Schema-Related Eye Movements Support Episodic Simulation

Jordana S. Wynn[1], Ruben D.I. van Genugten[1], Signy Sheldon[2], Daniel L. Schacter[1]

[1] *Department of Psychology, Harvard University, Cambridge, USA*
[2] *Department of Psychology, McGill University, Montreal, Canada*

Correspondence concerning this article should be addressed to: Jordana S. Wynn,
Psychology Department, Harvard University, 33 Kirkland St., Cambridge, MA, USA, 02138,
jordanawynn@g.harvard.edu

Abstract

Recent work indicates that eye movements support the retrieval of episodic memories by reactivating the spatiotemporal context in which they were encoded. Although similar mechanisms have been thought to support simulation of future episodes, there is currently no evidence to support this proposal. In the present study, we investigated the role of eye movements in episodic simulation by comparing the gaze patterns of individual participants imagining future scene and event scenarios to across-participant gaze templates for those same scenarios, reflecting their shared features (i.e., schemas). Our results provide novel evidence that eye movements during episodic simulation in the face of distracting visual noise are (1) schema-specific and (2) predictive of simulation success. Together, these findings suggest that eye movements support episodic simulation via reinstatement of scene and event schemas, and more broadly, that interactions between the memory and oculomotor effector systems may underlie critical cognitive processes including constructive episodic simulation.

Keywords: simulation, eye movements, schemas, memory, imagination

Introduction

Recall the last time you went to the beach. You might find yourself looking around as you mentally reconstruct the sights, smells, and sounds of that event. In fact, research using eye movement monitoring indicates that successful memory retrieval is accompanied by spontaneous gaze shifts reflecting spatial and temporal mnemonic content (e.g., Bochynska & Laeng, 2015; Foulsham & Kingstone, 2013; Johansson & Johansson, 2013; Olsen, Chiew, Buchsbaum, & Ryan, 2014; for review, see Wynn, Shen, & Ryan, 2019). Even when looking at a blank computer screen in which there is no visual input present to attract gaze (for examples of classic models of physical saliency-based visual attention see Treisman & Gelade, 1980; Itti & Koch, 2000), eye movements during retrieval tend towards regions of the screen associated with previously present and salient encoded information. This pattern of "looking at nothing" (LAN) has been proposed to support memory retrieval by projecting internal representations of spatial and/or temporal relations onto the external world (Altmann, 2004; Richardson & Spivey, 2000; for review, see Ferreira, Apel, & Henderson, 2008). Although LAN studies have largely focused on internal episodic representations (e.g., of learned stimuli), both memory retrieval and construction (e.g., of future events) rely heavily on schematic representations, knowledge networks extracted from multiple repeated experiences (for review, see Gilboa & Marlatte, 2017). Thus, extending previous work, in the current study we present the first examination of how eye movements, and specifically LAN, reflect and potentially support the reinstatement of mentally stored scene and event schemas during the construction of simulated future episodes.

Research over the past several decades has established a critical link between remembering the past and imagining the future. Both processes rely on *constructive episodic simulation*, the ability to reactivate and recombine spatial and temporal elements from one's

personal past (Schacter & Addis, 2007, 2020). In addition to this shared cognitive basis, both

episodic remembering and future imagining recruit a similar *core network* of brain regions,

including the prefrontal cortex, prarahippocampal cortex, and hippocampus (Benoit & Schacter,

2015). Importantly, recent work suggests that this network, and specifically the hippocampus, is

both anatomically and functionally connected to regions involved in visual imagery (Bird,

Capponi, King, Doeller, & Burgess, 2010; Hassabis, Kumaran, & Maguire, 2007; for review, see

Pearson, 2019) and oculomotor control (Ryan et al., 2019; Shen, Bezgin, Selvam, McIntosh, &

Ryan, 2016; for review, see Ryan, Shen, & Liu, 2020). Activity in these (memory- and imagery-

related) regions has also been linked to eye-movement-based mnemonic reinstatement (Ryals,

Wang, Polnaszek, & Voss, 2015; Wynn, Liu, & Ryan, 2021; see also, Bone et al., 2019), further

suggesting that the neural mechanisms that support constructive episodic simulation and gaze

reinstatement are tightly linked.

Recent work suggests that the ability to freely and voluntarily execute eye movements (as

opposed to maintaining gaze on a static or moving stimulus) is important for successful retrieval

of autobiographical memories (Lenoble, Janssen, & El Haj, 2019) and simulation of possible

future events (de Vito, Buonocore, Bonnefon, & Della Sala, 2015). However, whereas gaze

fixations have been positively correlated with autobiographical memory retrieval (Armson,

Diamond, Levesque, Ryan, & Levine, 2019), other work indicates that higher fixation rates are

negatively associated with future imagining (Sheldon, Cool, & El-Asmar, 2019). Given these

discrepant findings, it remains unclear what role eye movements play in constructive episodic

simulation (i.e., what accounts for the above-noted free-viewing advantage). A promising

hypothesis is that eye movements facilitate the broad reactivation of spatial and/or temporal

contextual representations from memory, facilitating the retrieval or generation of further

episodic details (see Wynn et al., 2019; see also, Conti & Irish, 2021). Importantly however, such reactivation would not be evident in fixations rates, but rather in reinstated gaze patterns.

In the present study, we utilized gaze similarity analyses (see Wynn, Ryan, & Buchsbaum, 2020) to probe the role of eye movements in constructive episodic simulation. Specifically, we leveraged existing data from Sheldon et al. (2019), in which participants imagined and described future scene (e.g., beach) and event (e.g., wedding) scenarios while looking at a blank screen or Dynamic Visual Noise[1], to investigate *how* eye movements during simulation reflect, and potentially support, the retrieval and reactivation of contextual details from memory. To this end, we generated gaze templates for cued schemas by aggregating the eye movements of all participants imagining future scene and event scenarios. Because schemas are based on gist-like details extracted across multiple repeated experiences, they show striking consistency across individuals (for review, see Ghosh & Gilboa, 2014; Gilboa & Marlatte, 2017; see also, Baldassano, Hasson, & Norman, 2018). This shared feature space allows us to measure the degree to which a schema is reactivated as a function of the degree to which those shared features, indexed here via aggregated (across-participant) eye movements, are expressed at the individual level, indexed here via individual (within-participant) eye movements. Accordingly, in the current study we present a novel multivariate eye-movement-based analysis for quantifying the schematicity of simulated events, which we validate with a novel linguistic measure (i.e., using natural language processing) for quantifying schematic content in narrative data.

Based on prior evidence of functional gaze reinstatement (i.e., gaze reinstatement that supports memory retrieval: for review, see Wynn et al., 2019), we predicted that: 1) if eye

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[1] These manipulations were originally included to 1) examine differences in the content used to construct simulations of scenes vs. events, and 2) investigate the role of visual imagery processes in episodic simulation.

movements express and/or support the reactivation of schema-related contextual details, they

should be more similar to the gaze template for the corresponding (matching) cue than to the

gaze templates for the other (mismatching) cues, and 2) if this reactivation contributes to

successful simulation, schema-related eye movements should be positively correlated with

objective (i.e., number of episodic details) or subjective (i.e., familiarity and pre-experiencing

ratings) measures of simulation success. Moreover, given that eye movements have been

proposed to support memory retrieval particularly when task difficulty is high (see Wynn et al.,

2019), we expected the predicted effects to be larger in the visual noise condition, in which

internal details were significantly reduced (Sheldon et al., 2019; see also, Anderson, Dewhurst,

& Dean, 2017), than in the control condition. Likewise, based on prior work linking eye

movements to reinstatement of visuospatial details (see Wynn et al., 2019), we anticipated that

the predicted effects would be larger for simulated scenes, which rely more heavily on perceptual

details (Sheldon et al, 2019), than simulated events. In line with our predictions, we provide

novel evidence that eye movements during simulation (in the face of distracting visual noise) are

both schema-specific and predictive of simulation success, suggesting a critical role for overt

gaze shifts in constructive episodic simulation.

Methods

Participants

Participants were 40 young adults (32 female) aged 18-35 ($M = 21$, $SD = 1.4$) with

normal or corrected-to-normal vision, English fluency, and no history or psychiatric or

neurological disorders. Participants were recruited through the McGill University participant

pool and online classified ads. All participants provided written informed consent in accordance

with the McGill code of ethics. Two participants were excluded from analysis due to incomplete

data collection and failure to follow instructions.

Based on significant effects in the data from Wynn et al., 2020 (match similarity >

mismatch similarity, $d = .47$), power analysis (using the pwr package in R) indicated that the

current sample size was sufficient to detect a reliable main effect of gaze similarity using a

paired-samples t-test ($\alpha = .05$) with 80% power.

Stimuli

Stimuli consisted of 4 scene cues and 4 event cues (see Table 1) selected from a larger set

of 30 cues based on ratings of scene and event representativeness, respectively (for selection

criteria, see Sheldon et al., 2019). During simulation, the screen was occupied by either a grey

square (control condition) or one of 6 possible Dynamic Visual Noise stimuli[2] (visual noise

condition).

Table 1. Simulation Cues

Cue	Scenario
Event	A future and plausible award you will receive
Event	A future and plausible exam you will write
Event	A future and plausible wedding reception that you will attend
Event	A future and plausible holiday meal
Scene	You are standing in the aisles at a public library
Scene	You are lying on a white sand beach in a beautiful tropical bay
Scene	You are standing by a tombstone in a cemetery
Scene	You are standing by a small stream somewhere deep in a forest

Apparatus

Stimuli were presented using E-Prime experimental software on a 24-inch monitor (1274

x 962 pixel resolution) positioned 30 cm away from participants. Monocular eye movements

were recorded using a head mounted EyeLink 1000 Plus eyetracking system at 1000 Hz

sampling rate (SR Research Ltd., Mississauga, Canada) while participants were positioned in a

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[2] The matching of visual noise stimuli to cues was fully randomized

chin rest to reduce head movements. Saccades and blinks were defined by EyeLink as saccades

greater than 0.5° of visual angle and the period in which saccade signal was missing for three or

more consecutive samples, respectively. All remaining samples were classified as fixations.
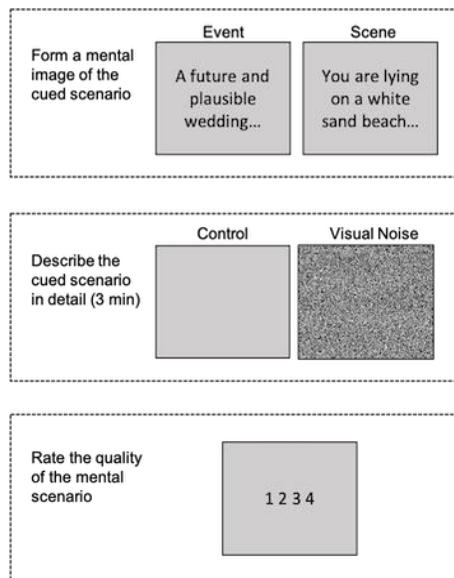
Procedure

Fig 1. Visualization of the experimental procedure (adapted from Sheldon et al., 2019). Participants are cued with a scene or event schema and must then describe the cued scenario in detail while looking at a blank (control) screen or visual noise stimulus. After 3 minutes or a button press, participants must rate the subjective quality of their imagined scenario.

The current study used the same stimuli and procedure as was previously reported in

Sheldon et al. (2019). Participants in the present study completed 8 trials of a simulation task, in

which they were instructed to imagine and describe, in as much detail as possible, cued scene

and event scenarios (Table 1, Fig 1), while maintaining their gaze on the screen. Participants

were specifically instructed to imagine a plausible future scenario and not to recall a past

memory. Scene and event cues were counterbalanced across participants, with each cue being

presented evenly in both the control condition (grey screen) and the visual noise condition

(Dynamic Visual Noise screen). Within participants, 2 of each of the scene and event cues were

presented in each condition. The temporal order of cue presentation was randomized within

participants. On each trial, participants heard one of 8 scene or event cues presented auditorily over headphones. Participants were instructed to construct a scenario based on the presented cue and to press a button to indicate that they had done so (access phase). Following the button press, participants saw a grey screen or Dynamic Visual Noise and were instructed to maintain their gaze on the screen while they described the scenario in as much detail as possible for up to 3 minutes or until they were finished, as indicated by a button press (elaboration phase). If participants pressed the button prior to the 3-minute mark, they were presented with the prompt "can you think of any other details?". After the 3 minutes elapsed, participants rated their simulation for sense of familiarity and pre-experiencing on 7 scales (see Sheldon et al., 2019). Finally, following all 8 trials, participants completed 3 neuropsychological tests; for the purposes of the present study, data from these tests was not analyzed. During the elaboration phase, simulations were audio recorded and transcribed and eye movements were recorded.

Data analysis

Description scoring

Simulations were scored using an adapted version of the Autobiographical Interview scoring procedure (Levine, Svoboda, Hay, Winocur, & Moscovitch, 2002) for imagined scenarios (for examples, see Madore, Gaesser, & Schacter, 2014; Madore, Szpunar, Addis, & Schacter, 2016; Sheldon et al., 2015). Briefly, simulations were segmented into details, which were then classified as either internal or external, reflecting episodic and non-episodic processes, respectively. Whereas internal details are directly related to the described scenario, external details are tangential to the described scenario (e.g., commentary, semantic knowledge, etc.). For further details on description scoring, see the Supplemental Materials.

Subjective ratings

Subjective ratings were reduced to 2 principal components using a principal component factor analysis with varimax rotation (see Table S1). The first component, defined here as *pre-experiencing*, included ratings for vividness, sense of presence, and spatial arrangement. The second component, defined here as *familiarity*, included ratings for scenario familiarity and reminders of past events. Scores for each component were obtained by averaging the scores from the constituent ratings. For further details regarding factor loadings and comparisons of scores, see the Supplemental Materials.

Eye movement similarity analysis

Analysis of eye movement data was based on eye movements made during the elaboration phase[3] (when participants were describing the scenario), excluding the first fixation and all fixations off screen. To quantify cue-specific viewing, we used a leave-one-subject-out (LOSO) cross validation procedure. Specifically, to investigate how well individual gaze patterns could be predicted by the group-average gaze patterns for the same cue, we correlated the fixation density maps for each cue (using the fixations of all participants) with the corresponding left out participant's density map for the same cue (match similarity), using the eyesim package (https://github.com/bbuchsbaum/eyesim; Wynn et al., 2020). To rule out the possibility that similarity between participant-specific and group-average gaze patterns was driven by cue-invariant viewing biases (e.g., center bias), we additionally computed the similarity between participant-specific density maps and group-average density maps for all other cues. The resulting scores were averaged to obtain a single mismatch similarity score. Mismatch similarity scores were subtracted from match similarity scores to obtain controlled gaze similarity scores,

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[3] For mean elaboration times for each cue, see Table S2.

reflecting cue-specific viewing that is not driven by generic viewing tendencies. For further

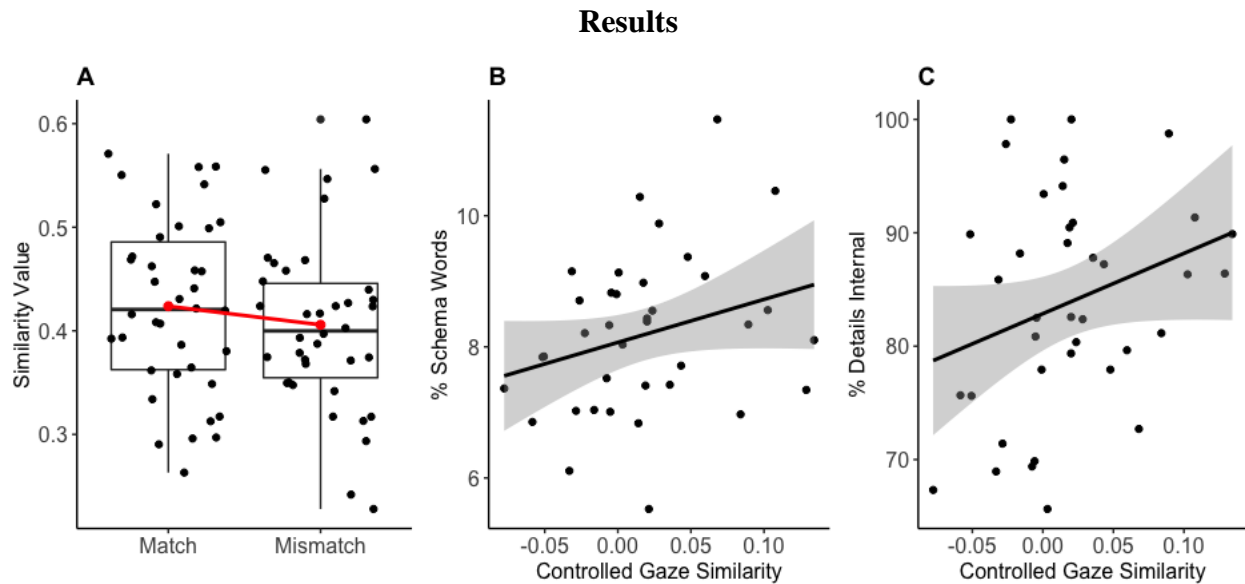details regarding the similarity analysis, see the Supplemental Materials.

Results

Fig 2. (A) Similarity between schema-specific gaze patterns and gaze templates for matching and mismatching schema cues. (B) Correlation between controlled gaze similarity (match – mismatch) and the proportion of total words that are classified as schematic using the natural language processing scoring approach. (C) Correlation between controlled gaze similarity (match – mismatch) and the proportion of total words that are classified as internal using the autobiographical interview scoring approach. All plots contain data from the visual noise condition only.

Eye movements during visual noise simulation are schema-specific

Statistical analyses were conducted with R (R Core Team., 2017). To investigate whether

eye movements during simulation aligned with the gaze template for the corresponding schema,

we ran an ANOVA using the *afex* package (Singmann et al., 2016) with similarity value as the

dependent variable, and cue (event, scene), condition (control, Dynamic Visual Noise), and

similarity template (match, mismatch) as independent variables. If individual gaze patterns

indeed reflect the cued schema, they should be more similar to the gaze template (i.e., group-

average density map) for the same schema than to the gaze templates for all other schemas (i.e.,

match similarity should be significantly greater than mismatch similarity).

Results of the ANOVA revealed a significant interaction of similarity template by condition [F (1,37) = 4.76, p = .036, η_p^2 = .11], as well as significant main effects of condition [$M(SE)_{Control}$ = 0.402(0.01), $M(SE)_{Visual\ Noise}$ = 0.415(0.01); F (1,37) = 4.22, p = .047, η_p^2 = .10] and cue [$M(SE)_{Event}$ = 0.405(0.01), $M(SE)_{Scene}$ = 0.412(0.01); F (1,37) = 4.51, p = .040, η_p^2 = .11]. Follow up paired-samples t-tests of the difference in mean match and mismatch similarity scores in each condition (control, visual noise) indicated that match similarity was significantly greater than mismatch similarity in the visual noise condition only [t (37) = 2.17, p = .036[4], d = .35, see Fig 2A; control condition: t (37) = -2.01, p = .051, d = .33]. Critically, these findings indicate that participant-specific eye movements during simulation in the face of visual noise reflect the specific cued schema. For all following analyses, only data from the visual noise condition were included, as these produced a significant difference between match and mismatch similarity scores in the expected direction (match > mismatch).

To further investigate whether the described eye movement measure captured the schematicity of a simulated event, we tested for a relationship between eye movements and a linguistic measure of schematicity based solely on participants' transcribed simulations. We derived this linguistic measure by counting the number of schema-relevant words in each simulation, then dividing by the total number of words in the simulation, to obtain the proportion of content that is schema-relevant. To identify schema-relevant words, we used methods from natural language processing (specifically, Global Vectors for Word Representation (GloVe), an unsupervised learning algorithm for obtaining vector representations for words; Pennington, Socher, & Manning, 2014). For each cue word, we extracted a list of 10,000 related words based on the frequency of word co-occurrences in a corpus of webpages. This approach yielded word

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[4] Mean match similarity (across all cues) was greater than all 7 mean mismatch similarity scores; p = .03 ~ .17.

lists that sufficiently captured schematic (cue-related) words, while excluding non-schematic words. We scored each word in the transcribed simulations based on its match to the cue-related word list. Any word appearing in the cue-related word list received a score of 1, while all other words received a score of 0. For each simulation, we then derived the proportion of total words that were related to the cue word (% schema words). This measure was validated against two external measures of schematicity. For further details on this scoring approach, including validation procedures, see the Supplemental Materials.

Prior to analysis, one participant was removed on the basis of mean % schema words >2.5 sd from the mean. A bootstrapped correlation ($n = 1000$) of mean controlled gaze similarity scores (indexed as the difference in match and mismatch similarity scores, for visual noise trials only), and mean % schema words (using the *wBoot* package, Weiss, 2016) was significant ($r = .28$, $p = .027$, *95%CI* [.038, .544], see Fig 2B), indicating that participants who on average exhibited more schema-specific gaze patterns also produced a greater number of schema-related details during simulation.

Schema-specific eye movements support simulation success

To investigate whether schema-related eye movements were associated with simulation success, we ran a linear mixed effects model (LMEM; using the *lme4* package, Bates, Mächler, Bolker, & Walker, 2015) on controlled gaze similarity (match similarity- mismatch similarity for visual noise trials) with all interactions of cue, number of internal details, number of external details, pre-experiencing ratings, and familiarity ratings as predictors[5] and a random intercept for participant. We used backwards model comparison ($\alpha = .1$) to determine the best fit model (see Table 2).

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[5] Cue was dummy coded as: Scene = 0, Event = 1. All other variables were *z*-scored.

Table 2. Controlled Gaze Similarity

Fixed Effects

	β	95% CI	SE	t	p
(Intercept)	.021	.001, .041	.010	2.081	.041 *
Internal Details	.022	.003, .042	.009	2.277	.024 *
Cue	-.001	-.024, .021	.011	-.094	.925
Familiarity	.011	-.001, .023	.006	1.845	.067
Internal Details X Cue	-.028	-.051, -.004	.012	-2.350	.020 *
Total Observations = 149					
	Variance		SD		
Random Effect for Participant (Intercept)	.002		.039		

Model equation: Controlled Gaze Similarity ~ Internal Details X Cue + Familiarity + (1 | Participant)

Results of the best fit model of controlled gaze similarity (Table 2) revealed a significant effect of internal details for scenes, and this effect was significantly attenuated for events. Consistent with our predictions, this finding indicates that successful simulations, indexed by a high number of internal details, are characterized by a high degree of consistency with the gaze template for the corresponding scene schema. The model also revealed a marginally significant effect of familiarity, with more familiar cues producing greater eye movement similarity. Notably, both external details and pre-experiencing ratings were omitted from the model, indicating that they were not significantly predictive of gaze similarity. Although we did not observe significant schema-related eye movements in the control condition, a LMEM on gaze similarity for control trials (see Table S3) revealed a significant positive effect of external details and a significant negative effect of familiarity on gaze similarity.

Table 3. Internal Details

Fixed Effects

	β	95% CI	SE	t	p
(Intercept)	-.089	-.335, .156	.122	-.732	.468
Controlled Gaze Similarity	.178	.054, .302	.063	2.839	.005 **
Fixation Rate	-.315	-.500, -.126	.092	-3.415	<.001 ***
Total Observations = 149					
	Variance	SD			
Random Effect for Participant (Intercept)	.488	.698			

Model equation: Internal Details ~ Controlled Gaze Similarity + Fixation Rate + (1 | Participant)

Given that Sheldon et al. (2019) previously observed a significant negative effect of fixation rate on internal detail generation, we ran an additional model on the number of internal details (for external details, see Table S4) with both fixation rate, controlled gaze similarity, and their interaction as predictors (Table 3). Results of the best fit model revealed significant and opposing effects of both gaze similarity and fixation rate[6], neither of which was significantly predictive of external details (see Table S4). Together, these findings indicate that whereas a greater rate of fixations is related to a reduced number of internal details generated, similarity of those fixations to the cued template is related to a greater number of internal details generated.

Finally, to investigate whether the effect of gaze similarity on simulation success extended across participants, we correlated mean controlled gaze similarity scores with the mean proportion of total details that were scored as internal (as opposed to external). A bootstrapped correlation ($n = 1000$) of mean controlled gaze similarity scores and mean % internal details was significant ($r = .28$, *95%CI* [.018, .526], $p = .041$, see Fig 2C), indicating that participants who on average exhibited more schema-specific gaze patterns also produced a greater number of internal details and a lower number of external details during simulation.

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[6] The interaction of gaze similarity and fixation rate was omitted from the model

Discussion

Research using eye movement monitoring has provided critical evidence that eye movements not only reflect, but also actively support memory retrieval (for review, see Wynn et al., 2019). However, whereas the relationship between eye movements and episodic memory has received significant attention and study, the role of overt gaze shifts in episodic simulation remains unclear. Recent work suggests that eye movements play an important role in imagining future events, such that restricting them (e.g., to a static or moving fixation cross) impairs simulation (de Vito et al., 2015; see also, de Vito, Buonocore, Bonnefon, & Della Sala, 2014). However, executing more gaze fixations disrupts future simulation rather than supports it (Sheldon et al., 2019). Given that future simulation relies on many of the same cognitive and neural mechanisms that support episodic memory (Benoit & Schacter, 2015; Schacter & Addis, 2007, 2020), we proposed that eye movements during simulation would serve a similar role as they do during episodic memory – that is expressing, and likely facilitating, the retrieval of stored spatiotemporal contextual (in this case, schematic) details. Accordingly, in the present study, we applied gaze similarity and linguistic analyses to eye movement and narrative data from Sheldon et al. (2019), in which participants imagined and described plausible future scene and event scenarios, to test the hypothesis that overt gaze shifts during episodic simulation reflect and support the reactivation of schematic details from memory.

Lending support to our prediction, our results indicated that when imagining future scenes and events (while looking at a blank screen), participants spontaneously moved their eyes to screen regions associated with the cued schema (i.e., LAN). Specifically, we found that in the visual noise condition, eye movements during simulation were more similar to the gaze template for the corresponding schema cue (generated from the eye movements of all other participants

simulating the same scenario) than to the gaze templates for the other schema cues. This finding

is consistent with previous work showing modulation of eye movements by prior knowledge

(e.g., schemas: Võ & Wolfe, 2013; Wynn, Ryan, & Moscovitch, 2020), and with research

indicating that gaze similarity supports memory retrieval, particularly when cognitive load

exceeds cognitive resources (e.g., by virtue of age, Wynn et al., 2018; or task difficulty, Wynn et

al., 2020; for review, see Wynn et al., 2019). Thus, when visual noise rendered simulation more

difficult (as indicated by a significant reduction in internal details relative to the control

condition; see Sheldon et al., 2019), presumably by interfering with visual imagery (see

Anderson, Dewhurst, & Dean, 2017), participants may have executed overt gaze shifts reflecting

the cued scenario in an effort to retrieve and visualize schema-specific contextual details.

Given the relationship between eye movements and visuospatial details evidenced by

previous work (for review, see Wynn et al., 2019), we predicted that gaze similarity would be

greater for simulated scenes than events. Notably, although match and mismatch similarity were

significantly increased for simulated scenes relative to events, controlled gaze similarity (i.e.,

schema-specific viewing) did not differ significantly by cue. This finding suggests that eye

movements may express both scene- and event-related schematic details. Indeed, prior work

indicates that fixations correspond to both remembered or described spatial relations (e.g.,

Spivey & Geng, 2001; Johansson, Holsanova, & Holmqvist, 2006) as well as implied temporal

order. Specifically, when retrieving past events, fixations trend more leftward than when

imagining future events (Martarelli, Mast, & Hartmann, 2017), suggesting that like spatial

context, temporal context (a key feature of schematic events) may be mapped using a spatial

frame of reference. Accordingly, when simulating future scene and event schemas, eye

movements may invoke visuospatial, temporal, or other contextual features that constitute a

schema (i.e., that are shared across individuals).

        To further validate gaze similarity as an index of the schematicity of a simulated

scenario, we developed a novel linguistic analysis to quantify the number of schema-specific

details present in narrative data. Leveraging tools from natural language processing (specifically,

GloVe), we generated lexicons for each of the cue words and used these to identify schema-

related words in described simulations. Results of the linguistic analysis revealed that the

proportion of total words that were characterized as schematic was significantly correlated with

gaze similarity, suggesting that eye movements capture the schematic content of simulations

similarly to linguistic details. While further work will be required to fully probe the manner in

which schematic and other mnemonic details are expressed via eye movements and natural

language, these findings provide initial evidence that these modalities may be more related than

previously thought (see also, Ferreira et al., 2008).

        The described results support our hypothesis that eye movements during future

simulation express reinstatement of schema-specific visuospatial contextual features.

Importantly, however, a central feature of *functional* gaze reinstatement is that it predicts

mnemonic performance (see Wynn et al., 2019). Accordingly, we proposed that processes central

to constructive episodic simulation (e.g., retrieval) would not only be evident in the gaze patterns

of participants during elaboration, but that such patterns would also be predictive of simulation

success. In line with this prediction, we found that gaze similarity (to the corresponding schema

gaze template) during visual noise simulation was positively correlated with the proportion of

internal details generated, an objective measure of simulation success. This finding is consistent

with recent work indicating that during autobiographical memory retrieval, activity in brain

regions associated with stored knowledge networks or *schemas* precedes activity in the

hippocampus, and further suggests that schemas may provide a foundation upon which episodic

memories and simulations are (re)constructed (McCormick, Barry, Jafarian, Barnes, & Maguire,

2020). Moreover, when modeled together, gaze similarity was positively predictive of internal

details, while gaze fixation rate was negatively predictive. Thus, while a greater rate of fixations

might be indicative of a failed mental search (see Sheldon et al., 2019), schema-specific fixations

appear to reflect and support active retrieval and construction processes (i.e., the generation of a

schema). In other words, simulation success is determined not by how much we look, but rather

by where we look.

In sum, the present results indicate that eye movements during episodic simulation in the

face of distracting visual noise are both schema-specific and predictive of successful simulation.

Considered together with prior evidence of functional gaze reinstatement, these findings suggest

that eye movements may support the retrieval and reactivation of relevant (i.e., schematic)

contextual details from memory by shifting attention to regions of the screen corresponding to

imagined content, and in doing so, may provide a foundation on which to generate and construct

an imagined scenario (see also, Hassabis & Maguire, 2007, 2009; McCormick et al., 2020). This

interpretation is consistent with the proposed role of functional gaze reinstatement during

episodic memory retrieval (for review, see Wynn et al., 2019) and simulation (see Conti & Irish,

2021), and provides a potential explanation for the detrimental effects of restricted viewing on

autobiographical memory retrieval (Lenoble et al., 2019) and future imagining. (de Vito et al.,

2015). Extending this work, the present results suggest that constructive memory is likely

supported by complex interactions between processes involved in gaze control, stored

knowledge, visual imagery, and memory retrieval (see also, Conti and Irish, 2021). The present

findings also raise important questions for future work. For example, how does construction-

related gaze reinstatement respond to changes in task difficulty (manipulated parametrically)?

And how does gaze reinstatement similarly or differentially reflect, and potentially support, the

imagination of spatial and temporal contextual features? Future work should continue to build on

the present study by exploring the ways in which eye movements (and other effector systems)

might support constructive episodic simulation across various tasks by reactivating stored

contextual information.

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