Prospective and Retrospective Metacognitive Abilities and Their Association with Impaired Self-awareness in Patients with Traumatic Brain Injury

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Abstract

■ Metacognitive impairment often occurs in patients with traumatic brain injury (TBI) and is associated with clinical problems. The aim of this study was to clarify the pathology of metacognitive impairment in TBI patients using a behavioral task, clinical assessment of self-awareness, and lesion-symptom mapping. Metacognitive abilities of TBI patients and healthy controls were assessed using a modified perceptual decision-making task. Self-awareness was assessed using the Patient Competency Rating Scale and the Frontal Systems Behavior Scale. The associations between estimated metacognitive abilities, self-awareness, and neuropsychological test results were examined. The correspondence between metacognitive disabilities and brain lesions was explored by ROI-based lesion-symptom mapping using structural magnetic resonance images. Overall, 25 TBI patients and 95 healthy controls were included in the analyses. Compared with that in healthy controls, the prospective metacognitive ability of TBI patients was lower, with metacognitive evaluations revealing a bias toward overestimating their abilities. Retrospective metacognitive ability showed a negative correlation with self-awareness but not with neuropsychological test results. In the lesion-symptom mapping analysis, the left pFC was associated with lower retrospective metacognitive ability. This study contributes to a better understanding of the pathology of metacognitive and self-awareness deficits in TBI patients and may explain the cause of impaired realistic goal setting and adaptive behavior in these patients. ■

INTRODUCTION

Metacognition is the ability to internally evaluate and control one's cognitive processes and is a crucial adaptive behavior for everyday life (Fleming & Dolan, 2012; Flavell, 1979). Metacognitive impairments often occur after acquired brain injuries, such as traumatic brain injury (TBI) and stroke, which manifest as impaired self-awareness and performance monitoring (Dromer, Kheloufi, & Azouvi, 2021a; Al Banna, Redha, Abdulla, Nair, & Donnellan, 2016; Ham et al., 2014; Barrett, Dienes, & Seth, 2013; Bach & David, 2006; Schmitz, Rowley, Kawahara, & Johnson, 2006), leading patients to underestimate their disability or overestimate their performance (Al Banna et al., 2016; Ham et al., 2014; Barrett, 2010). These impairments can lead to major clinical problems as they are associated with reduced awareness of one's own disability and performance, decreased involvement in medical care and rehabilitation, and worse functional outcomes (Rouault & Fleming, 2020; Pessiglione, Vinckier, Bouret, Daunizeau, & Le Bouc, 2018; Fleming & Lau, 2014; Zylberberg, Barttfeld, & Sigman, 2012). Currently, metacognitive ability is predominantly assessed through discrepancy scores—a signed difference between the patient's self-rating and a proxy rater (e.g., caregiver, family member, or health professional; Dromer et al., 2021a; Al Banna et al., 2016; Ham et al., 2014; Bach & David, 2006; Schmitz et al., 2006). Limitations of this approach include potential rater bias and proxy raters inaccurately estimating the patient's true abilities (Al Banna et al., 2016; Bach & David, 2006).

Metacognitive ability can also be assessed through postdecisional confidence ratings, as humans compute decision confidence by monitoring self-performance and external evidence, such as stimulus intensity and RT (Gherman & Philiastides, 2015; Murphy, Robertson, Harty, & O'Connell, 2015; Fleming & Lau, 2014; Zylberberg et al., 2012). Despite extensive research focusing on postdecisional responses and confidence ratings, characteristics of prospective metacognitive ability—self-performance estimation before decision-making—remain unclear (Lak et al., 2020). Indeed, when deciding whether to undertake a task, we compute the probability of success and effort based on our prediction of self-performance and task difficulty (Pessiglione et al., 2018). Recent behavioral computation evidence suggests that our decision confidence contributes to the estimation of our global beliefs about our abilities (Rouault, Dayan, & Fleming, 2019). Furthermore, internally computed neural signs of confidence

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measured using EEG signals predicted the ongoing adjustment of decision policies (i.e., speed-accuracy trade-off; Desender, Boldt, Verguts, & Donner, 2019). These findings imply that decision confidence affects self-performance estimation and precise self-performance evaluation contributes to shaping behaviors. Although impairments in prospective and retrospective metacognition lead to maladaptive behavior in TBI patients, its pathology is unclear, and existing clinical self-awareness measures are unable to assess these two metacognitive aspects separately. Thus, evidence establishing a common or distinct mechanism between predecisional self-performance estimation and postdecisional self-performance monitoring in TBI patients is insufficient.

Neuroimaging studies indicate a close relationship between the networks of prefrontal and parietal brain areas in computing decision confidence (Qiu et al., 2018; Cortese, Amano, Koizumi, Kawato, & Lau, 2016; Lebreton, Abitbol, Daunizeau, & Pessiglione, 2015; Kepecs, Uchida, Zariwala, & Mainen, 2008). The pFC, specifically the orbitofrontal and medial pFCs, was identified as crucial for metacognition (Bang & Fleming, 2018; Bor, Schwartzman, Barrett, & Seth, 2017; Lak et al., 2014). Patients with anterior pFC lesions who underwent surgical resection for brain tumor or epilepsy treatment showed a selective deficit in postdecisional perceptual metacognitive accuracy (Fleming, Ryu, Golfinos, & Blackmon, 2014). Furthermore, patients with TBI who demonstrated low performance monitoring—measured as error correction ability—showed abnormal anterior cingulate cortex activity (Ham et al., 2014). Although these findings focus on postdecisional metacognitive judgment, brain regions involved in predecisional metacognitive judgment remain unclear. A neuroimaging study reported that global self-performance estimation was represented in the ventral striatum, ventromedial pFC, and precuneus (Rouault & Fleming, 2020). The decline in metacognition is thought to be related to pFC lesions; however, evidence demonstrating the correspondence between brain lesions and both aspects of metacognitive abilities (predecisional and postdecisional) is limited.

We aimed to clarify whether TBI patients have prospective and retrospective metacognitive deficits using behavioral metacognitive estimation based on perceptual decision-making tasks and if these deficits correlate with clinically assessed self-awareness. Furthermore, we tested the hypothesis that TBI patients show metacognitive bias toward overconfidence. Finally, exploratory lesion-symptom mapping was performed to provide insight into the correspondence between metacognitive deficits and brain damage areas in patients with TBI. We hypothesized that frontal lesions were related to metacognitive deficits in patients with TBI.

METHODS

Participants

The sample size was determined with a power analysis (alpha = 5%, power = 80%, d = 1.05–1.40, two-sided) using G*power (Faul, Erdfelder, Buchner, & Lang, 2009) based on a previous study of brain injury patients (Fleming et al., 2014). The required sample size was 20–32 to detect the differences in metacognitive ability in TBI patients.

We recruited 28 TBI patients and 105 healthy controls. To obtain a general distribution of metacognitive abilities, healthy controls aged 20–60 years were recruited. We included TBI patients who had a history of hospitalization or visited the Hokkaido University Hospital with a diagnosis of TBI at least 6 months after injury. Patients with mental illnesses, developmental diseases, and severe upper limb paralysis or aphasia, which could complicate task engagement, were excluded.

Study Protocol Approval, Registration, and Patient Consent

The study protocol was approved by the Ethics Committee of the Hokkaido University Hospital (Approval Number: 019–0398) and was registered in the University Hospital Medical Information Network Clinical Trial Registry (UMIN-CTR, Study ID: UMIN000043884). All participants provided written informed consent.

Stimuli and Experimental Task

We modified a task used to measure retrospective metacognition that has been implemented in many previous studies (Rouault & Fleming, 2020; Lebreton et al., 2015; Murphy et al., 2015; Fleming et al., 2014; Fleming & Lau, 2014) and presented it using Psychopy (v3.1.0; Peirce et al., 2019). The prediction rating, perceptual discrimination, and confidence rating phases were contained in one trial (Figure 1). For each trial, participants were first presented with the number of dots to be compared (e.g., 7 vs. 10 dots) to indicate the task difficulty and then asked to predict their performance in 4 sec on a scale from 1 (*certainly wrong*) to 4 (*certainly correct*). Next, two gray circles containing differing numbers of white dots were presented for 0.3 sec, and participants were asked to identify the circle with the higher number of dots as quickly as possible. The difference in the number of dots between the right and left circles varied from one to three dots, and the total number of dots in both circles varied from 15 to 31. The position of each dot was randomly selected from 21 positions. The difficulty of the perceptual discrimination task was determined as a function of the difference in the number of dots between the two circles and the total number of dots in both circles.

After the task, participants estimated their confidence in each decision from 1 (*certainly wrong*) to 4 (*certainly correct*) in 3 sec. Participants performed 192 trials divided into four blocks after performing 15 practice trials. They were free to rest at the completion of each block. The order of each trial and block was randomized for each participant. For TBI patients, there was no time limit for prediction and confidence rating, and they performed 30

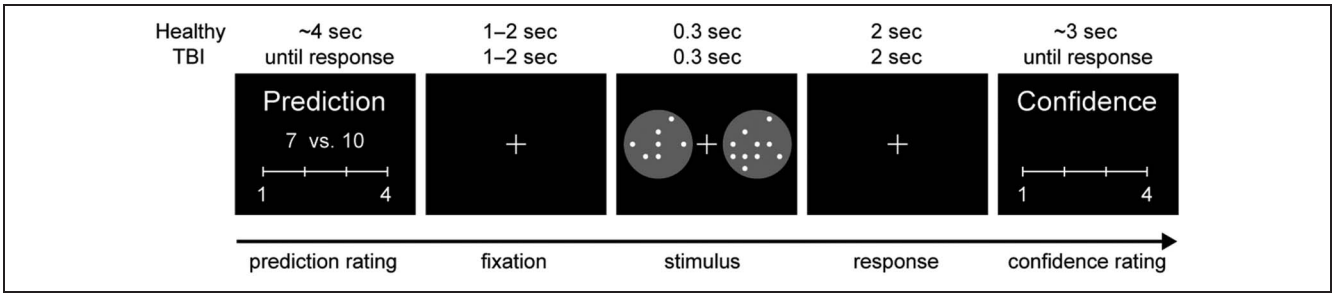

Figure 1. The trial consisted of prediction rating, perceptual discrimination, and confidence rating. Participants had to judge which of the two circles contained a greater number of dots. The difficulty of perceptual discrimination was decided based on the difference in the number of dots between the left and right circles and the total number of dots contained in both circles. Before perceptual discrimination, the number of dots to be compared (e.g., 7 vs. 10) was presented to provide information on the task difficulty, and participants estimated their ability to perform perceptual discrimination on a 4-point scale. After the perceptual discrimination task, they estimated their confidence in each judgment on a 4-point scale. No time limits were placed on TBI patients for prediction and confidence rating.

practice trials before the task. The remaining task settings were the same as those used for healthy controls.

Self-awareness and Neuropsychological Tests

For assessing self-awareness, we employed the Patient Competency Rating Scale (PCRS) and the Frontal Systems Behavior Scale (FrSBe), which are self-proxy rating discrepancy measures, comparing patients' self-assessments of their abilities with proxies—a relative or clinician.

The PCRS (Prigatano & Altman, 1990) is a widely used assessment for clinically evaluating self-awareness on a broad range of abilities (Dromer et al., 2021a) composed of 30 items, each scored on a 5-point scale ranging from 1 (*cannot do*) to 5 (*can do with ease*). A discrepancy score is calculated as total patient's–total proxy ratings scores. Thus, a positive score indicates an overestimation of one's ability compared with that estimated by the proxy. The PCRS has good internal consistency (Cronbach's alpha > .90).

The FrSBe (Stout, Ready, Grace, Malloy, & Paulsen, 2003; Grace, Stout, & Malloy, 1999) measures behaviors associated with frontal system damage using 46 items, each scored on a 5-point scale ranging from 1 (*almost never*) to 5 (*almost always*). A total score and three subscale scores (apathy, disinhibition, and executive dysfunction) are calculated and converted into a standardized (*T*) score. The scale includes ratings of patient behavior before and after injury, by patients and proxies. To calculate the discrepancy score, first, the difference in total *T* score before and after TBI is calculated for the patient and proxy and then the proxy's score is subtracted from the patient's score. To align the signs of the PCRS and FrSBe, the discrepancy score of the FrSBe was inverted, with positive scores indicating overestimation of ability and vice versa. The FrSBe has been reported to have good reliability (Cronbach's alpha = .88–.92) and validity (Stout et al., 2003).

Moreover, we assessed the cognitive decline commonly experienced after TBI using neuropsychological tests, including the Mini-Mental State Examination, the Symbol Digit Modalities Test, the Paced Auditory Serial Addition Test, the Rey's Auditory Verbal Learning Test as a memory function test, and the Wisconsin Card Sorting Test as an executive function test. The Symbol Digit Modalities Test and Paced Auditory Serial Addition Test scores were converted into standardized scores to account for age-related effects.

Considering patient fatigue, the TBI group underwent neuropsychological testing on a different day within 2 weeks. An honorarium of 2000 yen (healthy controls) or 14,000 yen (TBI group) was paid after all procedures.

Data Analysis

Quantifying Metacognitive Ability

We collected data for the accuracy and RT of perceptual discrimination, prediction, confidence rating, and RT for each rating from the perceptual decision-making task. To determine the participants' performance, we computed the discriminability index (d') based on the signal detection theory, which represents perceptual sensitivity. For metacognitive ability, we computed the metacognitive sensitivity (meta-d')—the ability to distinguish between one's correct and incorrect judgments, and metacognitive bias—the tendency to report confidence ratings that are too high or too low relative to one's performance (Seow, Rouault, Gillan, & Fleming, 2021; Fleming & Lau, 2014; Maniscalco & Lau, 2012). We modified an MATLAB code for calculating metacognitive sensitivity from the rating data, available at https://www.columbia.edu/~bsm2105/type2sdt/ (Fleming & Lau, 2014). Next, we computed the m-ratio index (meta-d'/d'), a measure that controls the influence of perceptual sensitivity (d') on metacognitive sensitivity (meta-d'). The m-ratio is the participant's level of metacognitive sensitivity given a certain level of task performance, which is known as metacognitive efficiency (Qiu et al., 2018; Fleming & Lau, 2014). These computations were applied for both prediction and confidence ratings.

In addition, to compare the effects of independent variables as predictors of accuracy in the perceptual decision-making task, we fit our data into a logistic regression

model. To match the prediction and confidence rating scales with task difficulty, we divided the sorted data into four categories by assigning scores from 1 to 4, starting with the lowest difficulty. The dependent variable was the dummy-coded value of correctness (1, correct response; 0, incorrect response), and the independent variables were prediction rating, confidence rating, and task difficulty. Intercepts and coefficients were calculated for each independent variable and participant. High coefficient values indicate that the independent variables have a high impact on response accuracy. Therefore, we can infer the effectiveness of the participants' prediction and confidence ratings for predicting correct and incorrect responses by comparing each coefficient. Notably, we did not compare the scores of healthy controls with those of TBI patients, as these values can be affected by the percentage of correct responses.

Drift-diffusion Model

The perceptual decision-making performance was characterized using the drift-diffusion model (DDM)—a type of sequential sampling model that assumes that choice is a process comprising a noisy accumulation of evidence from a stimulus. We applied the hierarchical Bayesian estimation of DDM parameters for each participant using the HDDM 0.6.0 toolbox in Python (Wiecki, Sofer, & Frank, 2013). Our model was fit to accuracy-coded data with three free parameters: nondecision time (t), decision threshold (a), and drift rate (v), and the starting point was fixed at $a/2$. To ensure the independence of the estimated parameters, each participant's data were fit separately and not incorporated into the hierarchical model. The upper (lower) boundary indicates correct (incorrect) responses. The HDDM uses Markov chain Monte Carlo sampling to approximate the posterior distribution over parameter estimates. For parameter estimation, three chains were run, each with 2000 samples, and the first 500 samples in each run were discarded as burn-in. In addition, we calculated Gelman and Rubin's $\hat{R}$ for each parameter to assess convergence. We extracted mean posterior estimate parameters for the subsequent statistical tests.

Lesion-symptom Mapping

We conducted lesion-symptom mapping to explore the relationships among metacognitive efficiency (m-ratio), self-awareness, and damaged brain areas. This analysis was based on patients' structural magnetic resonance imaging (MRI) scans conducted in the clinical stage. Imaging data were available for 25 patients, and all MRI data were collected from the Hokkaido University Hospital. Three patients' MRI data (P17, P21, and P22 in Table 1) were unavailable. The MRI sequences of the fluid-attenuated inversion-recovery image had significant variability in the repetition time (9000–12,000 msec), the echo time (109–120.4 msec), field of view (240×240 mm^2, or 240×180 mm^2), slice thickness = 3–5 mm, and the number of slices acquired (19–48) as MRI data were pooled for clinical use. Twenty-four patients had fluid-attenuated inversion-recovery images, and one had a T2-weighted image (repetition time = 4500 msec, echo time = 96 msec, field of view = 240×240 mm^2, slice thickness = 5 mm, the number of slices acquired = 19) for demarcation of lesions.

First, K.Y. outlined lesions using MRIcroN (https://www.nitrc.org/projects/mricron) before the behavioral data analysis. Then, two experienced investigators (D.S. and K.I.) who were blinded to the behavioral data checked and corrected the mapped lesions. After setting the AC-PC line manually, we used the Clinical Toolbox (Rorden, Bonilha, Fridriksson, Bender, & Karnath, 2012) run in SPM12 (https://www.fil.ion.ucl.ac.uk/spm/software/spm12/) to normalize the lesions, and the resampled voxel size was $1 \times 1 \times 1$ mm^3. We statistically analyzed the normalized lesions using NiiStat (https://www.nitrc.org/projects/niistat/) in MATLAB R2021a (The Math Works, Inc.). Finally, we visualized the results of statistical maps in MRIcroGL (https://www.nitrc.org/projects/mricrogl/). As the injury area of TBI patients is often dispersed, which may reduce statistical power, we performed two complementary methods to correlate lesion location with behavioral data in patients—voxel-based lesion-symptom mapping (VLSM) and ROI-based lesion-symptom mapping (RLSM). The Atlas of Intrinsic Connectivity of Homotopic Areas (AICHA), a gray matter atlas included in NiiStat that is a representative functional brain atlas of higher functional homogeneity in the ROI than that in an anatomical atlas, was applied to the RLSM analysis (Joliot et al., 2015).

Statistical Analysis

We conducted independent-samples t tests to compare accuracy rate, RT, and DDM parameters between the groups. Metacognitive efficiency (m-ratio) was analyzed using a two-way analysis of covariance (ANCOVA) with group (healthy controls or TBI patients) as a between factor, rating (prediction rating or confidence rating) as a within factor, and the factors of age and sex as covariance. We analyzed metacognitive bias using independent-samples t tests. To adjust for the effect of age and sex, we performed an ANCOVA with Group as the between factor and Accuracy Rate, Age, and Sex as covariance. To clarify the association between self-awareness and metacognitive ability, we conducted correlation analyses between self-awareness tests (PCRS and FrSBe) and metacognitive efficiency (meta-d'/d' of prediction and confidence), with false discovery rate correction. In addition, to clarify whether metacognitive ability correlates with neuropsychological tests of attention, memory, and executive function, we also conducted correlation analyses between metacognitive efficiency (meta-d'/d' of prediction and confidence) and neuropsychological tests. For fitting the

Table 1. Patient Information

Patient Number	*DH/Period Of Education (Years)*	*TSI (Years)*	*Coma-related Information from Medical Records*	*Lesion Location and Pathology*
P01	R/17	12.39	Comatose state	Brain contusion in the right TL and bilateral FL
P02	L/14	10.52	JCS score = 2	Brain contusion in the right FL, traumatic SAH
P03	R/12	26.47	Coma duration > 2 weeks	DAI and brain contusion in the FL
P04	R/12	11.17	JCS score = 200	DAI and brain contusion in the right TL
P05	R/16	6.16	GCS score = 4, JCS score = 200	Hemorrhagic DAI
P06	R/12	30.04	Coma duration > 4 weeks	Brain contusion in the right FL, traumatic SAH
P07	R/24	19.07	Coma duration > 4 weeks	Brain contusion in the bilateral FL
P08	R/16	15.08	GCS score = 4, JCS score = 200	DAI and brain contusion the bilateral TL and FL
P09	R/12	12.12	GCS score = 9, JCS score = 100	DAI in the cerebellum, brain contusion in the right TL
P10	R/12	9.63	GCS score = 12	Microbleeding in the right FL and TL
P11	R/18	13.22	JCS score = 200	Microbleeding in the left FL and cerebellum
P12	R/13	38.65	Coma duration > 4 d	DAI in the FL
P13	R/15	1.33	JCS score = 300	Hemorrhagic DAI, brain contusion in the left TL
P14	R/12	8.89	GCS score = 11	DAI in the right FL
P15	R/18	12.44	Coma duration > 7 weeks	Brain contusion in the left FL and TL
P16	R/17	3.92	GCS score = 8	Hemorrhagic DAI, brain contusion in the bilateral TL and FL
P17	R/17	24.56	Coma duration > 4 weeks	Brain contusion in the bilateral FL, acute epidural hematoma
P18	R/12	40.06	Coma duration > 4 days	Brain contusion in the bilateral TL and FL
P19	R/12	26.21	Coma duration > 12 weeks	Brain contusion in the bilateral TL and FL
P20	R/16	10.18	JCS score = 200	Brain contusion in the right FL, TL, and PL
P21	R/13	6.00	N/A	DAI, brain contusion in the left PL and FL
P22	L/12	18.50	Coma duration > 4 weeks	No detailed record, a left FL lesion
P23	R/15	12.93	Transient loss of consciousness	Brain contusion in the right TL
P24	R/14	28.39	JCS score = 300	Brain contusion in the right FL and PL
P25	R/14	28.52	Coma duration > 4 weeks	Brain contusion in the left TL and right FL
P26	R/10	31.98	Coma duration > 1 week	Brain contusion in the left TL
P27	R/12	10.87	Coma duration > 4 weeks	Brain contusion in the left TL and FL
P28	R/12	17.49	Coma duration > 4 weeks	DAI

coefficients of the logistic regression model for prediction, confidence, and task difficulty, we conducted a repeated-measures ANOVA for each group. When a significant difference was found, we conducted a post hoc paired *t* test with Bonferroni correction. In the VLSM and RLSM analyses, we included lesions with an overlap for ≥ four patients and conducted a one-tailed test with the Freedman-Lane permutation test (5000 times) to control for the effects of time since injury and lesion volume using NiiStat options. All statistical analyses except VLSM and

RLSM were conducted using R 4.1.0 and R studio (R Foundation for Statistical Computing), and the significance level was set at .05.

RESULTS

Ten healthy controls (no response trials over 20% [n = 3], logistic regression coefficients exceeding the mean ± 3 *SD*s [n = 7]) and three TBI patients (insufficient number of trials because of pressing the wrong key [n = 1], right eye blindness [n = 1], and metacognitive efficiency [m-ratio] exceeding the mean ± 3 *SD* [n = 1]) were excluded from the statistical analysis. Participants with these outliers exhibited biased responses (e.g., excessive concentration on one or two ratings); therefore, the calculated values may not reflect metacognition. In total, 95 healthy controls and 25 TBI patients were included in the statistical analysis and 22 TBI patients (mean age, 43.82 ± 8.89 years, range [25–57 years]; female, 6; education level, 14.23 ± 3.19 years) in the VLSM and RLSM analyses.

Behavioral Task Validity

Previous studies have shown that higher accuracy and shorter RT are related to higher confidence ratings (Seow et al., 2021; Desender et al., 2019; Bang & Fleming, 2018), which we sought to assess using our new behavioral task. Indeed, these associations were observed in both prediction (accuracy: $F[3, 350] = 19.76$, $p < .001$; RT: $F[3, 350] = 1.83$, $p = .14$) and confidence (accuracy: $F[3, 361] = 50.46$, $p < .001$; RT: $F[3, 361] = 9.34$, $p < .001$) ratings in healthy participants, thereby confirming task validity (Figure 2).

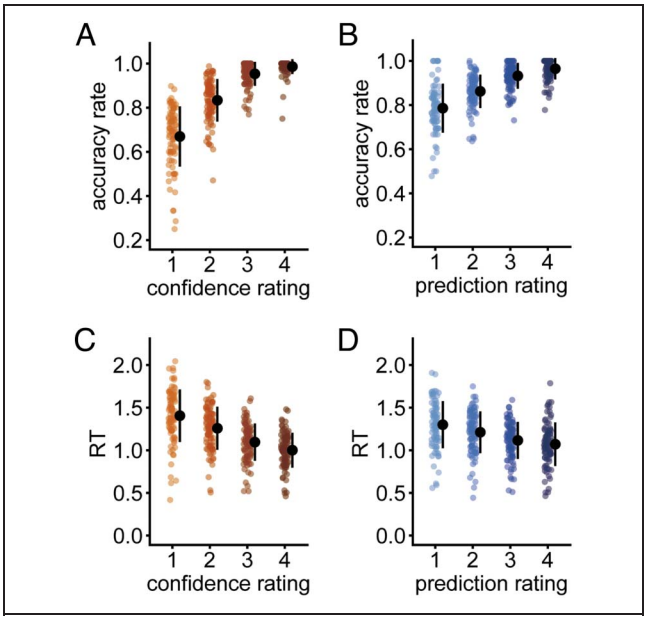

Figure 2. Relationship between response to stimuli of perceptual decision-making and confidence (A, C) and prediction (B, D) ratings. The higher accuracy and shorter RT relate to higher confidence and prediction ratings. Dot plots show data for each healthy participant, and error bars indicate standard deviation.

Perceptual Discrimination Performance

TBI patients showed a low accuracy rate for perceptual discrimination, with no differences in RT. From the DDM analysis, this performance difference was only related to the drift rate. Decision threshold and nondecision time were not statistically different between groups (Table 2). The ranges of the value in all parameter estimates in both groups indicated satisfactory convergence (healthy: 0.999–1.017; TBI: 0.999–1.004).

Table 2. Groupwise Comparison of Demographic Data and Perceptual Decision-making Task Performance

	Healthy n = 95	*TBI n = 25*	*Statistics*	*95% CI*	*p Value*
Age (years)	38.72 (11.77)	43.7 (8.9)	$t(48.5) = 2.32$	0.67, 9.32	.024
Sex (female), *n*	55	6			.003
Period of education (years)	15.45 (2.17)	14.02 (3.08)	$t(30.6) = -1.91$	−2.59, 0.08	.06
TSI (years)		13.22 (10.9–26.2)			
MMSE score		28.04 (1.90)			
Accuracy, *n* (%)	89.3 (3.9)	78.8 (5.9)	$t(29.9) = 8.46$	0.08, 0.13	< .001
RT (sec)	1.16 (0.23)	1.25 (0.25)	$t(35.3) = -1.76$	−0.20, 0.015	.08
Decision threshold	1.98 (0.38)	1.83 (0.32)	$t(43.9) = 1.89$	−0.01, 0.29	.06
Nondecision time	0.54 (0.17)	0.58 (0.19)	$t(34.4) = -1.1$	−0.13, 0.04	.28
Drift rate	1.31 (0.29)	0.83 (0.25)	$t(44.3) = 8.2$	0.36, 0.59	< .001

Values are expressed as the mean (standard deviation) or number (%) unless otherwise indicated. Only TSI is expressed as the median (interquartile range). Welch *t* test and Fisher's exact test were conducted.

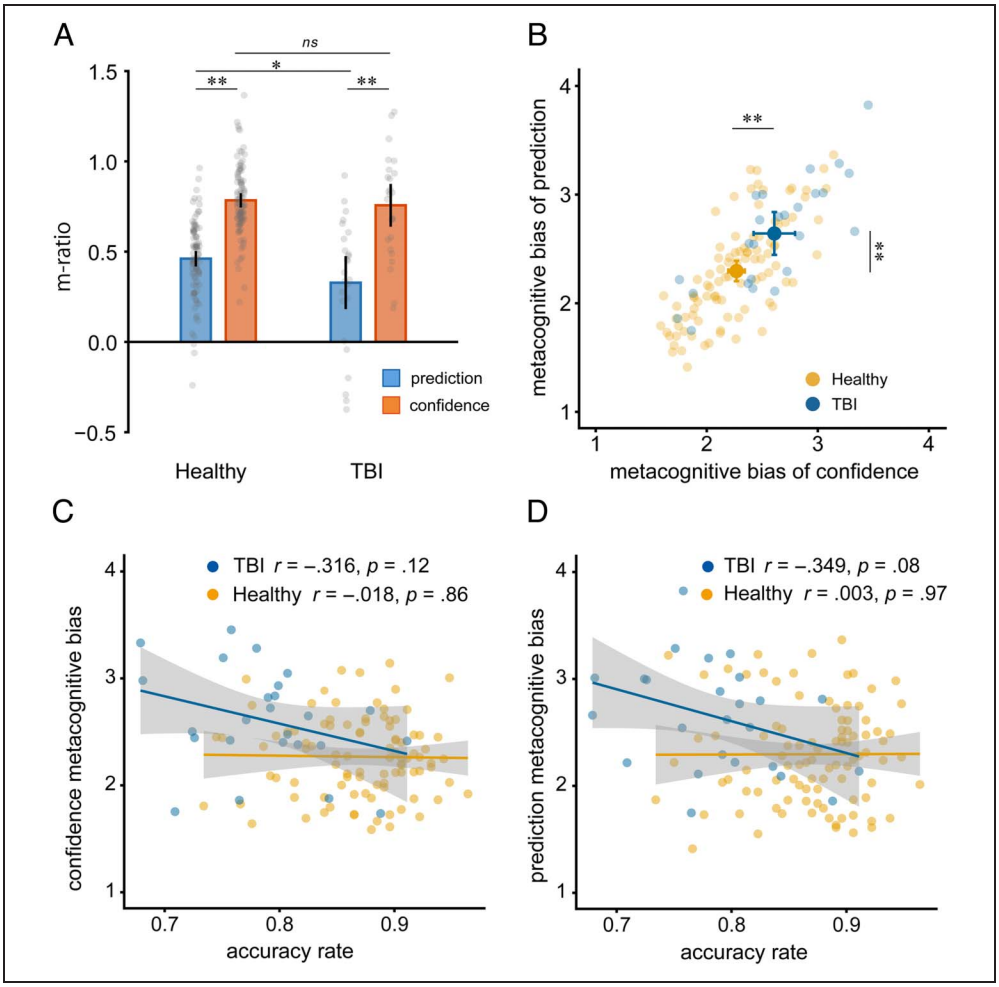

Figure 3. The results of group comparison in (A) m-ratio and (B) metacognitive bias for prediction and confidence ratings. The correlation between metacognitive bias of confidence and accuracy rate in the perceptual decision-making task (C) and the metacognitive bias of prediction and accuracy rate in the perceptual decision-making task (D). Dot plots show each participant's data, and error bars indicate standard errors. m-ratio = meta-d'/d'; *ns* = not significant; *$p < .05$, **$p < .01$.

Metacognitive Efficiency of Prediction and Metacognitive Bias

The two-way ANCOVA of metacognitive efficiency (m-ratio) revealed Condition, $F(1, 234) = 101.11$, $p < .001$, $\eta^2 = .43$, and Group, $F(1, 234) = 4.53$, $p = .034$, $\eta^2 = .02$, main effects, but no interaction, $F(1, 234) = 1.66$, $p = .198$. To assess group differences in metacognitive efficiency, we conducted an independent-samples t test as a post hoc analysis. TBI patients showed a lower m-ratio of prediction than that in healthy controls, $t(118) = 2.39$, $p = .018$, 95% CI [0.02, 0.24], $d = 0.54$, but the m-ratio of confidence was statistically comparable, $t(118) = 0.69$, $p = .48$, 95% CI [−0.06, 0.13], $d = 0.16$. In addition, the m-ratio of confidence was significantly higher than the m-ratio of prediction in both groups, healthy: $t(94) = 12.42$, $p < .001$, 95% CI [0.27, 0.38], $d = 1.58$; TBI: $t(24) = 5.19$, $p < .001$, 95% CI [0.26, 0.59], $d = 1.32$ (Figure 3A). The two-way ANCOVA of metacognitive bias revealed a Group, $F(1, 233) = 6.33$, $p = .012$, $\eta^2 = .03$, main effect, but no Condition, $F(1, 233) = 0.21$, $p = .65$, main effect or interaction, $F(1, 233) = 0.001$, $p = .97$. In the post hoc independent-samples t test, TBI patients showed significantly higher metacognitive bias in both

Table 3. Correlation Matrix between Metacognitive Ability and Clinical Assessments

n = 25	*Mean (SD)*	*Confidence m-ratio*	*Prediction m-ratio*
FrSBe (discrepancy score)	5.3 (18.2)	−0.45*	0.08
PCRS (discrepancy score)	15.8 (27.2)	−0.46*	0.07
Attention (z value)	−1.53 (1.24)	0.19	0.37
Executive function (categories completed)	3.68 (1.72)	−0.05	−0.09
Memory (%; delayed recall)	45.3 (20.5)	0.19	0.17

*$p < .05$.

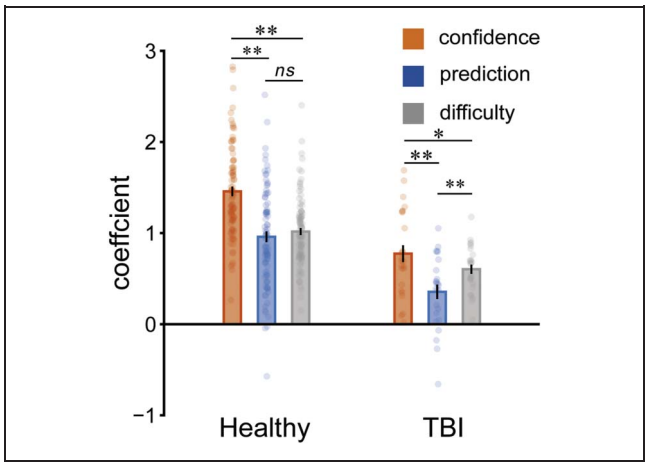

Figure 4. The results of comparison of logistic regression coefficients between prediction, confidence, and task difficulty in each group. *ns* not significant; *$p < .05$, **$p < .01$.

prediction, $t(118) = 3.24, p = .002$, 95% CI [0.13, 0.55], $d = 0.73$, and confidence, $t(118) = 3.82, p < .001$, 95% CI [0.16, 0.52], $d = 0.86$, ratings than that in healthy controls (Figure 3B). The TBI patients' metacognitive bias was weakly correlated with the accuracy rate of perceptual discrimination, but these correlations were not statistically significant (Figure 3C, D).

Metacognitive Efficiency and Self-awareness

There was a positive correlation between PCRS and FrSBe scores ($r = .75, p < .001$). Importantly, the m-ratio of confidence showed negative correlations with PCRS ($r = -.46, p = .041$) and FrSBe ($r = -.45, p = .041$) scores, indicating that low metacognitive efficiency is associated with overestimation of one's own abilities and underestimation of disability. Conversely, the m-ratio of prediction was not correlated with PCRS ($r = .07$) or FrSBe ($r = .08$) scores. In addition, the m-ratios for prediction and confidence were not correlated with any other neuropsychological tests (Table 3).

Logistic Regression Analysis

In both groups, the main effects of the coefficients were identified in the repeated ANOVA, healthy: $F(2, 282) = 28.22, p < .001, \eta^2 = .17$; TBI: $F(2, 72) = 7.62, p < .001$,

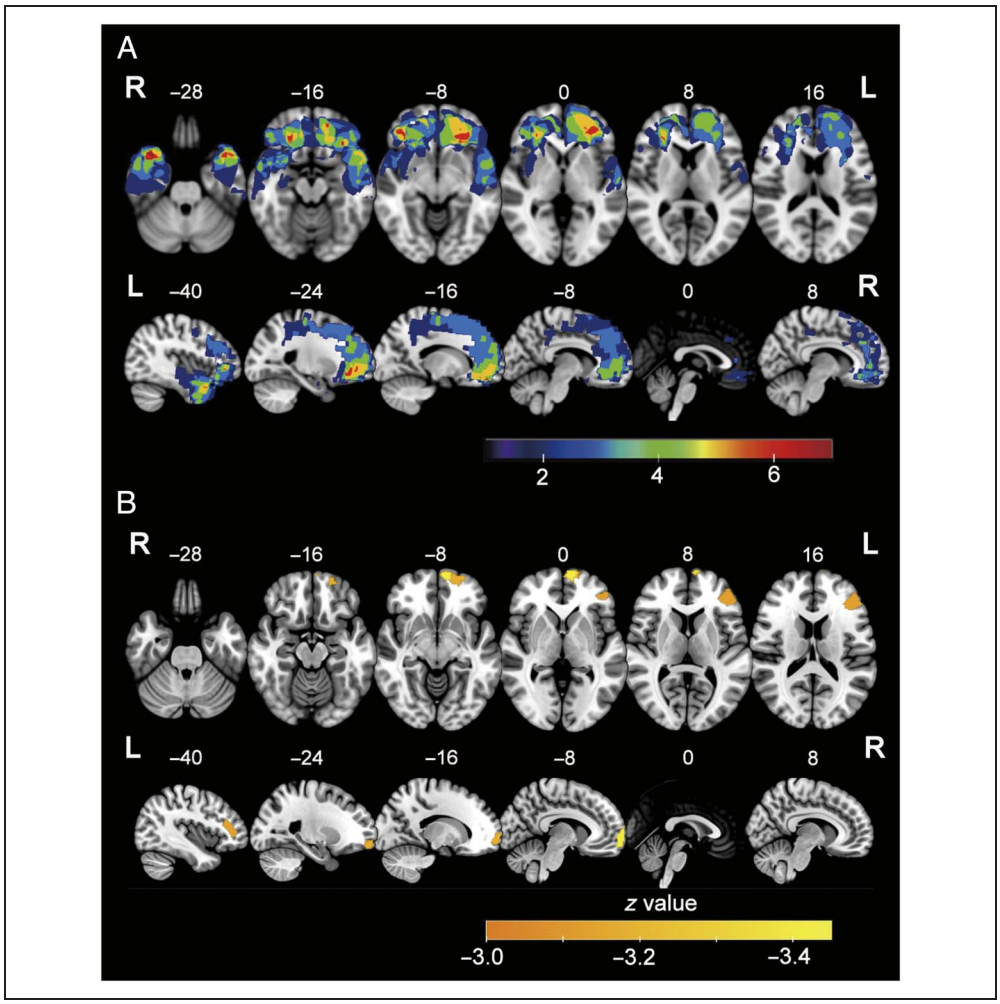

Figure 5. (A) Map of overlapping brain lesions for all TBI patients included in lesion-symptom mapping ($n = 22$). (B) In the lesion-symptom mapping analysis, the left orbitofrontal, left dorsolateral prefrontal, and left anterior pFCs were significantly associated with metacognitive efficiency of confidence. Only the colored areas exceeded the statistical threshold.

$\eta^2 = .17$. The post hoc analysis using t tests revealed that the coefficient for the confidence rating was higher than that for the prediction rating, $t(94) = 7.50$, $p < .001$, 95% CI [0.37, 0.63], $d = 0.91$, and task difficulty, $t(94) = 7.78$, $p < .001$, 95% CI [0.32, 0.55], $d = 0.96$, in the healthy group, with no difference between the coefficient for prediction rating and task difficulty, $t(94) = 1.08$, $p = 0.28$, 95% CI [−0.04, 0.16], $d = 0.12$ (Figure 4). In the TBI group, the coefficient for the prediction rating was lower than that for the confidence rating, $t(24) = -4.64$, $p < .001$, 95% CI [−0.23, 0.61], $d = -0.97$, and task difficulty, $t(24) = -3.65$, $p = .001$, 95% CI [−0.11, 0.38], $d = -0.74$, with a difference between coefficients for confidence and task difficulty, $t(24) = 2.26$, $p = .033$, 95% CI [0.01, 0.32], $d = 0.46$ (Figure 4).

VLSM and RLSM Analysis

In the VLSM analysis, no lesions survived the significance threshold. In the RLSM analysis using the AICHA, the left orbitofrontal cortex ($z = -3.41$, Montreal Neurological Institute [MNI] coordinates $[x, y, z] = -6, 60, -14$), left anterior pFC ($z = -3.18$, MNI coordinates $[x, y, z] = -22, 61, -8$), and left dorsolateral pFC ($z = -3.13$, MNI coordinates $[x, y, z] = -44, 38, 12$) were associated with metacognitive efficiency of confidence (Figure 5), suggesting that a decreased m-ratio of confidence is associated with brain damage in the left pFC. No other damaged regions were associated with self-awareness scale scores (PCRS and FrSBe) and m-ratio of prediction.

DISCUSSION

To clarify the pathology of impaired metacognition in TBI patients, we assessed prospective and retrospective metacognition using a behavioral task and examined the association between estimated metacognitive ability and clinical assessments.

TBI patients showed significantly lower accuracy and drift rates in decision formation than that in healthy controls. TBI patients found the perceptual decision-making task more challenging compared with healthy controls because a lower drift rate indicates less certain decisions. Moreover, while metacognitive efficiency for confidence did not differ between the groups, metacognitive efficiency for prediction was significantly lower in TBI patients. The result indicated that TBI patients had a similar level of metacognition of confidence compared with healthy controls, although they had particularly impaired metacognition of prediction, which is required before engaging in a task. Furthermore, we found that TBI patients had a significantly higher metacognitive bias in both prediction and confidence than healthy controls. The high metacognitive bias despite poor decision-making performance suggests that TBI patients may overestimate their abilities relative to healthy controls. Thus, consistent with previous studies (Vanderploeg, Belanger, Duchnick, & Curtiss, 2007; Bach & David, 2006), we found behavioral and quantitative evidence that TBI patients overestimate their abilities (or underestimate task difficulty) and optimistically estimate the results of their actions. Recently, it has been suggested that high confidence in decisions modulates postdecision neural processing and leads to the elimination of evidence that contradicts one's own decisions (Rollwage et al., 2020; Peters et al., 2017). Thus, the high metacognitive bias may explain some of the cognitive disability and behavioral inflexibility observed in TBI patients (Jilka et al., 2014; Kinnunen et al., 2011). Interestingly, we observed a tendency toward higher metacognitive bias in patients with lower accuracy rates. It can be hypothesized that impaired decision-making performance was associated with increased metacognitive bias and overestimation of oneself; however, this finding should be further explored in larger samples.

In the correlation analysis, a clinically important finding is that metacognitive efficiency (m-ratio) of confidence, and not prediction, was significantly correlated with PCRS and FrSBe scores, which are widely used as self-awareness rating measures for TBI patients (Dromer et al., 2021a). These findings suggest that self-awareness is supported by the self-monitoring ability rather than the self-performance estimation. Although this implication is consistent with previous studies (Dockree, Tarleton, Carton, & FitzGerald, 2015; Robertson & Schmitter-Edgecombe, 2015; Ham et al., 2014), we explicitly demonstrate the different contributions of the two metacognitive aspects to self-awareness by using a behavioral task. Considering the possibility that the self-proxy rating discrepancy score might include rater bias (Al Banna et al., 2016; Bach & David, 2006), measuring TBI patients' self-awareness using a behavioral task was clinically useful.

Previous review articles (Dromer, Kheloufi, & Azouvi, 2021b) have identified executive function, severity of disability, and impaired social cognition as predictors of impaired self-awareness (Dromer et al., 2021a). In this study, however, metacognitive efficiency did not correlate with any neuropsychological measures of attention, memory, executive function, and post-injury duration. This may suggest that metacognitive efficiency, as measured using a behavioral task, was independent of executive function, attention, and memory.

To compare the effects of prediction and confidence ratings and task difficulty on accuracy rates, we fitted our data into logistic regression models for each group. The task difficulty was defined as a function of the difference in the number of dots between the two circles and the total number of dots in both circles; therefore, if individual factors such as the estimation of one's ability and self-performance monitoring were considered in the prediction and confidence ratings, these ratings would have a higher effect on the accuracy rate versus task difficulty. Contrary to intuition, the effect of prediction rating was

similar to task difficulty in healthy controls, whereas this effect was significantly smaller than task difficulty in TBI patients. Consistent with the results of the metacognitive efficiency analysis, the effect of confidence rating was significantly higher than that of prediction rating in both groups; however, the effect of confidence rating for TBI patients was similar to the task difficulty. These results indicate that compared with healthy controls, TBI patients' confidence ratings did not have a gain (i.e., error detection and performance monitoring) over the task difficulty and that their ability to estimate their performance before the task did not reach the level where the actual task difficulty predicts accuracy rates. Thus, difficulty in estimating self-performance or task difficulty may lead to impaired ability in setting realistic goals and short-term task prediction (Dromer et al., 2021b; Fischer, Gauggel, & Trexler, 2004).

Lesion-symptom mapping suggested that the left anterior prefrontal and dorsolateral pFCs were related to decreased metacognitive efficiency of confidence. Generally, the medial pFC is the central area for the computation of local metacognition by confidence rating (Bang & Fleming, 2018), and the frontoparietal network, which includes the lateral prefrontal, frontopolar, and lateral parietal cortices, represents metacognition (Seow et al., 2021; Qiu et al., 2018; Cortese et al., 2016; Kepecs et al., 2008). Therefore, the left anterior prefrontal and left dorsolateral pFCs depicted in lesion-symptom mapping seem to be reasonable regions for metacognitive efficiency of confidence ratings. Notably, we did not detect a between-groups difference in metacognitive efficiency of confidence. One possible reason is that some TBI patients had impairments in metacognitive efficiency of confidence and some did not, and no group differences were detected. Conversely, no lesions were associated with self-awareness (PCRS and FrSBe) and metacognitive efficiency of prediction, possibly because metacognitive efficiency of prediction and self-awareness are complex and involve multiple regions in the brain. Indeed, lesion studies on TBI patients reported that multiple-site lesions predicted impaired self-awareness (Sherer, Hart, Whyte, Nick, & Yablon, 2005), and the neural bases remain unclear. Moreover, the power of RLSM to detect lesions related to self-awareness and metacognitive efficiency of prediction was possibly inadequate because of the limited sample size. Finding the corresponding lesions for impaired self-awareness and metacognitive efficiency of prediction may be achieved by adopting multivariate LSM (Price, Hope, & Seghier, 2017) for more critically selected samples and larger data sets.

This study has several limitations. First, there were age and sex differences between the healthy controls and TBI patients because we collected data from individuals with a wide age range to obtain a general distribution of the metacognitive ability of healthy controls. Second, we could not examine the effects of white matter injury, diffuse axonal injury, and brain atrophy on metacognition because we used AICHA, a gray matter atlas in LSM analysis. Third, we only conducted representative neuropsychological tests. More detailed assessments are needed to examine the independence of metacognition from other cognitive functions in future studies. Finally, the most critical limitation is the likely low power of the RLSM analysis because of the limited sample size. The RLSM analysis was exploratory and complementary and should therefore be interpreted with caution. Future studies are expected to validate these results with a larger sample size.

The current study findings contribute to a better understanding of the pathology of metacognitive disability and self-awareness deficits in TBI patients. We quantitatively assessed prospective and retrospective metacognition and demonstrated associations between metacognition and clinical assessment. In addition, we found that the brain lesion may be associated with retrospective metacognition based on our complementary analysis. Our results could explain the cause of impaired realistic goal setting and adaptive behavior in TBI patients. Furthermore, the results underscore the clinical utility of our task because it could avoid rater bias. The assessment of prospective and retrospective metacognition could be helpful in demonstrating the effectiveness of treatment and intervention for self-awareness and adaptive behavior in future studies.

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Data Availability Statement

The data and custom code used for the figures and statistics are available from the corresponding author (K.Y.) on reasonable request.

Author Contributions

Kazuki Yoshida designed the study and developed the protocol. Keita Ogawa, Takuroh Mototani, and Kazuki Yoshida collected the data. Daisuke Sawamura, Katsunori Ikoma, and Kazuki Yoshida analyzed the MRI data. Kazuki Yoshida conducted the statistical analysis. Kazuki Yoshida wrote the first draft of the manuscript, and Daisuke Sawamura and Shinya Sakai reviewed and edited the manuscript. All authors contributed to and have approved the final manuscript.

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Diversity in Citation Practices

A retrospective analysis of the citations in every paper published in this journal from 2010–2020 has revealed a persistent pattern of gender imbalance: Although the proportions of authorship teams (categorized by estimated gender identification of first-author/last-author) publishing in *Journal of Cognitive Neuroscience (JoCN)* during this time period were M(an)/M = .408 W(oman)/M = .335 M/W = .108 W/W = .149; the comparable proportions for the papers that these authorship teams cited were M/M = .579 W/M = .243 M/W = .102 W/W = .076 (Fulvio et al., *JoCN*, 33:1, pp. 3–7). Consequently, *JoCN* encourages all authors to consider gender balance explicitly when selecting which papers to cite, and gives them the opportunity to report their paper's gender citation balance.

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