter & Luke, 2018; Henderson & Luke, 2014). However, until recently, little attention had been paid to these individual differences in nonclinical populations. With regard to reading specifically, Radach and Kennedy (2004) noted that "little is known about the origins of [individual] differences and about how such individual variation in basic cognitive functions affects reading" (p. 19). This situation was unfortunate because these individual differences may represent a greater influence on eye movements in reading than exhaustively investigated influences such as word frequency or predictability (Kuperman & Van Dyke, 2011). Theoretically, this lack of attention to individual differences was also surprising. Much research points to the conclusion that eye movements are under cognitive control, meaning that they are responsive to the ongoing cognitive processing of the visual stimulus (Rayner, 2009; Rayner & Reingold, 2015). This position would predict that eye movements would be sensitive to cognitive differences between individuals.

In the past decade, some progress has been made in understanding the role of individual differences in eye-movement tasks, although most of this research has been restricted to

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reading (for reviews of individual differences in reading, see Radach & Kennedy, 2013; Rayner et al., 2015). Some of this research may be generalizable to other eye-movement tasks; the eyes are controlled by a single (widely distributed) neural system regardless of task (Choi & Henderson, 2015; Luke, Nuthmann, & Henderson, 2013; Nuthmann & Henderson, 2012), so it is likely that some individual differences in eye movements are task-independent. However, eye movements also vary between tasks in systematic ways (Henderson, Shinkareva, Wang, Luke, & Olejarczyk, 2013; Kardan, Berman, Yourganov, Schmidt, & Henderson, 2015; Kardan, Henderson, Yourganov, & Berman, 2016). Thus, it would be beneficial to investigate individual differences across multiple tasks to look both for cross-task commonalities and between-task differences. The goal of the present study was to look for task-independent and task-dependent individual differences in eye-movement control across three naturalistic eye-movement tasks: scene viewing, visual search, and reading.

Any given eye-movement task involves a common set of cognitive processes: the perceptual identification of visual stimuli; retrieving, constructing, and maintaining memory representations that include task goals, parts of the current stimulus (such as objects or words) and the relationships between them, and relevant past experience and knowledge; and careful control of attention to avoid distractions and stay on task. Individuals are known to vary measurably in the efficiency of these cognitive processes (Miyake et al., 2000; Salthouse, 1996). Given that eye movements are assumed to be under cognitive control, and given that measurable variability exists between individuals in working memory span and different aspects of executive control, it is reasonable to assume that individual differences in such variables might help explain the differences in eye-movement behavior outlined above. Some of these influences may be task independent, but because some tasks impose greater burdens on particular cognitive processes than do others, there may be task-specific effects of individual differences as well.

In the present study, therefore, we investigated whether, and how, individual differences in cognition are reflected in eye movements across different tasks. In the sections that follow, we outline what is known about the relationship between eye-movement behavior and individual differences in the two cognitive variables of interest: working memory span and executive control.

Working memory span

As noted above, eye movements are known to differ within individuals as a function of goal and task (Henderson et al., 2013), but much less is known about the source of interindividual differences in eye-movement behavior. One likely culprit is working memory span. Research has shown a

close relationship between working memory and eye movements; moving the eyes can disrupt the contents of spatial working memory (Postle, Idzikowski, Sala, Logie, & Baddeley, 2006), and the contents of visual working memory can influence eye movements (Belopolsky & Theeuwes, 2009; Hollingworth, Matsukura, & Luck, 2013; for a review, see Theeuwes, Belopolsky, & Olivers, 2009). Further, working memory span has been linked to attentional control, which is clearly important for any eye-movement task (Engle, 2002; Gazzaley & Nobre, 2012; Kane, Bleckley, Conway, & Engle, 2001; Van der Stigchel, 2010). Neuroimaging studies have consistently identified the dorsolateral prefrontal cortex, a region implicated in working memory (Curtis & D'Esposito, 2003) as a part of the eye-movement control network (Henderson & Choi, 2015; Henderson, Choi, Luke, & Desai, 2015; Pierrot-Deseilligny, Milea, & Müri, 2004).

If there is a relationship between working memory and eye-movement control, it will most likely show up not in the mean eye-movement measures but in the skewness of the fixation duration distribution (the proportion of long fixations). Studies using other reaction time tasks have found relationships between working memory and the skewness of the RT distribution (McVay & Kane, 2012a; Schmiedek, Oberauer, Wilhelm, Süß, & Wittmann, 2007; Tse, Balota, Yap, Duchek, & McCabe, 2010; Unsworth, Redick, Lakey, & Young, 2010). This relationship is consistent with the "worst performance rule" (Larson & Alderton, 1990): The slowest RT trials are most highly correlated with intelligence and working memory. Consistent with this idea, functional activity in the inferior frontal gyrus, a region associated with working memory, correlates across individuals with the proportion of long fixations made during reading (Henderson, Choi, Luke, & Schmidt, 2018). While different explanations for this relationship have been proposed, it appears to be robust across different RT tasks. Thus, we expect that it will be present in our eye-tracking tasks as well.

Executive control

Eye movements are commonly used to measure response inhibition (the antisaccade task; Antoniades et al., 2013), but little is known about how performance on these tasks is related to eye movements in more everyday tasks such as scene viewing or reading (but see Feng, 2012, for a comparison of the antisaccade task and reading). Given that some theories of eye-movement control incorporate inhibitory mechanisms (Engbert, Nuthmann, Richter, & Kliegl, 2005; Nuthmann, Smith, Engbert, & Henderson, 2010), it is possible that executive control could represent a significant cross-task influence on how the eyes move. In the present study, the executive control measures selected reflect

inhibitory control and not other aspects of executive control, such as task switching or updating.

The present study

The goal of the present study is to explore the relationship between individual differences in cognition and individual differences in eye-movement behaviors. That is, given that people differ in how they move their eyes, and given that some of this variability is thought to reflect cognitive processing, the present study examined whether these eye-movement differences can be predicted by cognitive differences between individuals. In the current study, we employed three different eye-movement tasks: scene viewing, visual search, and reading. These three tasks are commonly used in studies of eye-movement control (Henderson, 2003, 2007; Henderson et al., 2013; Nuthmann, 2016; Rayner, 2009; Wolfe, Vo, Evans, & Greene, 2011), and are naturalistic, being highly similar to tasks people perform every day outside of the laboratory. Thus, if cognitive variables predict eye movements in these naturalistic tasks, this would indicate that this relationship likely holds outside of the laboratory as well.

While these different tasks are similar in that they all involve eye movements, which are controlled using a common mechanism (Henderson & Luke, 2014; Luke et al., 2013), they also differ in significant ways (Henderson et al., 2013), meaning that they likely rely on different cognitive processes. We focused on two cognitive variables as predictors: working memory span and executive control (inhibition specifically). We measured working memory span using three standard dual span tasks (reading span, operation span, and symmetry span). Executive control was measured using the antisaccade task and the flanker task, both of which are thought to tap into inhibitory control processes. Individual differences in performance on these cognitive measures were used as predictors of eye-movement behaviors across the three eye-movement tasks, to explore the role of cognitive control in eye movements.

Hypotheses

As noted in the introduction, the research on individual differences in eye-movement control is sparse, so the current study is largely exploratory in nature, especially regarding the role of executive control in eye movements. Even so, one hypothesis was proposed. Based on the summary of previous research outlined above, we hypothesized that working memory span would be predictive of the skewness of the fixation duration distribution across tasks.

Method

Participants

A total of 126 participants were recruited for the study through the Brigham Young University Psychology department subject pool. All participants were native English speakers with normal or corrected-to-normal vision. Each participant completed two 60-minute sessions, and received course credit for participation. Eighteen participants were excluded because they did not complete the first session due to eye-tracking difficulties or because they did not return for the second session, and six were excluded because their data for the second session (<85% accuracy on the WM span tasks) or for the flanker task were not useable, leaving 102 participants in total (45 female; mean age = 20.46 years, SD = 2.53 years). The study was approved by the BYU institutional review board.

Our primary hypothesis was that working memory span would be related to the tail of the fixation duration distribution. Studies that have found this relationship using non-eye-tracking response-time measures have generally observed that the relationship between working memory span and the distribution tail (Tau) has a medium effect size (i.e., r = 0.2–0.4; Tse et al., 2010; Unsworth et al., 2010) with others reporting both smaller (McVay & Kane, 2012a) and larger (Schmiedek et al., 2007) effect sizes. Using the Pwr function in R (Champely, 2017) and assuming a medium effect size, we calculated the minimum n necessary to achieve desired power (0.8) to be 85 participants; we recruited 126 and ultimately included data from 102.

Apparatus

Eye-tracking tasks Eye movements were recorded via an SR Research Eyelink 1000 plus tower mount eye tracker (spatial resolution of 0.01°) sampling at 1000 Hz. Subjects were seated 60 cm away from a 24-in. LCD monitor with display resolution set to 1600 × 900, so that approximately three characters subtended 1° of visual angle. Scenes (800 × 600 pixel images) subtended 21 × 16 degrees of visual angle. Head movements were minimized with a chin and head rest. Although viewing was binocular, eye movements were recorded from the right eye. The eye-tracking experiments were controlled with SR Research Experiment Builder software.

Behavioral tasks The non-eye-tracking tasks (e.g., reading span) were controlled using E-Prime 2.0 Professional. Subjects were seated approximately 60 cm away from a 24-in. LCD monitor. Participants used the mouse and keyboard to make responses.

Individual difference tasks

Executive control tasks Participants completed two executive control tasks—an antisaccade task and an arrow flanker task.

Antisaccade task In the antisaccade task, participants fixated on a central fixation point. For prosaccade trials this point was green, and for antisaccade trials it was red. Two boxes were present at 10 degrees of visual angle to the left and right of the fixation point. After a delay of 1 second, a target square appeared inside one of the boxes. On prosaccade trials, participants were instructed to look to the side where the target appeared. On antisaccade trials, participants were instructed to look to the opposite side. The protocol conformed to the recommendations of Antoniades et al. (2013). Participants completed a block of 60 prosaccade trials (preceded by four practice trials), then three blocks of 40 antisaccade trials (with the first block preceded by four practice trials), then an additional block of 60 prosaccade trials, with breaks in between each block.

Arrow flanker Participants performed a speeded arrow version of the flanker task (F. A. Eriksen & Eriksen, 1974; C. W. Eriksen, 1995). Each trial began with a fixation cross in the center of the screen for 300 ms. Then, the stimulus, a row of arrows, appeared. The four flanker arrows appeared on-screen for 100 ms before the central arrow joined them on-screen, with all five arrows together remaining on-screen for 600 ms. In the congruent condition, all arrows pointed in the same direction (<<<<< or >>>>>). In the incongruent condition, the center arrow pointed in a different direction than the outer arrows (<<><< or >><>>). Each version of each condition appeared in equal numbers. Participants were instructed to respond to the center arrow only, by pressing a button with their left index finger if the arrow pointed left, and with their right index finger if the arrow pointed right. If no response was made within 1,000 ms, the trial timed out, and the next trial began. Participants completed eight practice trials (two of each congruence/direction combination), then three blocks of 40 trials with breaks in between.

Working memory span tasks Participants completed three automated WM span tasks: operation span, symmetry span, and reading span (Unsworth, Heitz, Schrock, & Engle, 2005). Participants completed the tasks in a separate session in the order listed, with breaks in between. More information on each task is presented below. For more detailed descriptions, see Unsworth et al. (2005).

Operation span A simple math problem (e.g., $(2 \times 2) - 1 = ?$) was presented on the computer screen followed by a potential answer. Using the mouse, participants selected "true" or "false," depending on whether they judged the answer as

correct. Subsequently, a letter appeared that participants were instructed to remember. After a set of problem-letter trials, participants recalled the letters in the order received by selecting those letters on the screen. Problem-letter trials were grouped into set sizes ranging from three to seven, and participants completed three trials of each set size. Prior to the test trials, participants practiced the math problems, letter recall, and the combined problem-letter trials.

Symmetry span An 8×8 grid image was presented on the computer screen and participants selected "yes" or "no," depending on whether they judged the image to be symmetrical along the middle vertical axis. Subsequently, a 4×4 grid appeared with one square highlighted that participants were instructed to remember. After a set of these trials, participants recalled the highlighted squares in the order presented by selecting them on the screen. Trials were grouped into set sizes ranging from two to five, with three trials of each set size. Prior to the test trials, participants practiced the symmetrical judgment alone, the square recall alone, and the combined sequence.

Reading span A sentence appeared on the computer screen, and participants selected "True" or "False," depending on whether they felt the sentence made sense. Subsequently, a letter appeared that participants were instructed to remember. After a set of these trials, participants recalled the letters in the order presented by selecting them on the screen. Trials were grouped into set sizes ranging from three to seven, and participants completed three trials of each set size. Prior to the test trials, participants practiced the sentence judgment alone, the letter recall alone, and the combined sequence.

Eye-movement tasks

Participants completed three eye-movement tasks: visual search, reading, and scene viewing. These three tasks were chosen because they are highly reflective of eye-movement tasks that people regularly perform in everyday life. This means that participants required little instruction, and also that their eye-movement behaviors were similar to what they would be in everyday situations. Thus, the results of the present study should generalize to situations outside of the laboratory. While these different tasks are similar in that they all involve eye-movement control via a common mechanism (Henderson & Luke, 2014; Luke et al., 2013), they also differ in significant ways (Henderson et al., 2013), indicating that they likely tap into different cognitive processes. The visual search task in particular comes in multiple variants, most of which involve simple symbols or shapes presented context free in random arrays, but we elected to present as search targets objects embedded in real-world scenes. This variant of the visual search task was chosen to make search more

consistent with the scene viewing task and with previous research and to make the task more reflective of real-world search. In sum, the eye-movement tasks selected were as similar as possible to day-to-day tasks that people regularly perform outside the laboratory. Prior to each task, a 9-point calibration routine was used to map eye position to screen coordinates. Successful calibration required average error less than 0.49° and maximum error less than 0.99°. Tasks were completed in the order listed below.

Visual search A total of 82 real-world scenes were presented. These included both indoor and outdoor scenes. Each scene contained a unique object that served as a search target. For example, participants searched for a bus stop sign on a busy street, a bunch of bananas in a kitchen, and the only palm tree on a beach. A circular interest area with a radius of 2° of visual angle was defined around each search target location. Each trial proceeded as follows. The trial began with a gaze trigger, a black circle presented in the center of the screen. Once a stable fixation was detected on the gaze trigger, the name of the target object was presented in 20-pt font in the center of the screen for 1 second. Then the scene appeared, and remained on screen until the participant pressed a button on the button box, indicating that the target had been found, or until 12 seconds had elapsed.

Reading Fifteen short paragraphs, a subset of those used in Luke and Christianson (2016, 2017), were selected as stimuli. Black text was presented on an off-white background in Courier New 15-pt font. Interest areas were defined around each word, consisting of the letters of each word and half of the white space between words. Each trial proceeded as follows. The trial began with a gaze trigger, a black circle presented in the position of the first word in the passage. Once a stable fixation was detected on the gaze trigger, the text appeared. Participants read the text at their own pace, then pressed a button when done. A yes/no comprehension question then appeared, which participants answered by pressing the corresponding button. Then a new gaze trigger appeared. The 15 critical trials were preceded by a practice trial.

Scene viewing The final eye-movement task was a simple scene preference task. Unlike the other two tasks, participants had no explicit viewing goal for this task; they were told to view the scene for a fixed amount of time, and then to rate how much they liked it afterward. For this task, 32 photographs of real-world scenes served as stimuli; these scenes were different from those used for the search task. These included both indoor (e.g., kitchens, bedrooms, hallways, public spaces) and outdoor scenes (e.g., exterior views of buildings, beaches, gardens, amusement parks).

None of these scenes were used in the visual search task. Each trial proceeded as follows. The trial began with a gaze trigger, a black circle presented in the center of the screen. Once a stable fixation was detected on the gaze trigger, the scene appeared. Participants viewed each scene for 10 seconds. After the scene was removed, participants were prompted to rate how much they liked the image on a scale from 1 to 4, by pressing to corresponding button on the button box. Then, the next trial began.

Procedure

Participants completed all tasks in two 1-hour sessions. In the first session, participants completed the antisaccade task, the flanker task, and then the visual search, reading, and scene-viewing tasks. The second session was no more than 7 days later. In this session, participants completed the working memory span tasks. All tasks and trials were presented in the same fixed order for each participant. See Swets, Desmet, Hambrick, and Ferreira (2007) for a justification of this approach when exploring individual differences

Results

Predictor variables from individual difference tasks

Table 1 summarizes the individual difference predictor variables used in the analyses. More information on these variables can be found in the sections below. Table 2 shows the intercorrelations of these different measures. In order to create latent variables for working memory and executive control, an exploratory factor analysis was conducted on the individual difference variables prior to analysis. Scores were entered into a principal components analysis with varimax rotation, using the Princomp function in R (R Core Team, 2015). Factors with eigenvalues greater than 1 were retained. Table 3 shows the factor loading scores for this analysis. Two factors were identified, accounting for 50% of the total variance. Factor loadings of 0.45 and above were used to guide factor interpretation. The working memory tasks loaded highly onto Factor 1, while the executive control tasks loaded highly onto Factor 2. These two factors were used as predictor variables in the analyses reported below. Both predictor variables were centered on their means and standardized (e.g., transformed to z scores) using the Scale() function in R (R Core Team, 2015). Prior to this, the working memory factor was multiplied by −1, so that higher values would reflect greater WM span (note that the WM tasks load negatively onto Factor 1).

Antisaccade task For the antisaccade task, saccade latency and accuracy was computed for each participant. Trials during which a blink occurred shortly before or after target onset were

Table 1 Descriptive statistics for individual difference variables

	Mean	SD	Min	Max
Reading span	0.78	0.14	0.25	1
Operation span	0.77	0.15	0.24	1
Symmetry span	0.75	0.14	0.36	1
Antisaccade accuracy	0.87	0.1	0.45	1
Antisaccade RT difference (ms)	58	24	4.84	148
Flanker RT difference (ms)	59	28	−81	125

Note. RT = reaction time; ms = milliseconds

excluded, as were trials where no saccade was made or the saccade was not made either to the left or right (2.5% of the data). Outliers where the saccade latency was greater than 2.5 standard deviations from the participant's overall mean were removed. A response was coded as accurate if the first saccade after target onset was in the appropriate direction (toward the target for prosaccade trials, away from the target for antisaccade trials). Accuracy rate in the antisaccade trials was used as one measure of executive control. The mean latency difference between the correct antisaccade and prosaccade trials was included as another measure.

Arrow flanker task For the flanker task, latency was computed for each trial. Outliers where the saccade latency was greater than 2.5 standard deviations from the participant's overall mean were removed, as were trials where no response was made (5.4% of the data). Latencies were computed only for correct trials. The difference in RTs between the congruent and incongruent trials (incongruent − congruent) constituted the variable of interest.

Working memory span tasks Partial-credit load scores were computed for each WM span task for each participant. Partial scoring gives credit for any items recalled correctly in a trial (e.g., two letters recalled correctly from a trial set size of five). The load score is the total number of correctly recalled items divided by the total number possible across the whole task (e.g., 60/75 for the operation span).

Table 2 Intercorrelations of cognitive variables

	1	2	3	4	5
1. Reading span	–				
2. Operation span	0.57*	–			
3. Symmetry span	0.41*	0.29*	–		
4. Antisaccade accuracy	0.06	0.02	0.05	–	
5. Antisaccade RT difference	−0.03	−0.05	−0.04	−0.12	–
6. Flanker RT difference	−0.01	−0.01	0.01	−0.08	0.03

Note. * *p* < .05 after correction for multiple comparisons

Table 3 Factor loadings from principal components analysis of cognitive measures

	Factor 1 (working memory)	Factor 2 (executive control)
Reading span	**−0.63**	
Operation span	**−0.58**	
Symmetry span	**−0.5**	
Antisaccade accuracy	−0.11	**−0.65**
Antisaccade RT difference (ms)		**0.58**
Flanker RT difference (ms)		**0.47**

Note. RT = reaction time; ms = milliseconds; WM = working memory; EC = executive control. Bold loadings (>0.45) were considered significant and used to guide factor interpretation.

Eye-movement measures

For the three eye-movement tasks, several global measures were computed. These measures were available for all three tasks. They are: mean saccade amplitude and the three components of the ex-Gaussian distribution for fixation duration (Mu, Sigma, Tau). The distribution of fixation durations is often highly skewed, with most fixations being between 200 ms and 300 ms, but with many that are significantly longer. The overall mean fixation duration is influenced by the location of the peak of the distribution but also by the proportion of longer fixations. For this reason, it often proves useful in eye-tracking studies to divide the distribution into a normal part that represents the center of the distribution and an exponential part that captures the skewness (Luke et al., 2013; Luke, Smith, Schmidt, & Henderson, 2014; Staub & Benatar, 2013; White & Staub, 2012). Representing a fixation duration distribution (or any other skewed distribution) in this way yields three parameters: Mu, the center of the normal part of the distribution; Sigma, the standard deviation of the normal part; and Tau, the parameter that represents the exponential part of the ex-Gaussian distribution and thus captures the skewness of the distribution. Mu and Tau are usually independent of each other (Staub & Benatar, 2013). For more information on distribution analyses using the ex-Gaussian distribution, see Balota and Yap (2011). The ex-Gaussian distribution was fitted to the data from each participant in each task using QMPE software (Heathcote, Brown, & Cousineau, 2004). These three components were analyzed instead of mean fixation duration.

Descriptive statistics for these dependent measures are presented in Table 4. For reference, mean fixation duration is also included. For the reading task, saccades greater than 22 degrees were eliminated to exclude return sweeps in reading, and for all tasks saccades containing blinks were eliminated. Fixation-related measures were derived after first excluding

Table 4 Means (and standard deviations) for the dependent variables across participants for each task

	Reading	Search	Scene Viewing
Saccades			
Amplitude	3.23 (0.6)	4.38 (0.43)	4.48 (0.65)
Fixations			
Mean duration	206 (20)	236 (24)	275 (31)
Mu	141 (15)	136 (15)	167 (20)
Sigma	32 (15)	39 (11)	49 (15)
Tau	64 (19)	93 (15)	102 (25)

Note. Mu, Sigma and Tau are components of the distribution of fixation durations. Mu = the center of the normal part of the distribution, and Sigma is the standard deviation of the normal part. Tau is the tail of the distribution (exponential part), so it represents the proportion of longer fixations

fixations that occurred before or after blinks. Fixations shorter than 50 ms or longer than 1,400 ms were also eliminated. The final data set contained three observations per variable for each participant for each dependent variable, one for each of the three eye-movement tasks. That is, there were three Mu values for each participant, one for the reading, search, and scene viewing tasks, respectively. This was true for all dependent variables.

The purpose of these analyses was to explore task-independent and task-specific influences of the individual difference variables on eye movements. All analyses included the individual difference predictor factors listed in Table 3 as well as a categorical variable for task. The task variable was dummy coded, with the scene-viewing task selected as the baseline condition and the two more cognitively intensive tasks compared to it.

Statistical analyses

The dependent variables in the analyses were global eye-movement measures that were common to all three eye-movement tasks (see Table 4 for descriptive statistics). For all analyses, fixations, saccades, and other eye-movement measures were defined by SR Research Data Viewer software using the default settings (SR Research Ltd., Version 1.11.1).

All analyses were performed using linear mixed-effects models, using the Lme4 package (Bates, Mächler, Bolker, & Walker, 2015) in R (R Core Team, 2015). Prior to analysis, both continuous predictor variables (the working memory and executive control factors) were centered and standardized (e.g., transformed to *z* scores) using the Scale() function in R. All mixed-effects models included random by-participant intercepts. The individual difference variables were between subjects, and so could not be included as random slopes. For all models, *p* values were obtained using Satterthwaite approximation as implemented in the LmerTest package in R

(Kuznetsova, Brockhoff, & Christensen, 2014), as this method minimizes Type I error (Luke, 2017). All interactions were tested, but are only reported, and were only retained in the models, if they reached significance ($p < .05$).

Visual inspection of scatterplots revealed some outliers in the individual difference variables that had the potential to unduly influence the results. To statistically identify data points with oversized influence, we computed Cook's *D* (Cook, 1977) separately for each participant for each of the significant factors in each model, using the Influence.ME (Nieuwenhuis, te Grotenhuis, & Pelzer, 2012) package in R (R Core Team, 2015). If the data from an individual participant exerted a larger-than-expected influence for a given effect (defined using a cutoff of 4/n for Cook's *D*), that participant's data were removed and the model was refitted to the remaining data. No effect or interaction became nonsignificant due to the removal of one of these participant's data.

Saccades Mean saccade amplitude was significantly shorter in reading than in scene viewing; there was no significant difference between search and scene viewing. WM span interacted with task, indicating that it was predictive of mean saccade amplitude in reading, with longer mean saccades for higher span individuals, but was not predictive in the other tasks. For a summary of these results, see Fig. 1 and Table 5.

Cross-task correlations of ex-Gaussian parameters Previous research (Henderson & Luke, 2014) has shown that fixation duration and saccade amplitude are consistent across different eye-movement tasks. However, cross-task correlations of the different ex-Gaussian components of the fixation duration distribution have not been reported previously. They can be found in Table 6. Mu was significantly correlated across all tasks, as was Tau.

Fixations[1] Mu was significantly larger in scene viewing than in reading and search. Working memory interacted with task, indicating that higher span individuals had larger Mu, but only in the scene-viewing task. In the analysis of Sigma, the same pattern was observed. Tau was larger in scene viewing than in reading and search. Further, WM span predicted Tau, with higher span individuals having smaller Tau, and this effect did not interact with task, indicating that it was present across all three tasks (see Figs. 2, 3, and 4 and Tables 7, 8, and 9.

Summary Across all three eye-movement tasks, WM Span was predictive of Tau, with fewer outlier fixations for higher span individuals. Several task-specific effects were also

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[1] Because the present study focused on the influence of individual differences on the ex-Gaussian components of the fixation duration distribution, no analysis of mean fixation durations is reported. The mean analysis revealed no significant effects or interactions involving individual differences, which further underscores the value of the ex-Gaussian approach.
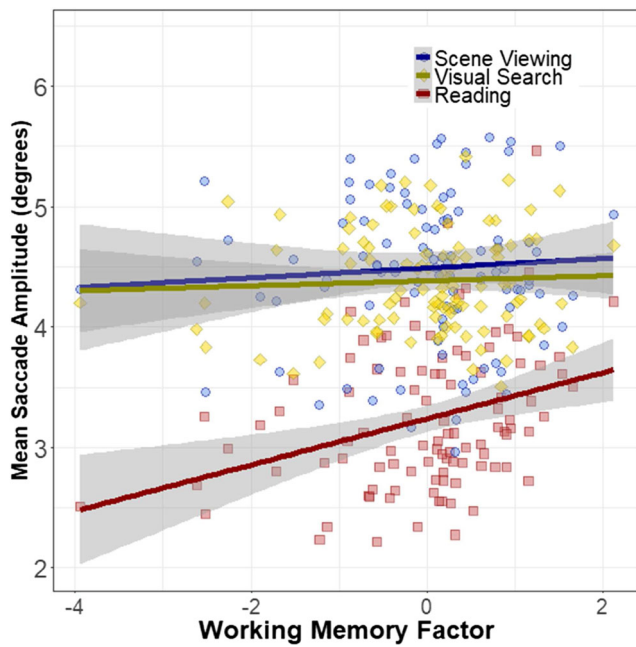
Fig. 1 Effects of working memory span on mean saccade amplitude for the three eye-movement tasks

observed. In reading, individuals with higher WM spans made longer saccades. In scene viewing, WM span was predictive of Mu and Sigma, the center and spread of the normal component of the fixation duration distribution.

Discussion

In the present study, we investigated the role of individual differences in eye-movement control. Participants completed measures assessing their working memory span and executive control. They also completed three eye-movement tasks: scene viewing, visual search, and reading. Below, we summarize and discuss the working memory span results, then outline some implications. Executive control was not predictive of any of the eye-movement variables studied here; we discuss this in the final section on study limitations and future directions.

Table 5 Mean saccade amplitude

	b	SE	t value	p value
(Intercept)	4.49	0.055	80.95	<.0001
Task = Reading	−1.25	0.06	−20.7	<.0001
Task = Search	−0.11	0.06	−1.75	0.082
WM span factor	0.04	0.056	0.73	0.47
Executive control factor	−0.0038	0.043	−0.088	0.93
Task = Reading × WM Span	0.15	0.061	−2.5	0.013
Task = Search × WM Span	−0.019	0.061	0.32	0.75

Eye-movement control and working memory span

There was only one individual difference variable that appeared to influence eye movements across all three of our tasks: working memory span. Consistent with expectations, WM span was significantly related to the size of the tail of the fixation duration distribution (the skewness). In other words, participants with higher WM spans made fewer long fixations. This finding is consistent with other research showing a relationship between Tau and WM capacity in response time tasks (McVay & Kane, 2012a; Schmiedek et al., 2007; Tse et al., 2010; Unsworth et al., 2010). A common explanation for the relationship between WM span and Tau is that increases in the tail of the fixation duration distribution reflect lapses of attention; WM span has been implicated in attentional control processes, with higher span individuals more able to maintain focus on a task and less likely to mind-wander (see, e.g., McVay & Kane, 2012b, who examined the relationship between mind-wandering and WM span directly). An alternate explanation comes from research on eye-movement control in visual scenes; in scene viewing, a sudden change in the visual scene that leads to an increase in perceptual integration difficulty can increase the Tau parameter (Glaholt, Rayner, & Reingold, 2013; Walshe & Nuthmann, 2014). Thus, higher WM span may facilitate integration of perceptual information (words, objects) into the overall stimulus representation, thereby reducing Tau. More work is needed to distinguish between these possible explanations, if they are indeed mutually exclusive.

Participants with larger WM spans had consistently longer fixations (larger Mu) in the scene-viewing task (in addition to the effect of WM span on Tau discussed above). This is consistent with research by Meghanathan, van Leeuwen, and Nikolaev (2015), who found that fixation duration is sensitive to WM load during free viewing. Given that visual scenes are highly complex, this finding suggests that participants with higher spans are able to take in more information from peripheral vision, and so have longer fixations, on average. This suggestion is speculative because the perceptual span in scene viewing has not been studied extensively (see discussion in Rayner, 2009), but there is some evidence that, as in reading, individual differences in scene perceptual span exist (Nuthmann, 2013).

Participants with high WM span made longer saccades in reading. This is consistent with the idea that, during reading, high-span individuals are able to take in more information during a fixation, and so make longer saccades. However, the few studies that have directly investigated the relationship between working memory and parafoveal preview in reading have either found no relationship (Kennison & Clifton, 1995) or have found that high-span individuals are *less* disrupted by the loss of parafoveal information (Osaka & Osaka, 2002). Thus, the idea that higher WM-span readers have a greater

**Table 6** Intercorrelations of Mu, Sigma, and Tau across the three tasks

	Mu		Sigma		Tau	
	Reading	Search	Reading	Search	Reading	Search
Search	0.54*		0.18		0.28*	
Scene Viewing	0.51*	0.61*	0.16	0.34*	0.33*	0.42*

Note. Mu, Sigma, and Tau are components of the distribution of fixation durations. Mu = the center of the normal part of the distribution and Sigma is the standard deviation of the normal part. Tau is the tail of the distribution (exponential part), so it represents the proportion of longer fixations. * = significant following Bonferroni correction for multiple comparisons

perceptual span, though intuitively appealing, has little empirical support. Clearly, more work is needed.

That working memory was found to predict saccade amplitude in reading should not seem surprising, given that previous research has found that WM span is predictive of reading comprehension (Baddeley, Logie, Nimmo-Smith, & Brereton, 1985; Daneman & Carpenter, 1980, 1983; Daneman & Merikle, 1996; Just & Carpenter, 1992; Masson & Miller, 1983). However, other research (Kuperman & Van Dyke, 2011; Van Dyke, Johns, & Kukona, 2014) that used online measures of reading behavior such as eye tracking found that working memory span is not a significant predictor of reading when other variables such as language skill and general intelligence are controlled for. The absence of WM span effects on Mu and Sigma in our reading data is consistent with these later findings. The present results suggest the possibility that working memory may influence *where* the eyes move during reading but not *when* they move (with the exception of some longer fixations).

This relationship between saccade amplitude and working memory span that was observed in the reading task is in contrast to the findings from scene viewing, where saccades were not associated with working memory span but Mu was. This difference in findings likely reflects differences between these tasks. In scene viewing, peripheral information is informative, while in reading it is not. This means that for individuals with larger spans, pausing longer to take in visual information outside the point of fixation makes sense during scene viewing. In reading, useful visual information is restricted to a smaller region around the point of fixation; letters too far from the fovea are uninterpretable visually (Rayner, 1998, 2009). Readers with high WM spans therefore probably maximize their intake of visual information even during a short fixation. For high-span readers, looking at the page longer will do little to increase visual information, but moving the eyes further (larger saccades) is a useful strategy as it maximizes the amount of unique visual information from each fixation. Future research should explore the contributions of working
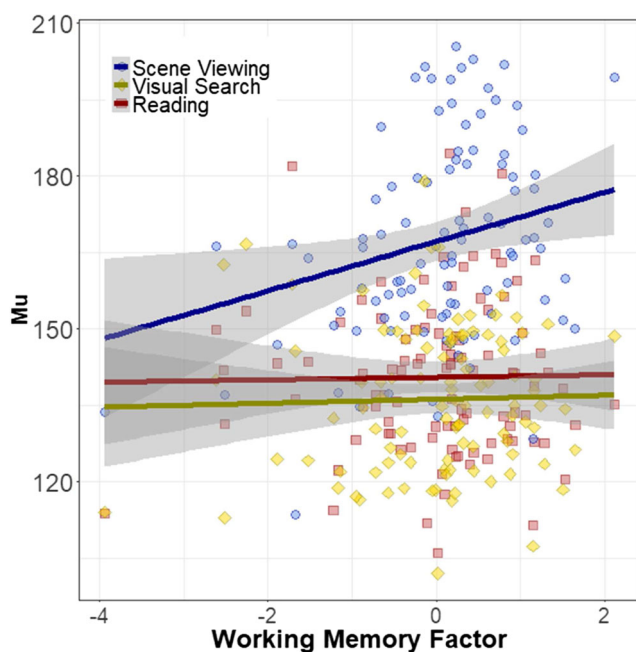
Fig. 2 Effects of working memory span on Mu for the three eye-movement tasks.

Fig. 3 Effects of working memory span on Sigma for the three eye-movement tasks
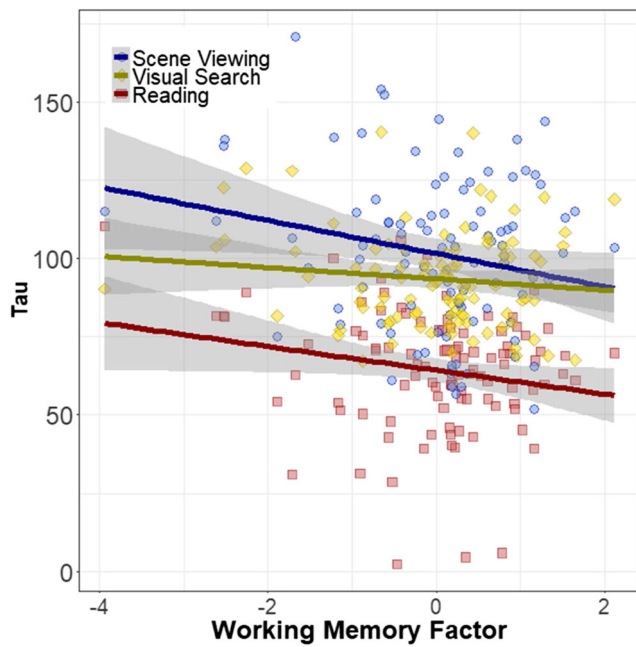
Fig. 4 Effects of working memory span on Tau for the three eye-movement tasks

memory, intelligence and language skill to eye movements across tasks more closely.

Implications for models of eye-movement control

Existing models of eye-movement behavior focus primarily on the influence of the stimulus on eye movements. For example, in reading, the influence of lexical variables such as word length, frequency, and predictability have been carefully modeled (Engbert et al., 2005; Nuthmann & Engbert, 2009; Reichle & Drieghe, 2013; Reichle et al., 2013; Reichle, Pollatsek, Fisher, & Rayner, 1998; Reichle, Pollatsek, & Rayner, 2012). As noted in the introduction, however, individual differences in the speed and efficiency of eye movements do exist, and these differences are highly stable across time, trials, and tasks (Carter & Luke, 2018; Henderson & Luke, 2014). The present results suggest that these stable differences in eye-movement behavior reflect, at least to some extent, individual differences in the efficiency of cognitive

Table 7 Mu

	b	SE	t value	p value
(Intercept)	167.13	1.65	100.99	<.0001
Task = Reading	−26.65	1.56	−17.14	<.0001
Task = Search	−30.97	1.56	−19.91	<.0001
WM span factor	4.82	1.66	2.91	0.0041
Executive control factor	0.044	1.39	0.032	0.97
Task = Reading × WM Span	−4.58	1.56	−2.94	0.0037
Task = Search × WM Span	−4.43	1.56	−2.844	0.0049

Table 8 Sigma

	b	SE	t value	p value
(Intercept)	49.15	1.34	36.72	<.0001
Task = Reading	−16.94	1.65	−10.26	<.0001
Task = Search	−10.17	1.65	−6.16	<.0001
WM span factor	3.58	1.34	2.67	0.0081
Executive control factor	−0.082	0.94	−0.087	0.93
Task = Reading × WM Span	−5.036	1.65	−3.043	0.0027
Task = Search × WM Span	−3.61	1.65	−2.18	0.03

processes. Thus, incorporating individual differences into computational models of scene viewing, visual search and reading should therefore greatly improve the predictive power of these models. Future experimental work will also benefit from attempts to model these individual difference variables, which should generate testable hypotheses about how different cognitive functions are involved in eye-movement control.

Furthermore, eye movements in reading are thought to be under cognitive control, meaning that eye movements are responsive in a moment-by-moment fashion to ongoing cognitive processing (Rayner, 2009; Rayner & Reingold, 2015). Not all eye movements, however, appear to be cognitively controlled (Henderson & Luke, 2012; Luke & Henderson, 2013, 2016; Luke et al., 2013). By associating different eye-movement measures with different cognitive processes, the present study is a step toward clarifying which eye-movement behaviors are under cognitive control and, further, identifying specifically which cognitive processes modulate which eye-movement behaviors.

Clinical implications of the current findings

As noted in the introduction, eye movements are disordered, impaired, or at least measurably different in a variety of clinical populations. The present study found that even in a relatively homogenous, healthy population of college students, eye movements reflect underlying interindividual cognitive differences in working memory. While the purpose of the present study was to explore the influence of individual differences on eye movements, our findings suggest that it should be possible to invert this approach and infer individual

Table 9 Tau

	b	SE	t value	p value
(Intercept)	101.61	1.98	51.34	<.0001
Task = Reading	−37.3	2.32	−16.056	<.0001
Task = Search	−8.1	2.32	−3.49	0.0006
WM span factor	−3.64	1.46	−2.5	0.014
Executive control factor	−0.41	1.46	−0.28	0.78

differences from eye-movement measures. Indeed, it should be possible to go further and associate particular properties of eye movements with specific regions or networks in the brain (Choi & Henderson, 2015; Henderson & Choi, 2015; Henderson, Choi, Lowder, & Ferreira, 2016; Henderson, Choi, & Luke, 2014; Henderson et al., 2015). Eye-movement behaviors are highly stable over time, as reliable or more so than many standardized cognitive tests (Carter & Luke, 2018; Henderson & Luke, 2014). All of this means that eye movements represent a promising tool for the measurement of individual differences and for clinical diagnosis.

The eye-movement tasks employed here (reading, visual search, scene viewing) have a number of advantages over other standardized and commonly used measures of individual differences. The first is simplicity of instruction. Moving the eyes comes naturally, and the eye-movement tasks employed here required little or, in the case of free-viewing of scenes, no instruction. Second, eye-movement tasks could be shorter than current standardized tests and assessments; the eyes move two to five times a second (Henderson, 2003; Rayner, 2009), meaning that it is possible to gather a great deal of data in a short period of time. Third, the precise timing and targeting of eye movements are not open to conscious control, so it would be difficult to deliberately alter the results of an eye-movement-based test. In the present study, individual differences were used to predict eye-movement behaviors. In the future, eye movements may prove a useful way to measure individual differences as well as interactions with neurological conditions that affect these behaviors.

Study limitations and future directions

The present study represents an early step toward understanding how individual differences in cognition, particularly working memory and executive control, are manifest in eye movements. Our study has a few limitations that must be acknowledged and that should inform future work on this topic. One such limitation is the cognitively homogenous nature of the sample; our participants were all young, neurologically healthy college students. A more diverse sample that included nonstudents would provide a greater range of cognitive ability, making the results more generalizable. Future studies should also explore a wider age range, including children, middle-aged adults, and the elderly, and should include clinical populations.

Another limitation was the nature of the executive control measures selected. While our working memory factor appeared robust, the executive control factor was derived from only two executive function tasks, both of which are primarily used to assess inhibition, which is only one aspect of executive control. Thus, it is difficult to confidently conclude based on the current results that executive control is not related to eye movements in some or all of these tasks; it is possible that our

tasks did not effectively measure inhibitory control, and they clearly did not (because they were not intended to) measure other aspects of executive control, such as task switching or updating. Future research should explore the relationship between executive control and eye movements further.

Another limitation was the absence of any measure of fluid intelligence. Given that fluid intelligence and working memory are related (Van Dyke et al., 2014), the omission of a fluid intelligence measure means that the observed effects of working memory may actually reflect fluid intelligence. Finally, the present study explored the relationship between global measures of eye movement behavior and cognitive variables, specifically working memory. By showing that a relationship exists between working memory and the skew of the fixation duration distribution, this approach yielded some interesting results and hypotheses. However, more controlled manipulations of task and stimulus will be necessary to test different hypotheses about this relationship to understand the cognitive/neural mechanisms that connect working memory and eye movements. Such manipulations might include more controlled visual search tasks in which the number and nature of the distractors is manipulated, reading tasks with sentences designed specifically to tax working memory in different ways, or visual scenes that vary in object congruity or the informativeness of scene context.

Conclusions

In the present study, we explored the influence of working memory and executive control on eye movements in three different tasks: visual search, reading, and scene viewing. We observed that working memory was negatively predictive of the skewness of the fixation duration distribution. Further, larger working memory span was predictive of larger saccades in reading and shorter and less variable fixations in scene viewing. These results indicate that eye movements reflect interindividual differences in cognitive processing, and open the door to more efficient use of eye tracking in assessment and diagnosis.

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