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Intact speech-gesture integration in narrative recall by adults with moderate-severe traumatic brain injury

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ABSTRACT

Purpose: Real-world communication is situated in rich multimodal contexts, containing speech and gesture. Speakers often convey unique information in gesture that is not present in the speech signal (e.g., saying "He searched for a new recipe" while making a *typing* gesture). We examine the narrative retellings of participants with and without moderate-severe traumatic brain injury across three timepoints over two online Zoom sessions to investigate whether people with TBI can integrate information from co-occurring speech and gesture and if information from gesture persists across delays.

Methods: 60 participants with TBI and 60 non-injured peers watched videos of a narrator telling four short stories. On key details, the narrator produced complementary gestures that conveyed unique information. Participants retold the stories at three timepoints: immediately after, 20-min later, and one-week later. We examined the words participants used when retelling these key details, coding them as a Speech Match (e.g., "He *searched* for a new recipe"), a Gesture Match (e.g., "He searched for a new recipe *online*), or Other ("He *looked* for a new recipe"). We also examined whether participants produced representative gestures themselves when retelling these details.

Results: Despite recalling fewer story details, participants with TBI were as likely as non-injured peers to report information from gesture in their narrative retellings. All participants were more likely to report information from gesture and produce representative gestures themselves one-week later compared to immediately after hearing the story.

Conclusion: We demonstrated that speech-gesture integration is intact after TBI in narrative retellings. This finding has exciting implications for the utility of gesture to support comprehension and memory after TBI and expands our understanding of naturalistic multimodal language processing in this population.

1. Introduction

Language is multimodal, containing both speech and gesture. Gesture plays an important role in language comprehension, contributing to the listener's understanding and memory of a message. To achieve this benefit, listeners must bind linguistic information from speech and visuospatial information from gesture to generate an integrated representation of a message. Studying speech-gesture integration in clinical populations can reveal unique insights into how this process might be disrupted and the cognitive and neural resources that support it. In the current study, we examined speech-gesture integration in narrative retellings of adults with and without moderate-severe traumatic brain injury (TBI). We examined whether information presented uniquely in the gesture modality is reported in participants' retellings of stories and if it persists over time across delays. We aimed to better understand the impact of brain injury on comprehension in everyday multimodal communication contexts, as well as the potential benefit of gesture for supporting communication and memory after TBI.

Although there are many kinds of gestures, iconic gestures have a well-documented role in language comprehension. Iconic gestures are representative, visually depicting attributes of a referent such as its size, shape, position, or movement (McNeill, 1992) and have been shown to have an overall moderate beneficial effect on language comprehension (Dargue et al., 2019; Hostetter, 2011). Although these spontaneous movements of the hands and arms are semantically and temporally linked to the information in speech, they offer unique affordances and

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contributions to communication. For example, the onset of gesture often proceeds its semantic affiliates in speech (Fritz et al., 2021; Morrel-Samuels and Krauss, 1992; ter Bekke et al., 2020), and gestures commonly convey meaning that is not present in the speech signal, especially when communicating visuospatial information and actions (Alibali, 2005; Feyereisen and Havard, 1999; Hostetter and Alibali, 2019; Melinger and Levelt, 2004). Speech-gesture integration has been described as an implicit cognitive process that combines semantically related audiovisual information into a single representation (Green et al., 2009). Although multimodal language processing often occurs without overt attention to the speaker's gestures (Gullberg and Holmqvist, 2006; Gullberg and Kita, 2009), gestures with more communicative relevance attract more visual attention, as in the case of verbal language impairment in aphasia (van Nispen et al., 2022). The automaticity of speech-gesture integration may be moderated by a variety of factors (Kandana Arachchige et al., 2021). In a recent review, Kandana Arachchige and colleagues summarized several methodological factors that influence speech-gesture integration, including the method of investigation (e.g., behavioral, electrophysiology, functional magnetic resonance imaging, eye-tracking), the relationship of speech and gesture (redundant, complementary, incongruent), the stimuli content (e.g., single words, sentences, narration), the task demands on the participant (e.g., passive observation, attentional task, dual task paradigm, decision or judgement task), and more. We briefly summarize the evidence for speech-gesture integration across methodological approaches below.

1.1. Evidence for speech-gesture integration from behavioral studies

Behavioral approaches to studying speech-gesture integration have used story retelling and reaction time tasks in which the gestures communicate information that is additional or contradictory to the information in speech. For example, a speaker might say, "He searched for a new recipe," while making a typing gesture, conveying only in gesture the *manner* of searching (i.e., online as opposed to a physical cookbook). These are often referred to as *complementary* gestures. To examine the impact of complementary gestures on comprehension, studies have looked for evidence of the gestures in participants' retelling of narratives (e.g., reporting, "He searched for a new recipe *online*"). Indeed, when participants watched videos of a narrator telling a story with complementary gestures, their retellings often reflected the gestures they saw (Cassell et al., 1999; McNeill et al., 1994). In this case, not only did participants attend to information in gesture, but also, information encoded through gesture crossed modalities at recollection, reappearing in their speech. Another method used to study speech-gesture integration has been to examine the effect of *incongruent* gestures on language comprehension. These mismatching gestures are contradictory to the information provided in speech (e.g., pairing "I searched for a new recipe online" with a page-turning gesture). When listeners view incongruent gestures in stories, they report more inaccuracies in their retellings (Cassell et al., 1999; McNeill et al., 1994). In another study, participants were asked to identify whether information presented in speech or gesture was related to action primes viewed earlier; they were faster and more accurate when speech and gesture were congruent compared to incongruent, and reaction time was moderated by the degree of the incongruency (Kelly et al., 2010). Gestures can also serve a pragmatic function, facilitating the comprehension of indirect requests beyond speech alone (Kelly et al., 1999). Thus, bimodal information from speech and gesture interacts during language comprehension to form an integrated representation of a message. In the first study of speech-gesture integration in TBI, we build on this prior work to examine the influence of complementary gestures on their narrative retellings.

1.2. Evidence for speech-gesture integration from neuroimaging studies

Neuroimaging approaches to studying speech-gesture integration have used electroencephalography and functional magnetic resonance imaging to identify the timecourse and neural correlates of multimodal language comprehension (For a review, see Kandana Arachchige et al., 2021; Özyürek, 2014). Event-related potentials display a negative deflection consistent with the N400 effect indicative of semantic processing when the listener views gestures that are semantically incongruent with the linguistic context (Holle and Gunter, 2007; Kelly et al., 2004; Kutas and Hillyard, 1980; Özyürek et al., 2007). Manipulating the timing of speech-gesture synchrony disrupts the N400 effect, suggesting that speech-gesture integration is most efficient when speech and gesture onsets are closely linked in time (Habets et al., 2011). Obermeier et al. (2011) proposed that while temporally synchronous speech and gesture are integrated automatically, more active memory processes are required to combine temporally asynchronous speech and gesture. However, speech-gesture asynchrony may not impede semantic integration when the proceeding linguistic context constrains the gesture's meaning (Fritz et al., 2021). Patterns of fMRI activation also indicate that speech-gesture integration shares neural resources with semantic processing of speech. Studies have consistently identified patterns of activation recruiting the left-lateralized frontal-posterior temporal network, including the left inferior frontal gyrus, middle temporal gyrus, posterior superior temporal sulcus, and motor cortex (Dick et al., 2009; Green et al., 2009; Holle et al., 2008; Straube et al., 2012; Willems et al., 2007, 2009).

1.3. Evidence for speech-gesture integration from clinical populations

These studies increase our understanding of how and where in the brain semantic processing of speech and gesture occurs. However, less is known about individual differences in speech-gesture integration or whether this process is disrupted in populations with cognitive and neural differences. Toward this aim, an increased number of studies have begun to examine speech-gesture integration in clinical populations. For example, studies have highlighted impaired speech-gesture integration abilities in children with specific language impairment (Botting et al., 2010; Wray et al., 2016) and autism (Perrault et al., 2019; Silverman et al., 2010). Studying adults with acquired neurogenic communication disorders also offers a unique opportunity to understand the neural and cognitive mechanisms of speech-gesture integration; however, to date, investigation into the speech-gesture integration abilities of these populations is limited (See Clough and Duff, 2020 for a review). Within acquired neurogenic communication disorders, the bulk of attention has been on people with aphasia. Eye-tracking studies have shown that people with aphasia were more likely to fixate on gestures than healthy comparison participants during face-to-face interaction (Preisig et al., 2018) but not during video exploration (Eggenberger et al., 2016; Preisig et al., 2015). Examining behavioral responses, Cocks and colleagues (Cocks et al., 2009, 2018) found that people with aphasia were less able to integrate speech and gestures than healthy comparison participants, showing reduced accuracy identifying a corresponding picture cue for the target sentence when presented speech and gesture together than in either modality alone. The authors propose that disrupted speech-gesture integration in aphasia is most likely due to difficulties with attention allocation or reduced cognitive resources (Cocks et al., 2018). This suggests that when cognitive resources are limited or cognitive demands are high, individuals may weight audiovisual signals differently. More work is needed to identify whether neuroanatomical profile (i.e., lesion location, size), aphasia-type syndrome, or cognitive-linguistic abilities moderate a benefit of gesture comprehension in aphasia.

Other populations of adults with neurogenic communication disorders have received much less attention and less is known about whether the cognitive and communicative benefits of gesture extend to adults with cognitive-communication disorders, such as traumatic brain injury, dementia, and right hemisphere brain damage (Clough and Duff, 2020). These populations not only provide a unique opportunity to identify the cognitive resources that support speech-gesture integration, but also may yield insights into the therapeutic utility of gesture to support comprehension, learning, and memory in rehabilitation. For example, our group has examined the relationship between gesture and declarative memory in a rare group of patients with hippocampal amnesia and found that they successfully integrate information from complementary gestures into their immediate retellings of stories at higher likelihoods than non-brain injured and brain-damage control participants with focal injury to the ventromedial prefrontal cortex (Hilverman et al., 2018a). Gesture has also been shown to improve word learning performance in individuals with hippocampal amnesia (Hilverman et al., 2018b) and facilitate memory encoding in amnestic mild cognitive impairment (Sgard et al., 2020). Although these studies point to a benefit of gesture, even in populations with profound memory impairment, the enduring nature of those benefits is unknown. In fact, very little is known about the duration of those benefits more broadly in typical populations. Thus, studying the relationship between gesture and memory in clinical populations, over time, has the potential to advance both basic science and clinical translation.

1.4. Social communication in traumatic brain injury

Although converging evidence from behavioral, electrophysiological, fMRI, and clinical methods support an interaction between speech and gesture in language comprehension, more work is needed to understand when and for whom gesture benefits, the long-term effects of gesture on learning and memory, and the cognitive and neural mechanisms that support speech-gesture integration. One population that has the potential to yield novel insights into these processes is TBI. To our knowledge, only a couple of studies have examined gesture comprehension in adults with TBI. Bara et al. (2001) asked people with TBI to watch silent movies containing only gestures and found that they were as successful as non-injured adults at interpreting simple and complex standard communication acts (e.g., gesturing for someone to take a seat) but significantly worse at interpreting gestures communicating deceit or irony (e.g., a child pointing blame to another child after breaking a vase). Evans and Hux (2011) provided evidence that people with TBI can benefit from gesture to improve comprehension of indirect requests (e.g., pointing to their partner's sandwich while saying, "I'm still pretty hungry"). Despite having overall reduced accuracy interpreting indirect requests, participants with TBI interpreted indirect requests with greater accuracy when provided both speech and gesture combined compared to either modality alone. These two studies provide mixed evidence as to whether people with TBI might be able to leverage gesture to improve comprehension of non-literal language (e.g., irony, sarcasm, indirect messages), for which they have well-documented deficits (Channon et al., 2005; Martin and McDonald, 2005). Further, although the above studies focused mostly on the use of deictic or pointing gestures and at a single timepoint, it is unknown how people with TBI integrate iconic gestures with co-occurring speech context and their ability to retain information from gesture over time.

Indeed, disruptions to social communication are a hallmark characteristic of TBI and can negatively impact psychosocial reintegration, return to work, and maintenance of relationships post injury (Flynn et al., 2018; Meulenbroek and Turkstra, 2016; Wagner et al., 2002). From a comprehension standpoint, Individuals with TBI can have difficulties interpreting the intended meanings of others, making inferences, and comprehending nonliteral language and nonverbal cues like facial expression and eye gaze. In turn, their expressive communication can be disorganized, inappropriate, or irrelevant. Disruptions in the ability to process and integrate multimodal signals may underlie these social communication deficits. Real-world communication is dynamic and requires the integration of perceptual, emotional, and situational cues with shared world knowledge in rich multimodal contexts (MacDonald, 2017). Thus, studying communication in such rich dynamic contexts is critical for advancing assessment and treatment of language deficits in TBI.

1.5. Aims and hypotheses

As a first step, the current study addressed this aim by studying spoken language comprehension alongside gesture in a naturalistic story retelling paradigm. We examined whether people with TBI successfully integrated unique information conveyed through complementary gestures in their retellings of short stories. Given the well-documented nature of social communication deficits following TBI, we predicted that individuals with TBI will be less likely to report information from gesture in their narrative retellings than non-brain injured peers, reflecting impaired speech-gesture integration abilities. To our knowledge, this is the first study of speech-gesture integration in TBI in a discourse context. Given the role of gesture in supporting learning and memory, and additional aim of this study is to examine whether information from gesture persists in memory after short and long delays. There are two main possible outcomes of this study: Evidence of impaired speech-gesture integration in TBI would provide support for the hypothesis that disruptions to the processing and integration of multimodal signals underlie social communication deficits in TBI. On the other hand, evidence of intact speech-gesture integration in TBI would provide the first evidence that gesture can support comprehension and memory after brain injury. Either outcome opens novel avenues of investigation into the assessment and treatment of cognitive-communication disorders.

2. Materials and methods

2.1. Participants

Participants were 60 adults with chronic moderate-severe TBI (30 male, 30 female), at least six months post injury (*M* time since injury = 74.62 months, *SD* = 74.23) and 60 non-injured comparison (NC) participants (30 male, 30 female). TBI and NC participants were matched pairwise on sex, age (M_{TBI} = 40.13 years, SD_{TBI} = 10.60 years; M_{NC} = 39.95 years, SD_{NC} = 10.39), and education (M_{TBI} = 14.93 years, SD_{TBI} = 2.51 years; M_{NC} = 14.97 years, SD_{NC} = 2.43). All participants were recruited from the Vanderbilt Brain Injury Patient Registry (Duff et al., 2022). NC participants completed a medical history interview to rule out diagnoses and medications that can interfere with cognition (e.g., neurological or psychiatric conditions, developmental or learning disorders, untreated diabetes or sleep apnea). All participants with TBI sustained their injuries in adulthood and met inclusion criteria for moderate-severe TBI using the Mayo Classification System (Malec et al., 2007) verified through medical records and intake interviews. In accordance with the Mayo Classification System, participants were classified as moderate-severe if at least one of the following criteria were met: (1) Glasgow Coma Scale (GCS) < 13 within 24 h of acute care admission, (2) positive neuroimaging findings (acute CT findings or lesions visible on a chronic MRI), (3) loss of consciousness (LOC) > 30 min, or (4) post-traumatic amnesia PTA >24 h. Table 1 shows demographic and injury details for participants with TBI.

2.2. Stimuli

We used the same stimulus materials as Hilverman et al., 2018a. Participants watched videos of a narrator telling four stories in North American English about an unlucky man named Carl (See Appendix A). The stories were about 30 s long, consisted of six sentences, contained four iconic gestures, and were made up of 10–12 story details (See Appendix B). Each story contained four gestures: Two gestures were redundant with speech, depicting overlapping information with speech (e.g., "he formed the meat into balls" paired with a *meatball-patting* motion), and the other two gestures were complementary to speech, providing unique information (e.g., "He searched for a new recipe"

Table 1
Demographic and injury information for participants with TBI.

ID	Age	Edu	Etiology	TSO	LOC	Neuroimaging	GCS	PTA
5002	41–45	16	Non-motorized vehicle accident	250	LOC >30 min	ICH	3	>24 h
5003	26–30	18	Ped vs. auto	46	N/A	SDH	11	>24 h
5014	51–55	16	MVA	207	LOC >30 min	N/A	N/A	>24 h
5016	18–25	16	MVA	39	LOC >30 min	SAH	13	>24 h
5017	31–35	16	Ped vs. auto	191	LOC >30 min	SAH; IVH	4	>24 h
5021	41–45	18	MVA	52	LOC >30 min	EDH; SAH	3	>24 h
5027	31–35	16	Ground-level fall	35	LOC >30 min	SAH	9	>24 h
5029	31–35	14	Non-motorized vehicle accident	34	LOC <30 min	SDH: IPH; SAH	14	<24 h
5034	36–40	16	MVA	61	LOC >30 min	SAH	3	>24 h
5038	41–45	16	Ground-level fall	41	LOC >30 min	SDH; multifocal hemorrhages; post-traumatic hemorrhagic contusions	N/A	>24 h
5041	31–35	16	MVA	76	No LOC	No acute intracranial findings	10	>24 h
5046	46–50	18	Non-motorized vehicle accident	68	LOC <30 min	SAH	14	>24 h
5047	26–30	16	Assault	40	LOC <30 min	SDH	15	<24 h
5048	46–50	16	MVA	366	LOC >30 min	N/A	N/A	>24 h
5050	31–35	18	Ground-level fall	36	LOC >30 min	SAH; IPH	15	<24 h
5051	51–55	16	MVA	21	LOC <30 min	SAH; SDH	14	<24 h
5058	36–40	12	MCC	135	LOC <30 min	SAH; SDH; PCH	8	>24 h
5062	18–25	12	MVA	85	LOC <30 min	SDH	15	<24 h
5068	26–30	16	Fall from height	55	LOC <30 min	ICH	3	>24 h
5070	46–50	16	Fall from height	69	LOC <30 min	SAH; hemorrhagic contusions	15	>24 h
5071	26–30	12	MVA	59	LOC >30 min	SDH	3	>24 h
5073	31–35	14	Non-motorized vehicle accident	127	LOC >30 min	EDH	14	>24 h
5079	36–40	18	MVA	102	LOC >30 min	PCH; SAH	5	>24 h
5082	46–50	12	Assault	89	LOC >30 min	SDH; SAH; bifrontal contusions	14	<24 h
5091	46–50	12	MVA	34	LOC >30 min	SDH; SAH; hemorrhagic shear injuries	6	>24 h
5095	41–45	12	Other	50	LOC >30 min	ICH; parenchymal contusions, SAH; SDH	3	>24 h
5098	51–55	14	Struck by object	165	LOC <30 min	front-temporal contusion; IPH; SAH; ICH	N/A	<24 h
5099	31–35	20	Assault	46	LOC >30 min	SDH	13	<24 h
5100	51–55	18	Other	30	LOC >30 min	IVH; IPH	3	>24 h
5104	36–40	20	Struck by object	22	LOC <30 min	SDH; scattered SAH; right temporal hemorrhage	15	<24 h
5109	26–30	14	MVA	102	LOC >30 min	SDH; IPH; IVH	5	>24 h
5111	26–30	16	MVA	72	LOC <30 min	Shear Injury; DAI	N/A	>24 h
5112	51–55	16	MVA	49	LOC >30 min	frontal hematoma; IPH; IVF	10	>24 h
5115	36–40	12	MVA	206	No LOC	SAH	N/A	>24 h
5117	46–50	12	MCC	115	LOC <30 min	DAI	15	>24 h
5118	26–30	18	MVA	45	LOC >30 min	SDH	10	>24 h
5119	36–40	16	MVA	222	LOC >30 min	SAH; Possible right frontal contusion	N/A	>24 h
5121	51–55	12	MCC	13	LOC <30 min	SAH; SDH; PCH	12	>24 h
5122	51–55	18	Non-motorized vehicle accident	20	LOC <30 min	SAH	15	>24 h
5123	51–55	12	MCC	21	LOC <30 min	IPH; SDH; SAH	14	>24 h
5124	18–25	12	Fall from height	30	LOC >30 min	ICH; IVH	3	>24 h
5125	51–55	12	Ground-level fall	9	No LOC	SDH; SAH	15	No
5127	51–55	12	Fall from height	10	LOC <30 min	SAH; SDH	10	<24 h
5128	36–40	16	MVA	185	LOC >30 min	N/A	N/A	>24 h
5129	51–55	12	Other	9	LOC <30 min	SDH; SAH	12	<24 h
5131	41–45	12	MVA	9	LOC >30 min	SDH	12	>24 h
5133	18–25	12	MCC	22	LOC <30 min	contusions; SDH; IVH	15	<24 h
5134	46–50	16	MCC	8	LOC <30 min	IPH	12	<24 h
5137	26–30	16	Ped vs. auto	11	LOC >30 min	EDH; SDH: SAH	3	>24 h
5141	26–30	12	MVA	8	LOC >30 min	SDH	13	<24 h
5145	31–35	20	MVA	129	LOC >30 min	No acute intracranial findings	12 (est.)	>24 h
5146	51–55	12	Fall from height	17	LOC <30 min	ICH; SDH; SAH; IPH	15	>24 h
5147	51–55	16	MVA	118	LOC >30 min	Diffuse Shear Injury	N/A	>24 h
5149	18–25	14	MVA	12	LOC <30 min	IPH; SAH; DAI	3	>24 h
5150	36–40	12	MVA	13	LOC >30 min	SAH	10	>24 h
5151	36–40	12	MVA	11	N/A	IPH; SDH; SAH	13	>24 h
5152	51–55	18	MCC	175	LOC >30 min	SDH; SAH; Shear injuries	7	>24 h
5153	46–50	16	MVA	155	LOC >30 min	PCH; IPH; ICH; SAH	3	>24 h
5156	51–55	12	MVA	42	LOC >30 min	SDH	15	No
5157	51–55	16	MCC	8	LOC <30 min	SDH; SAH; IPH	15	No

Note: ID = participant ID number. Education (Edu) reflects years of highest degree obtained. MVA = motor vehicle accident. MCC includes both motorcycle and snowmobile accidents. Non-motor = non-motorized vehicle accident. Ped vs. auto = participant was hit by car while walking or running. Time since onset (TSO) is presented in months. Loss of consciousness (LOC) is presented in minutes. SDH = subdural hematoma. SAH = subarachnoid hemorrhage. IPH = intraparenchymal hemorrhage. IVH = intraventricular hemorrhage. ICH = intracranial hemorrhage. EDH = epidural hematoma. DAI = diffuse axonal injury. PCH = parenchymal hemorrhage. Glasgow Coma Scale (GCS) is total score at time of first post-injury measurement. PTA = post-traumatic amnesia. N/A = information was not available.

paired with a *typing* motion). Each story had two versions in which the narrator produced different complementary gestures (e.g., "He searched for a new recipe" paired with a *typing* motion in one version and a *page-turning* motion in the other). Participants were randomly assigned to one of the versions for the set of four stories. Fig. 1 displays examples of redundant and complementary gestures that participants saw.

2.3. Procedure

Data collection sessions were conducted via Zoom conference call. Participants were instructed to sit away from the camera to maximize the view of their gesture space. Participants were not told explicitly that their gestures might be examined. Instead, they were told that the goal of the camera angle was to capture a full-body view, characteristic of

Fig. 1. An example of a redundant (left) and complementary (right) gesture produced by the narrator during one of the Carl stories. In the redundant gesture example, the narrator says, "He formed the meat into balls," while producing a *meatball-patting* movement. In the complementary gesture example, the narrator says, "He searched and searched for a new recipe," while producing a *typing* movement.

face-to-face communication. Participants were also instructed to hide their self-view to reduce distractions from their own video. Due to limitations with space, setting, equipment, and personal comfort, there was variability in how much of the participants' gesture space was captured on the Zoom call. See the exploratory analysis results section below for more details. The videos of the narrator were presented using Gorilla Experiment Builder (Anwyl-Irvine et al., 2020), played on the participants' personal computer. Participants shared their screen with the experimenter who controlled the screen remotely. The experimenter played a sample audio file during which participants were able to adjust their volume controls until they self-reported the signal was loud enough. To ensure they understood the task, participants first watched a practice video of an unrelated story about a different character (Suzy). Then they watched the four Carl stories in a set order. Each video started with a picture prompt displaying a scene from the story and the title of the story. The experimenter read the title of the story aloud and advanced the screen to initiate the video play. The picture prompt was replaced by the video, but the story title remained on the screen. Immediately after each video ended, the experimenter stopped the participants' screen sharing so that they viewed only the experimenter's video on Zoom, maximizing the view of their listener. Participants were instructed to retell the story in as much detail as they could remember.

After completing this process for the practice video and all four stories, participants engaged in a 20-min filled delay in which they completed a standardized language assessment with the experimenter. After the filled delay, the participants were prompted to retell the stories again. The experimenter provided the title of each story and asked them to again retell the story in as much detail as they could remember. Participants retold the stories one more time on a Zoom call one-week later and again were prompted with the story titles. If participants did not recall anything about a story after hearing the title, they were briefly shown the picture prompt to facilitate their recall. If they still did not remember, they were asked to make up a story about the picture with a beginning, a middle, and an end. Participants rarely required picture prompts at the one-week delay (2 NCs and 4 TBIs) and when required, prompts were needed for only 1 or 2 stories. Thus, participants retold all four Carl stories three times: Immediately after (no delay), 20-min later (short delay), and one-week later (long delay).

2.4. Recall coding

All retellings were transcribed using Rev professional audio transcription services (https://www.rev.com). The audio files were transcribed verbatim by their team of human transcribers. These transcripts were then double checked by a research assistant who watched the participant videos and filled in utterances marked "unintelligible" by Rev whenever possible. Each story was divided into 10-12 story details (Appendix B). To calculate the number of story details recalled at each timepoint, coders read each story transcript and assigned the details a value of 1 if it was present and 0 if it was absent. All coding was completed by two coders (Authors SC and VGP; VGP was blind to study hypotheses). Prior to beginning recall coding, the coders completed a training set of a random selection of one timepoint for 12 participants for each of the 4 stories. Disagreements were discussed and a consensus was reached for the training set. The two coders then independently coded an overlapping set of 52 participants for all stories and delays (43% of the data). Percent agreement on whether a story detail was recalled was 92.2%, Cohen's Kappa = 0.81, 95% CI [0.79, 0.82].

2.5. Speech coding

To examine whether complementary information in gesture was integrated into the participants' retelling of the narrative, we focused on the specific words participants produced when retelling the key details of the stories that had been paired with gestures. When participants recalled story details that were paired with redundant and complementary gestures, the coders categorized whether the participants' produced (1) a *Speech Match* – the participant said the same word the narrator said when she produced the gesture (e.g., "He *searched* for a recipe"), (2) a *Gesture Match* – the participant said a word that clearly reflected the gesture the narrator produced (e.g., "He searched for a recipe *online*"), or (3) *Other* – the participant said a word that neither directly matched the narrator's speech or gesture (e.g., "He *looked* for a recipe"). *Gesture Matches* provide an indication that participants integrated unique information from gesture into their narrative retellings. Details paired with redundant gestures could only be coded as a *Speech Match* or *Other* since there is no unique information conveyed by the gesture (see Appendix B for speech coding guide). The same two coders categorized Match type on the same set of 52 participants. One of the coders automated the process by using an Excel VBA Macro to identify keywords that corresponded to Match types. In some cases, participants said a word that matched a gesture that the narrator did not produce in that version (e.g., if they said, "He looked through a *cookbook*" but they saw the version with the *typing* movement). All *Gesture Match* codes were cross-checked with the version participants saw, and in cases where participants' speech matched the gesture from the wrong version, we changed the *Gesture Match* code to *Other*. Percent agreement on Match type for details paired with gestures was 93.7%, Cohen's Kappa = 0.88, 95% CI [0.85, 0.90]. See Table 2 for an example participant transcript with recall and speech coding.

Table 2
Example coded transcript from a non-injured comparison participant.

Example Transcript	Carl is going to make dinner for his friends. So he's looking for recipes, and eventually he finds one for meatballs, and he's excited. So he grinds up the meat and packs them into balls and then puts them in the oven. He goes to talk to his friends and gets distracted and burns the meatballs to a crisp.									
Story Details (From Narrator)	Carl decided to make a new recipe	Carl is having friends over for dinner	Carl **searched** [COMPUTER or BOOK] for a recipe	Carl decided to cook meatballs	Carl ground up the meat	Carl formed the meat into **balls**	Carl started **cooking** [SKILLET or OVEN] the meatballs	Carl **talked** to his friends	Carl got distracted and forgot the meatballs	The meatballs burned
Corresponding Transcript Details (From Participant)	NA	Carl is going to make dinner for his friends	So he's **looking** for recipes	and eventually he finds one for meatballs, and he's excited.	So he grinds up the meat	and packs them into **balls**	and then puts them in the **oven**	He goes to **talk** to his friends	and gets distracted	and burns the meatballs to a crisp
Recall Coding	0	1	1	1	1	1	1	1	1	1
Speech Coding			Other			Speech Match	Gesture Match	Speech Match		

Note: The *Example Transcript* row contains the verbatim transcript for one of the Carl stories at one timepoint for a non-injured participant. The *Story Details* row indicates the 10 story details the story was divided into based on the narrator's telling. Bolded words in *Story Details* row indicate the key words paired with gesture. For supplementary gestures, the alternative versions of the gestures the narrator produced are indicated in brackets. The *Transcript Details* row indicates which portions of the participant's transcript were considered to match one of the narrator's details (NA indicates no match). Highlighted and bolded words in the *Transcript Details* row indicate the word the participant produced, corresponding to the narrator's key words. The *Recall Coding* row denotes the presence (1) or absence (0) of a story detail in the participant's retelling. For the four details paired with gesture, the *Speech Coding* row reflects the relationship between the word the participants said and the narrator's words or gesture.

2.5. Gesture coding

Our primary measure of interest was the words participants used when they retold details paired with complementary gestures; However, we were also interested in whether the participants reproduced representative gestures when retelling story details in which the narrator gestured. Participants saw 16 gestures across the four stories. When participants recalled a story detail paired with gesture, we coded whether they also produced a gesture on the same key word as the narrator. When the participants gestured, we coded gesture type as either a representative gesture (i.e., meaningful movements that visually depict actions, shape, movement, or abstract concepts), or a beat gesture (i.e., short, rhythmic movements that are temporally but not semantically linked to the speech signal) (Kita and Emmorey, 2023; McNeill, 1992). Gesture coding was completed by the same two coders above. The coders trained on a set of 5 participants, examining all timepoints and stories. Disagreements were discussed until a consensus was reached. We then coded a randomly selected overlapping set of 18 participants (15% of the data). Percent agreement on whether a gesture was produced was 97.1%, Cohen's Kappa = 0.93, 95% CI [0.91, 0.96]. When a gesture was produced, agreement on gesture type (e.g., representative or non-representative) was 93.1%, Cohen's Kappa = 0.75, 95% CI [0.63, 0.87]. Gesture coding was hindered by the inconsistent gesture space visibility due to the Zoom data collection format (see *Exploratory Analysis: Gesture Production* section below for details). Despite high inter-rater agreement, we used these data only in an exploratory analysis below.

2.6. Analysis

To examine whether our experimental manipulation was effective, we predicted the likelihood of participants saying a different word than what the narrator said (coded as a *Gesture Match* or *Other*) as a function of gesture type (redundant vs. complementary). We examined only the no delay timepoint as an indication of how gesture type affected the words participants produced immediately after hearing the stories. We used a generalized linear model and dummy coded the redundant gesture type as the reference level.

For all other analyses, we used binomial mixed effect regression models using the glmer function in *lme4* (Bates et al., 2015) in R version 4.2.1 (R Core Team, 2022) to predict the likelihood of participants producing our dependent variables of interest as a function of participant group (TBI, NC), timepoint (No Delay, Short Delay, Long Delay) and their interactions. For all analyses, the NC group and No Delay timepoint were dummy coded as the reference levels. Thus, the main effect of group reflects the change in the dependent variable observed in the TBI group relative to the NC group at the No Delay timepoint. Because the NC group is coded as the reference level, the two main effects of delay (Short delay relative to No Delay and Long delay relative to No Delay) are interpreted as the simple effects for NC participants. This allows us estimate baseline effect sizes for how time impacts story recall and speech-gesture integration in the non-injured population. To detect whether effects of delay on the dependent variables differ for our TBI group, we looked to the interaction effects. A significant interaction between group and either delay contrast indicates that the magnitude of the effect is significantly different for the TBI group relative to the NC group. To probe significant interactions, we reverse dummy-coded the model, setting the TBI group as the reference level (NC = 1, TBI = 0), allowing us to determine the simple effect of delay for the TBI participants.

The random effects structure, including whether the model includes random intercepts and slopes by person and story were determined using the *Buildmer* package in R (Voeten, 2020) for each analysis. This package identifies the largest possible regression model that will converge and uses stepwise elimination to find the most parsimonious model based on information criteria. Significant coefficients for logit-linked binomial regressions were interpreted with odds ratios. To examine story recall, we predicted the likelihood of recalling a story detail, where each detail was coded as present (1) or absent (0) in each participant's recall. To examine whether participants integrated unique information from gesture in their narrative retellings, we analyzed the likelihood of participants producing a word that matched the narrator's gesture (*Gesture Match* = 1, *Speech Match* and *Other* = 0) for the 8 story details presented with complementary gestures. Finally, we conducted an exploratory analysis to investigate whether participants with and without TBI were more likely to produce a representative gesture (representative gesture = 1, non-representative gesture = 0) at the key moments in which the narrator produced gestures across timepoints.

3. Results

3.1. Story Recall. Mean number of story details recalled by participants with and without TBI across timepoints are shown in Fig. 2. We examined the likelihood that participants would recall a detail (present

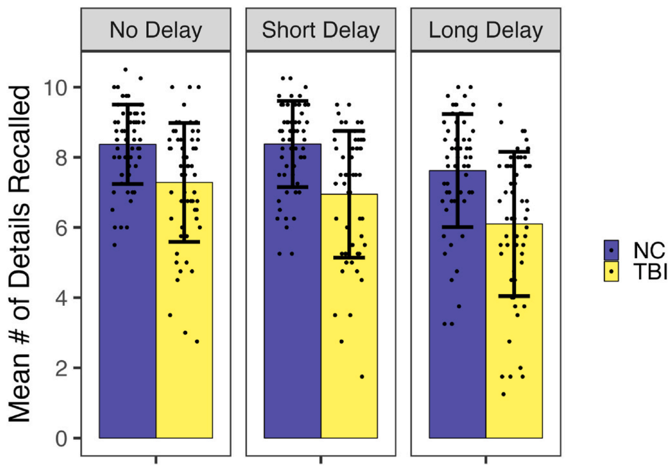

Fig. 2. Mean number of story details recalled by NC and TBI participants at each of the three timepoints. Bars represent standard deviation of the mean. The analysis detected a significant main effect of group at the No Delay Timepoint such that participants with TBI were less likely to recall a story detail than NC peers. There were no significant interactions between participant group and delay, indicating that this pattern was similar at Short and Long Delay timepoints.

= 1, absent = 0) as a function of participant group (TBI relative to NC), delay (Short delay relative to No Delay; Long delay relative to No Delay), and their interactions, with random intercepts for participant and story. There was a significant effect of group; participants with TBI were significantly less likely to recall a story detail than their non-injured peers ($\beta = -0.60$, $z = -3.89$, $p < .001$), where the odds of a non-injured participant recalling a detail were 1.82 times greater than a participant with TBI. There was no significant effect of the short delay relative to no delay on story recall ($\beta = 0.01$, $z = 0.07$, $p = .94$). There was a significant effect of the long delay; non-injured participants were less likely to recall a story detail after the long (one-week) delay compared to no delay ($\beta = -0.43$, $z = -6.23$, $p < .001$), where the odds of recalling a detail immediately after hearing the story were 1.54 times greater than after a one-week delay. There was no significant interaction between participant group and the short delay timepoint ($\beta = -0.17$, $z = -1.79$, $p = .07$) or between participant group and the long delay timepoint on story recall ($\beta = -0.18$, $z = -1.90$, $p = .06$), indicating that the effect of time on story recall did not significantly differ by participant group.

3.1. Gesture type manipulation

Next, we examined whether complementary gestures were more likely than redundant gestures to lead participants to use a different word than the narrator during retellings. We analyzed the likelihood that participants said a word that was different than the narrator (i.e., Other or Gesture Match = 1; Speech Match = 0) as a function of participant group (TBI relative to NC) and gesture type (complementary relative to redundant). The effect of participant group did not reach significance ($\beta = 0.45$, $z = 1.87$, $p = .06$), indicating that participants with and without TBI did not significantly differ in their likelihood of changing the narrator's target words in their retellings. There was a significant effect of gesture type ($\beta = 2.45$, $z = 12.08$, $p < .001$), where the odds of participants using a different word than the narrator were 11.59 times greater when retelling details paired with complementary gestures compared to those paired with redundant gestures. There was no significant interaction between participant group and gesture type on the likelihood of using a different word than the narrator ($\beta = -0.51$, $z = -1.84$, $p = .07$). These results suggest that our intended gesture type manipulation was effective; complementary gestures containing unique information beyond what was conveyed in speech were more likely to result in participants using different words than the narrator in their retellings. Lack of interaction between group and gesture type suggests that the magnitude of this effect did not significantly differ between NC and TBI groups.

3.2. Gesture integration

For our primary analysis, we examined the likelihood of participants producing a *Gesture Match* (*Gesture Match* = 1; *Speech Match* or *Other* = 0) during retellings of details paired with complementary gestures (Fig. 3) as a function of participant group (TBI relative to NC), delay (Short delay relative to No Delay; Long delay relative to No Delay), and their interaction, with random intercepts for participant and story. There was no significant effect of group ($\beta = -0.004$, $z = -0.02$, $p = .99$), indicating that participants with TBI did not significantly differ from non-injured peers in their likelihood of integrating information from gesture into their retellings. There was no significant effect of short delay relative to no delay on gesture integration ($\beta = 0.20$, $z = 1.29$, $p = .20$); however, there was a significant effect of the long delay relative to no delay on gesture integration ($\beta = 0.38$, $z = 2.42$, p=.02), where non-injured participants were 1.47 times more likely to produce a gesture match at the long delay timepoint than no delay. There was no significant interaction between participant group and the short delay contrast ($\beta = 0.08$, $z = -0.33$, $p = .74$) or long delay contrast ($\beta = -0.23$, $z = -0.98$, $p = .33$), indicating that the effect of delay on likelihood of producing a *Gesture Match* did not significantly differ by participant group.

Per reviewer request, we conducted a post hoc Bayesian multilevel analysis to distinguish between evidence of absence or absence of evidence (Keysers et al., 2020) for the fixed effect of participant group on our primary analysis of speech-gesture integration. The analysis was conducted in R using the *brms* package (Bürkner, 2017, 2018). Parameter distributions for all fixed effects and the intercept were given weakly informative priors with a mean of 0 and standard deviation of 1. Default prior settings were used for random effects. The models were estimated using MCMC sampling with four chains of 10,000 iterations and a warmup of 2000 iterations. To quantify evidence for a lack of effect of participant group on the likelihood of producing a gesture match, we calculated a Bayes Factor comparing a null model with a fixed effect of delay only against the alternative model contained both fixed effects of delay and group. The Rhat values of both models were equal to 1, indicating convergence. The Bayes factor was 5.49 in favor in the null model, indicating that the observed data are 5.49 times more likely under the null model and providing moderate evidence for the absence

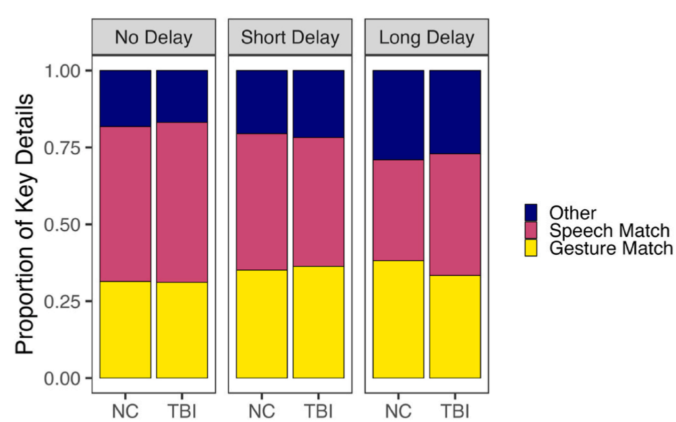

Fig. 3. Of the story details presented with complementary gestures that were recalled at each time point (max = 8), the proportion of participants' retellings that matched the narrator's speech (speech match), matched the narrator's gesture (gesture match), or neither (other) for non-injured comparison participants (NC) and participants with traumatic brain injury (TBI).

of an effect of participant group on the likelihood of producing gesture matches.

To examine evidence for null effects across all parameters, we calculated the percentage of the 89% Highest Density Interval credible interval (CI) of each parameter distribution that falls within the region of practical equivalence (ROPE) in the full model using the *bayestestR* package in R (Makowski et al., 2019). The higher the percentage of the CI inside of the ROPE, the more likely the effects are practically equivalent to zero or negligible. If the credible interval of a posterior distribution falls completely inside the ROPE, the null hypothesis is accepted. If the credible interval of a posterior distribution falls completely outside the ROPE, the null hypothesis is rejected. Otherwise, results are inconclusive. All parameters had some percentage of the 89% CI inside the ROPE, precluding rejection of the null hypotheses. However, the effect of long delay on production of gesture matches resulted in only 5.89% of overlap of the CI with the ROPE. Other parameters ranged from 43.33% to 71.65% of the CI inside the rope (Fig. 4), indicating that the null hypothesis can be neither accepted or rejected for these parameters. Overall, the Bayesian post hoc tests are consistent with results from the generalized linear mixed effect model which found that participant group was not a significant predictor of likelihood of producing gesture matches and that the long delay a significant positive effect on the likelihood of producing gesture matches.

3.3. Exploratory Analysis

Gesture Production. In an exploratory analysis, we investigated whether participants with and without TBI were more likely to produce a representative gesture at the key moments in which the narrator produced gestures across Delay timepoints. Because the study was conducted on Zoom, there was variability in how much of the participants' body and gesture space was visible. Gesture space was coded as the height of the bottom video frame relative to the participant's body. At the no- and short-delay timepoints (session 1), gesture space corresponded to Chest ($n_{NC} = 11$, $n_{TBI} = 15$), Elbow ($n_{NC} = 30$, $n_{TBI} = 25$) and Hip height ($n_{NC} = 19$, $n_{TBI} = 20$). At the long delay timepoint (session 2), gesture space corresponded to Chest ($n_{NC} = 14$, $n_{TBI} = 15$), Elbow ($n_{NC} = 19$, $n_{TBI} = 18$) and Hip height ($n_{NC} = 27$, $n_{TBI} = 24$). One participant with TBI was unable to connect their web camera and had no visible gesture space at the long delay. A generalized linear model predicting the likelihood of producing a representative gesture as a function of visible gesture space indicated that participants were significantly less likely to produce a representative gesture when the bottom of the video frame was elbow relative to hip height ($\beta = -0.05$, $z = -3.25$, $p = .001$) and chest relative to hip height ($\beta = -0.14$, $z = -8.01$, $p < .001$), suggesting that data loss occurred when visible gesture space was restricted. However, a chi square test indicated that there was no difference in the distribution of gesture space categories by participant group at either the session 1 (X^2 (1, $N = 120$) = .16, $p = .92$) or session 2 timepoints (X^2 (1, $N = 117$) = 1.10, $p = .58$). Likewise, although there are numerically more participants with hip-height gesture space at session 2 compared to session 1, a chi square test did not reveal any significant differences in the distribution of gesture space categories for the session 1 and session 2 timepoints (X^2 (1, $N = 237$) = 5.25, $p = .07$).

For the story details in which the narrator produced a gesture (n = 16), Fig. 5 shows the proportion of details in which participants produced no gesture, beat gestures, and representative gestures by group and delay. When participants recalled a detail that was paired with a gesture (redundant or complementary), we analyzed the likelihood that they produced a representative gesture (representative gesture = 1; beat gesture or no gesture = 0) when retelling that detail as a function of participant group (TBI relative to NC), delay (Short delay relative to No Delay; Long delay relative to No Delay), and their interaction, with a random slope for delay by participant and a random intercept for story. There was no significant effect of group on the production of representative gestures ($\beta = -0.32$, $z = -0.78$, $p = .43$); participants with TBI did not significantly differ from non-injured peers in their likelihood of producing representative gestures when retelling key details. There was no significant effect of the short delay on representative gesture production ($\beta = 0.08$, $z = 0.45$, $p = .66$), indicating that non-injured participants did not differ in their likelihood of producing representational gestures at the short compared to the no delay timepoint. There was a significant effect of the long delay on representative gesture production ($\beta = 1.11$, $z = 5.38$, $p < .001$); non-injured comparison participants were significantly more likely to produce a representational gesture when retelling key details at the long delay compared to no delay timepoint, where the odds of producing a representational gesture one week later was 3.04 times greater than immediately after hearing the story. There was no significant interaction between group and the short delay timepoint ($\beta = 0.16$, $z = 0.68$, $p = .50$) or between group and long delay timepoint on representative gesture production ($\beta = 0.08$, $z = 0.29$, p=.77), indicating that the magnitude of the effects of delay did not significantly differ between the TBI and NC groups.

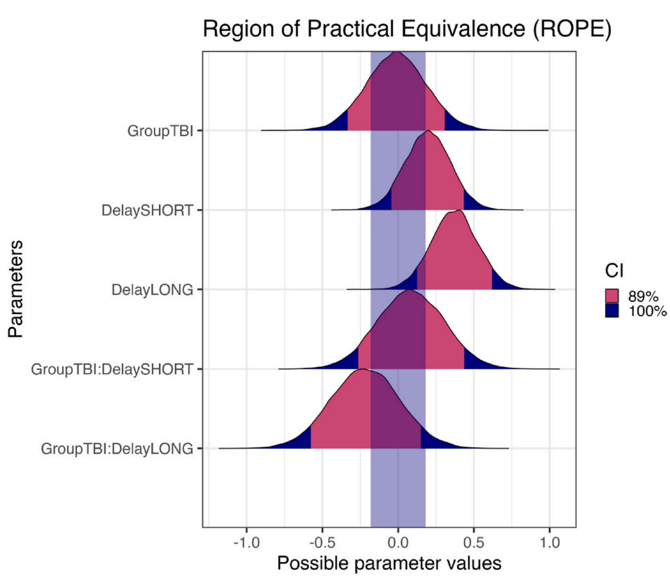

Fig. 4. The percentage of the 89% and 100% credible intervals of posterior distributions of model parameters that fall within the ROPE limits (shown in transparent blue/purple). The percentage of the 89% CI for parameters are as follows: GroupTBI = 71.75%, DelaySHORT = 45.80%, DelayLONG = 5.89%, GroupTBI:DelaySHORT = 62.71%, GroupTBI:DelayLONG = 43.33%. All parameters have some degree of overlap between the 89% CI and ROPE region, providing inconclusive evidence for rejection or acceptance of the null hypotheses.

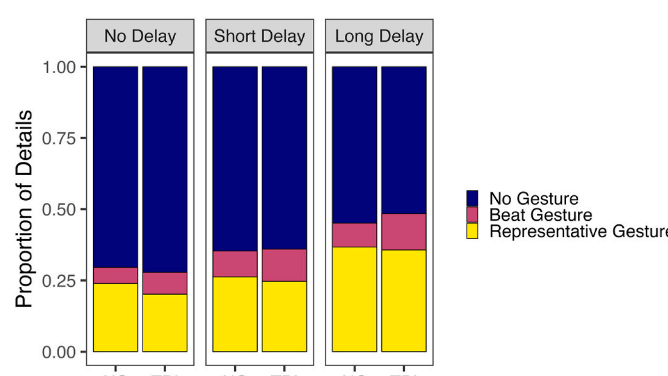

Fig. 5. Proportion of details in which participants produced no gesture, beat gestures, and representative gestures when retelling details in which the narrator gestured (n = 16).

4. Discussion

Despite recalling significantly fewer story details than non-injured peers, participants with TBI were as likely to integrate unique information from the narrator's gesture into their narrative retellings and produce representative gestures when retelling key details. In addition, all participants were more likely to report information from gesture in their speech retellings and produce representative gestures themselves one-week later compared to immediately after hearing the story. This suggests that although memory for stories is more verbatim in immediate retellings, over time, information from gesture is integrated and potentially strengthened in the mental representation, even for people with traumatic brain injury.

4.1. Speech-gesture integration in TBI: Successes and limitations

In the current study, we found no evidence of a deficit in speech-gesture integration in adults with moderate-severe TBI. Participants with TBI did not significantly differ from non-injured peers in their likelihood or reporting information from gesture in their retellings of narratives. Although our finding of intact speech-gesture integration in TBI has exciting implications for the utility of gesture to support comprehension and memory in TBI, these findings are contrary to our prediction. We hypothesized that disruptions in multimodal integration may underlie the difficulties people with TBI encounter when communicating in rich, dynamic social settings that require processing and integration of multiple co-occurring cues (e.g., speech, gesture, facial expression, eye gaze, voice, body language, situational context, and communication partners' knowledge states). In the current study, we isolated speech and gesture cues to examine if brain injury disrupts speech-gesture integration. All gestures were highly salient iconic gestures that were large, produced clearly, and embedded in an entertaining narrative, thus offering the best shot at capturing participants' attention. It is possible that people with TBI would have more difficulty relative to non-injured peers when processing speech and gesture in more dynamic settings such as dyadic or multiparty conversation or with the layering of multiple social cues. Although we see accumulating evidence of intact processing of social cues in isolation, including eye gaze (Mutlu et al., 2019), interpersonal distance (Mutlu et al., 2019), disfluencies (Diachek et al., 2023), and now gesture, the combinatorial effect of these cues have not been investigated in TBI.

Self-report from participants in this study suggest that some individuals may have difficulty processing language in rich communicative contexts. For example, three participants with TBI initially closed their eyes when asked to listen to and retell the stories and when prompted to watch the video of the narrator and said, "I was doing that to help my brain to focus on the story itself," and "I can't look at the screen. If I sit there and look at the person telling the story, I'll concentrate on what her mannerisms are and how she's saying it, and it will distract me from actually paying attention to what's being said." These direct quotes suggest that for some individuals, attending to, processing, and integrating both audio and visual information is difficult. More work is needed to understand when and how breakdowns in multimodal processing or integration occur and who is most at risk at the individual level.

4.2. Impaired narrative recall in TBI: The role of gesture and time

In the current study, we also demonstrated evidence of a memory impairment in our sample of TBI participants, who recalled fewer story details than their non-injured peers across timepoints. Memory disruption is highly prevalent in TBI, yet successful rehabilitation and community reintegration depends on (re)learning. Identifying ways to support memory and learning in this population is paramount for improving treatment outcomes. Given that participants with TBI showed successful integration in speech and gesture, it is possible that gesture could be leveraged to support learning and memory for individuals with TBI. Our group has demonstrated that even patients with hippocampal amnesia and severe memory impairment show benefits of gesture for comprehension and memory (Hilverman et al., 2018a; Hilverman et al., 2018b), suggesting that gesture may be weighted more heavily as a particularly salient resource when memory is severely disrupted. Indeed, despite recalling fewer details for stories overall, patients with amnesia were more likely to report information from gesture in their immediate retellings than non-injured and brain-damage comparison participants (Hilverman et al., 2018a). Although the current design did not test whether gesture improved memory for stories compared to a no-gesture condition, it is possible that the built in repetitions and use of gesture supported participants' memory for stories in the TBI group. Thus, more work is needed to identify the extent to which these factors support memory and learning in populations with cognitive-communication disorders.

Implementation of short and long delay timepoints was a critical feature of the current study's design. Although there is growing evidence that gesture supports long-term retention of learning in children (Congdon et al., 2017; Cook et al., 2008) and adults (Cook et al., 2010; Macedonia et al., 2011; Macedonia and Klimesch, 2014; Sweller et al., 2020), there is a need for more longitudinal studies to examine the durability of these benefits across all functions of gesture and in special populations. Critically, Congdon et al. (2017) found that differences in gesture training conditions only emerged after a delay, suggesting that study paradigms which do not extend testing beyond immediate timepoints may miss condition or group effects entirely. In the current study, participants were more likely to report information from gesture and produce gestures themselves one week later, suggesting that gesture may receive an additional boost during memory consolidation. The finding that the effect of the one-week delay on producing *Gesture Matches* did not differ by participant group suggests that the benefit of gesture is durable, even in individuals with TBI. This is particularly exciting as our group has recently shown that not only do people with TBI have difficulty with initial encoding of new information, but they also have increased difficulty holding onto it; in a word learning paradigm, people with TBI show immediate deficits in word learning relative to their non-injured peers, but this performance gap grew at the one-week post-test (Morrow et al., 2023). In addition to the inclusion of gesture, there are other factors that might have supported retention of learning in the current study. For example, learning was embedded in short entertaining narratives with built in rehearsal at the immediate and short-delay timepoints prior to the long-delay recall. Continued investigation into the factors that scaffold learning and memory and promote retention over time is needed. It is an open question whether gesture can boost learning, maintenance, and generalization of new learning in traumatic brain injury to narrow this gap.

4.3. Limitations and future directions

One limitation of the current study is the use of Zoom for data collection, a necessary design decision due to the Covid-19 pandemic. This resulted in inconsistent capturing of the participants' gesture space and impeded our ability to do a full analysis of gesture production. Still, we provide a novel finding that people with TBI did not differ from non-injured peers in their likelihood of producing representative gestures during narrative recall. This suggests that people with TBI can effectively use gesture to communicate. Studies of gesture production in TBI are limited, with one examining gesture production during a naming test (Kim et al., 2015) and others using rating scales of nonverbal or pragmatic language skills (Aubert et al., 2004; Rousseaux et al., 2010; Sainson et al., 2014). Much work is needed to examine the frequency, type, and functions of gesture after TBI, particularly in social interaction. For example, the gestures of non-injured participants reflect their sensitivity to others' knowledge states (Campisi and özyürek, 2013; Hilliard and Cook, 2016; Holler and Bavelas, 2017; Holler and Wilkin, 2009, 2011), and even patients with hippocampal amnesia who have severe declarative memory impairment modulate gesture height (Hilverman et al., 2019) and frequency (Clough et al., 2022) based on shared knowledge with their listener. Given that people with TBI can present with theory of mind and social cognition deficits (Lin et al., 2021; McDonald, 2013), future work should examine how people with TBI produce and adapt their gestures across communication contexts and partners.

Although often cited as a barrier, the inherent heterogeneity of cognitive and neural profiles in individuals with TBI affords the ability to unravel the mechanisms supporting cognitive functions and responsiveness to intervention (Covington and Duff, 2021). Future directions should leverage more naturalistic communication paradigms that reflect the language processing demands of everyday life to advance this study. Although gesture is an integral component of language, it is not routinely examined in studies of communication and language processing in individuals with neurogenic communication disorders. This omission gives us an incomplete understanding of their communicative abilities and hinders development of mechanistic accounts of cognitive-communication disorders. Consequently, gesture is also not routinely assessed in clinical practice when treating adults with neurogenic communication disorders. These results support the need for a multimodal approach to both assessment and treatment of language disorders. Ecologically valid assessments that reflect real-world complex communication demands in which listeners must integrate incoming information from multiple sources may be more sensitive to communication disruptions after brain injury. Further, we provide preliminary evidence that gesture may support comprehension and memory after brain injury, in which people with TBI showed intact integration and maintenance of gestured information over time. Expanding research paradigms to address maintenance and generalization of new learning is critical, as this is the goal of all speech-language rehabilitation.

5. Conclusion

These results expand our understanding of language comprehension of multimodal communication following traumatic brain injury. By studying speech and gesture together, this research more closely approximates the real-world communication contexts that characterize and enrich everyday life and yields more ecologically valid assessments. This approach may in turn inform mechanistic accounts of cognitive-communication disorders and new treatment targets to improve the communicative lives of people with TBI. This evidence of intact speech-gesture integration in TBI has exciting implications for future work exploring whether gesture may be leveraged in rehabilitation to improve learning and memory after TBI. Future work should build on this foundation to explore whether the cognitive and communicative benefits of gesture that are widely documented in non-injured individuals extend to patient populations with cognitive-communication disorders.

Credit author statement

Sharice Clough: Conceptualization, Methodology, Data Curation, Formal Analysis, Investigation, Writing – Original Draft, Visualization, Funding acquisition; Victoria-Grace Padilla: Data Curation, Writing – Review & Editing; Sarah Brown-Schmidt: Formal Analysis, Writing – Review & Editing, Supervision, Funding acquisition; Melissa C. Duff: Conceptualization; Resources, Writing – Review & Editing, Supervision, Funding Acquisition.

Data availability

Data will be made available on request.

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Appendix A. Carl Stories

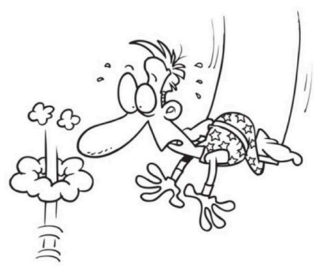
Carl Celebrates Halloween

For Halloween, Carl decided he wanted to be Frankenstein (**BOLTS**). He was going to a Halloween party, and he knew that the girl he liked would be there and he wanted to impress her. So, he went to the costume store and got bolts for his neck and one big google eye (**EYE**). Then on his way to the party, he stopped and got a flower (**PICKED/CUT**) to give to the girl. Before he even got to the party, he saw her outside and got excited and ran toward her, but she didn't recognize him and got scared so she hit him (**PUNCH/SLAP**).

Carl Chops Some Wood

Carl wanted to start a fire in his backyard, so he got an ax to split wood. All of his friends told him to get face protection (**GOGGLES/MASK**), but he didn't think he needed it. He took the ax outside and wildly chopped at the wood (**AX SWING**). His neighbor was watching and came over and asked if he'd chop some logs for her too. So, Carl got excited and chopped faster and faster and faster (**AX SWING**). And of course, when he least expected it, half of a log flew up and hit him in the face (**NOSE/FOREHEAD**)

Carl Cooks Dinner
Carl decided to try a new recipe for his friends when he had them over for dinner. He searched and searched (**BOOK/COMPUTER**) for a new recipe to try and finally found one for meatballs. He ground up the meet himself and then formed the meat into balls (**BALLS**). When his friends came over, he started cooking the meatballs (**OVEN/STOVE**). Then he went in the other room and talked and talked and talked (**TALK**) to his friends. But he forgot about the meatballs, and when he went back into the kitchen, they were burnt to a crisp.



Carl Goes to the Circus
One day, Carl decided to try his luck on the flying trapeze. He went to the store and bought a new outfit covered in stars (**STARS**) that he thought would make him look like a professional. Then he caught a ride (**HITCHHIKE/TAXI**) down to the nearby circus to talk to the ringmaster. The ringmaster was desperate for a trapeze artist and asked Carl to do his first show that very same night (**TONIGHT**). But Carl didn't mention that he had never actually been on a trapeze before, so as soon as Carl got up on the bar, he got scared and let go and flew off into the crowd (**FLIP/SOAR**).

Appendix B. Speech Coding Guide

In each story, the narrator produced four gestures. Two of these gestures were redundant gestures which depicted information overlapping with speech, and two of the gestures were complementary gestures which depicted new information that was not available in speech. The key words indicated in boldface represent the word the narrator said when she produced each gesture. When participants recall the details below, code their response as a *Speech Match* if they say the same word as the narrator, a *Gesture Match* if they say a word that reflects the narrator's gesture, and *Other* if their words do not directly match the narrator's speech or gesture. For complementary gestures, participants saw one of two versions listed in parentheses after the key word. Gesture matches depend on the version the participants saw. For example, a response of "She slapped him" would be coded as a *Gesture Match* if they saw the version where the narrator made a slapping movement on the phrase "She hit him" but would be coded as *Other* if they saw the version where the narrator made a punching movement. Details paired with redundant gestures can only be coded as *Speech Match* or *Other* since there is no unique information provided in gesture. See guide below for examples of responses corresponding to code categories.

KEY DETAIL	SPEECH MATCH	GESTURE MATCH	OTHER
Carl decided he wanted to be **Frankenstein**.	Frankenstein Frankenstein's monster	NA	zombie
He got bolts for his neck and one big googly **eye**.	Eye eyeball	NA	Stuff Things bolts
He stopped and **got** (PICKED/CUT) a flower to give to the girl.	Got Get	picked Picked up grabbed Cut Snipped trimmed	Bought Brought took
She got scared and she **hit** (SLAPPED/PUNCHED) him.	Hit hitting	slapped Smacked whacked Clocked socked popped decked walloped	Beat up
All of his friends told him to get face **protection** (GOGGLES/MASK).	protection	goggles Eye protection Safety glasses mask Face covering Face shield	Safety gear Something for his face

(*continued on next page*)

(*continued*)

KEY DETAIL	SPEECH MATCH	GESTURE MATCH	OTHER
		Head gear Head protection	
He wildly **chopped** at the wood.	chopped	NA	Split cut
Carl got excited and chopped **faster** and faster.	faster	NA	Wildly Frantically Quickly Sped up Excitedly vigorously crazy frenzied carried away Chopping and chopping harder
Half of a long flew up and hit him in the **face** (NOSE/FOREHEAD).	face	Nose Forehead head	Eye mouth
He **searched** and searched (BOOK/COMPUTER) for a new recipe to try.	searched	Cookbook Menu Recipe book Computer Online Internet Google	Looked Looked up
He formed the meat into **balls**.	Balls meatballs	NA	Patty Shape Circle
He started **cooking** (OVEN/STOVE) the meatballs.	cooking	Oven Put them in to cook Baking (sheet) Stove Put them on to cook frying pan	Fixing dinner
He went in the other room and **talked** to his friends.	talked	NA	(chit) chatted Conversations Speaking Entertaining Visited Hang out socializing
He bought a new outfit covered in **stars**.	stars star spangled	NA	Sparkly Flashy Shiny designs
He caught a **ride** (HITCHHIKE/TAXI) down to the nearby circus.	ride	hitched hailed Waved down Flagged down	Took a car Took a bus Went down Headed down Walked drove Hightailed traveled
The Ringmaster asked Carl to do his first show that very same **night**.	Night tonight	NA	Day evening
He let go and **flew** (FLIP/SOAR) off into the crowd.	flew	flipped Whirled Twirled Spun tumbled soared Flung Shot Flew straight	Fell Crashed Swung Let go Drops Slipped Plummeted sailed

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