Decision-making abilities under risk and ambiguity in adults with traumatic brain injury: what do we know so far? A systematic review and meta-analysis

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ABSTRACT

Traumatic brain injury (TBI) is a major health and socio-economic problem since it is one of the major sources of death and disability worldwide. TBI patients usually show high heterogeneity in their clinical features, including both cognitive and emotional/behavioral alterations. As it specifically concerns cognitive functioning, these patients usually show decision-making (DM) deficits. DM is commonly considered a complex and multistep process that is strictly linked to both hot and cold executive functioning and is pivotal for daily life functioning and patients' autonomy. However, the results are not always in agreement, with some studies that report huge alterations in the DM processes, while others do not. The present systematic review and meta-analysis aims to integrate past literature on this topic, providing a clear and handy picture both for researchers and clinicians. Thirteen studies addressing domain-general DM abilities were included from an initial N = 968 (from three databases). Results showed low heterogeneity between the studies ($I2 = 7.90$, $Q(12) = 13.03$, $p = .37$) supporting the fact that, overall, TBI patients showed lower performance in DM tasks as compared to healthy controls ($k = 899$, $g = .48$, 95% CI [0.33; 0.62]) both in tasks under ambiguity and under risk. The evidence that emerged from this meta-analysis denotes a clear deficit of DM abilities in TBI patients. However, DM tasks seemed to have good sensitivity but low specificity. A detailed description of patients' performances and the role of both bottom-up, hot executive functions and top-down control functions have been further discussed. Finally, future directions and practical implications for both researchers and clinicians have been put forward.

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Introduction

Traumatic brain injury (TBI) is a major health and socio-economic problem (Maas et al., 2008) and it is considered a "silent epidemic" since that about sixty-nine million (95% CI, 64–74) individuals are estimated to suffer from this pathology each year (Dewan et al., 2018). TBI represents a very heterogeneous disease characterized by a large variety of possible physical mechanisms of insult (e.g., closed or penetrating brain injury), type of injuries (focal and/or diffuse), and pathophysiology (Azouvi et al., 2017; McGinn & Povlishock, 2016; Pavlovic et al., 2019). Furthermore, other characteristics such as medical complications, chronicity of the injury, subjects' age, and pre-injury neuropsychiatric status directly impact patients' recovery trajectories (Ponsford, 2013). TBI patients are commonly classified as mild, moderate, or severe according to clinical features such as the level of consciousness (usually assessed by the Glasgow Coma Scale of 15–13: mild, 12–9: moderate and 8–3: severe) and the duration of post-traumatic amnesia (PTA; Sherer et al., 2008). All these variables interact with each other in determining the cognitive, emotional, and behavioral outcomes of TBI patients (Azouvi et al., 2017; Chen & Batchelor, 2019; Hart et al., 2016; McAllister, 2022; Ponsford et al., 2008, 2016; Ponsford & Wood, 2013; Williams et al., 2015), giving rise to the wide heterogeneity that is nowadays considered a hallmark and ineliminable characteristic of this clinical population (Covington & Duff, 2021).

More in-depth, as concerns cognitive disorders, TBI patients commonly suffer from a wide range of alterations that include speed of information processing (Madigan et al., 2000), attention (Dymowski et al., 2015; Mathias & Wheaton, 2007), memory, etc (Yeates et al., 2017). Moreover, considering that frontal lobes and anterior brain networks are vulnerable to TBI, it is not surprising that patients frequently exhibit alterations in "integrative/executive skills" (e.g., mental flexibility, planning, set-shifting, inhibition, working memory) and behavioral disorders (e.g., disinhibition,

impulsivity, irritability, aggressiveness) – (Azouvi et al., 2017; José et al., 2020; Ozga et al., 2018; Rabinowitz & Levin, 2014; Sherer & Sander, 2014). In addition, increasing evidence underlines the recurrence of social cognition deficits in emotions' perception (Rosenberg et al., 2018), empathy, theory of mind (McDonald, 2013) and an impairment in the moral cognition domain (Beauchamp et al., 2019; Rowley et al., 2018; Vascello et al., 2018). These deficits contribute, in different ways, to alterations in decision-making (DM) abilities, goal-oriented behaviors (Newcombe et al., 2011; Sherer & Sander, 2014) and in the ability to adapt to complex situations of daily life (see Azouvi et al., 2017 for a review), seriously affecting patients' quality of life (Franzen, 2000; Newcombe et al., 2011; Rabinowitz & Levin, 2014).

Specifically, DM is a complex and multistep (i.e., motivation, goal selection according to values assignment and expected outcomes, action selection, evaluation and execution, and monitoring) cognitive process (Mirabella, 2014) that involves the selection of an option among a set of choices (e.g., decision space; Rabinowitz & Levin, 2014). It plays a crucial role in solving adaptively everyday problems and dealing with interpersonal, social, and moral issues (Colautti et al., 2021) and is essential to maintain independence, autonomy, and a sense of competence throughout life (Mather, 2006; Rouault et al., 2019). It is worth noting that, in accordance with this complexity, it requires the interplay of several cognitive functions, including basic mechanisms such as memory, emotion/affect, and feeling, over than higher-level executive functions, to make decisions that are advantageous in the long term (Bechara & Van Der Linden, 2005; Rabinowitz & Levin, 2014). Additionally, it is also believed that DM, and the cognitive functions associated with it, are dependent on the task-set (Mirabella, 2014): for example, several studies support the evidence of a different involvement of functional networks and executive functions in DM under ambiguity (Iowa Gambling Task, IGT-like tasks), where the probability of a positive or negative outcome is unknown, and in DM under risk (Game of Dice Task, GDT-like task; Lauriola et al., 2007) where the probabilities of the occurrence of possible outcomes are known (see Brand et al., 2006). "Cold" executive functions, supported by a predominantly dorsolateral and top-down network that sustains attentional, executive, and control functions, have been associated both with tasks under risk conditions and in the last part of tasks under ambiguity (Brand et al., 2006; Wood & Worthington, 2017), while "hot" executive functions, supported by orbito-frontal/ventromedial pathways, would be mainly implicated in ambiguous conditions (Brand et al., 2006; Wood & Worthington, 2017) where an integration of hot and cold components is required (Colautti et al., 2021).

Even if the study of DM processes in TBI patients has a long tradition and pioneristic works (Bechara et al., 1994, 1997, 2005) had already highlighted clear alterations in different aspects of DM, these early studies have the main limitation to consider indiscriminately patients with different acquired brain injuries (i.e., vascular, traumatic, neoplastic, etc.) and therefore with underlying different pathophysiological mechanisms. From these preliminary works, the study of DM in neurological patients has grown exponentially; however, this has also led to a large number of articles considering so many different aspects of DM such as, for example, choices in specific domains (e.g., ethical, medical, moral, etc.), which might involve different cognitive processes, and this has led to high heterogeneity of results. However, even when trying to consider only general (i.e., not specifically pertaining to a context/field) DM abilities, it is still not easy to find clear and consistent results. More in detail, DM deficit was frequently found in moderate-to-severe TBI (Rabinowitz & Levin, 2014) – while seems to be rarer in the mild TBI severity spectrum (Levine et al., 2005), even if some others found alterations even in these patients (e.g., Fogleman et al., 2017). In contrast, other studies did not show any relevant performance difference in DM tasks between TBI patients and healthy controls (e.g., Fogleman et al., 2017; Newcombe et al., 2011; Van Noordt & Good, 2011). These conflicting results might be due to different factors that can have a significant influence on patients' performances but that have not always been controlled in these studies: a) the heterogeneity of TBI patients itself in terms of trauma severity (i.e., mild, moderate, or severe), lesional data (e.g., frontal vs non-frontal lesions; focal vs diffuse), and time of the assessment (sub-acute and/or chronic stage of recovery); b) the different measures employed (risk vs ambiguity): almost all studies in the literature use DM tasks under ambiguity, such as the IGT or similar/modified version (e.g., Adlam et al., 2017; Fogleman et al., 2017; Levine et al., 2005; etc.), while few studies have considered DM under risk conditions (e.g., Rzezak et al., 2012; Salmond et al., 2005; etc.). However, the comparison of these two tasks' performances in TBI patients could be crucial for further investigation of the differential cognitive processes involved.

Accordingly, several interpretations have been provided by researchers to explain DM deficits in TBI patients, including a preference for immediate prospects and present stimuli over those more abstract and/or delayed (Bechara et al., 2000a), insensitivity to future

consequences (Bechara et al., 2000b), impulsivity (Fogleman et al., 2017; Newcombe et al., 2011; Rzezak et al., 2012; Salmond et al., 2005; Wood & McHugh, 2013), impaired learning from feedback or a general deficit in somatic markers (i.e., the visceral and emotional states associated with each item in the decision space according to the prior experience of the subject; Bechara et al., 2005; Van Noordt & Good, 2011) which alter patients' anticipation of future negative consequences (Rouault et al., 2019).

Results are therefore conflicting and sometimes difficult to integrate due to both theoretical and methodological (i.e., heterogeneity and type of task) issues. To our knowledge, there is a lack of recent reviews or meta-analyses that specifically considered general DM abilities under risk or ambiguity in patients with TBI. Thus, the present study aims to systematically review and integrate past literature data specifically focused on this topic, providing a clear and handy picture both for researchers and clinicians.

Method

The present systematic review and meta-analysis were conducted following the Preferred Reporting Items for Systematic reviews and Meta-Analyses guidelines (PRISMA; Page et al., 2021) and PRISMA checklist is provided in **Supplementary Material**. The study was not pre-registered in PROSPERO.

Search strategy

The online search strategy was performed through four different electronic databases (PubMed, Scopus, Web of Sciences, and PsychINFO) and ended on 21 June 2021. The following keywords were used for the different databases: decision-making AND traumatic brain injury AND cognit* NOT pharmac* for PubMed, decision-making AND traumatic brain injury AND cognit* NOT medic* NOT pharmac* for Web of Sciences, decision-making AND traumatic brain injury AND cognit* NOT pharmac* for PsychINFO and TITLE-ABS-KEY (decision-making AND traumatic AND brain AND injury) AND (LIMITTO (DOCTYPE, "ar") OR LIMIT-TO (DOCTYPE, "re")) AND (LIMIT-TO (SUBJAREA, "NEUR") OR LIMITTO (SUBJAREA, "PSYC") OR LIMIT-TO (SUBJAREA, "SOCI")) AND (LIMITTO (LANGUAGE, "English")) AND (LIMITTO (EXACTKEYWORD, "Human") OR LIMITTO (EXACTKEYWORD, "Humans")) for PubMed. No date limit was set, and only contributions from full-text journal articles published in English were included. Considering the lapse of time from the last search, a further search in PubMed with the same keywords for studies published from 2021 to 2023 was conducted on January 25th, 2023. All the results (N = 46) were discarded by reading abstracts and titles because they did not meet the inclusion criteria. Considering the null results, these papers were not added to the decision flow which represents the selection process that was built on the systematic analysis carried out with Raayaan (https://www.rayyan.ai/; Ouzzani et al., 2016), whose procedure is described in the next section (Figure 1). Cross-references of the selected studies were also considered to identify possible additional relevant articles, while gray literature was not considered.

Inclusion and exclusion criteria

Studies were included if they met the following criteria: articles published in English in an international peer review journal; participants with age at least of 16 years (adults); evidence of TBI, determined using one or more of the following methods: (a) Glasgow Coma Scale (GCS) score, (b) evidence of posttraumatic amnesia (PTA), (c) intracranial neuroimaging abnormalities, (d) reported loss of consciousness (LOC), (e) qualitative and/or clinical interview and/or outpatient records. In order to achieve the highest degree of generalization of our results, we excluded studies involving participants with non-traumatic acquired brain injury (e.g., cerebrovascular disease, encephalitis, and brain tumor). Only observational studies (cross-sectional and longitudinal) that have addressed patients' DM abilities through performance tasks were considered. Single cases and case series, as well as abstracts, reviews/meta-analyses, research protocols, qualitative studies, and opinion/perspective papers, were excluded. Finally, we considered only studies that assessed general DM abilities, thus excluding all the articles conducted only in specific domains such as social, medical, ethical, etc.

Study selection and data collection

The study selection process is shown in Figure 1. The search provided N = 968 potentially relevant articles. After duplicate removal, N = 706 papers were available for screening.

Then, three authors (C.S., M.B., and C.C.) independently screened the titles and abstracts of the database outputs to check for inclusion criteria. The authors were blinded via Rayyan (Ouzzani et al., 2016). Among the initial results, 83 contributions were identified through first-level searches and their full texts were accessed (N = 623 studies were removed after a first-level screening because they were not focused on the current topic and/or did not meet inclusion criteria by the reading of abstract and title). The same three authors of the

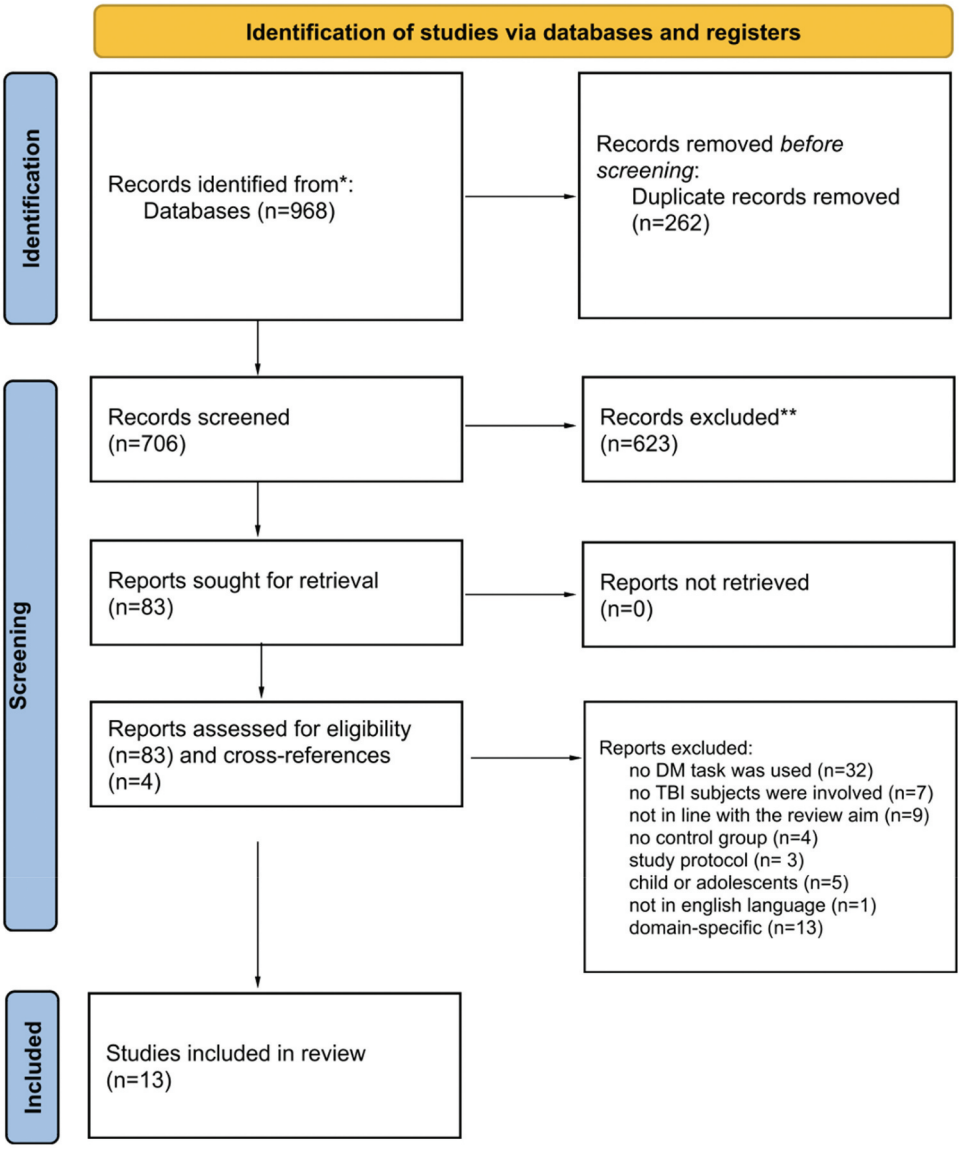

Figure 1. PRISMA flow-chart displaying study selection process. *Note*. www.prisma-statement.org; Page et al. (2021).

screening process performed the eligibility stage by reading full texts that passed the screening to determine whether they met inclusion criteria. For both screening and eligibility stages, disagreements were resolved by a fourth and fifth independent rater (G.F. and M.C.). A total of N = 13 were included in the review and checked for data extraction.

Data extraction was performed by five Authors (C.S., M.B., C.C., G.F., and M.C.). The following outcomes were reported from the selected studies: Authors and year; the number of participants; patients' descriptive data (i.e., age, education, and sex); neuroimaging or lesional data if present; TBI level (i.e., mild, moderate, and severe); time from the lesion (i.e., days/months/years); presence and main characteristics of a control group; DM task employed; a brief report of the findings. A detailed overview of the key points for each record is provided in Table 1.

Coding

Two of the researchers (G.F. and M.C.) applied a coding protocol to extract all the needed information from the original articles. To ensure the accuracy, simplified Stock's training was applied (Cooper, 2015). First, the coding scheme was defined; secondly, it was tested and lastly, after any possible disagreement was discussed and resolved, the coding scheme was applied. The following coding scheme was applied if the information were present: (a) characteristics of the sample such as: gender (% of females in the whole sample); considering that age and education have always been given by all the selected

Table 1. Included studies' (N = 13) main characteristics.

Authors (Year)	Sample descriptives	HC group	TBI meas.	TBI severity	Time from TBI	Lesional data	Aim	DM Task	ES (rater2)	Findings
DM under ambiguity										
Levine et al., 2005	N = 71; mTBI: W = 12; age: M = 32.5, SD = 12.4; edu: M = 14.1, SD = 2.6; moTBI: W = 13; age: M = 31, SD = 10.2; edu: M = 14.7, SD = 2.5; seTBI: W = 4; age: M = 28.5, SD = 7.6; edu: M = 13.7, SD = 2.5	N = 19; W = 15; age: M = 29.6, SD = 8.9; edu: M = 15.1, SD = 2.0	GCS	mTBI (N = 25), moTBI (N = 26), seTBI (N = 20) (GCS: mTBI = 14.5, moTBI = 10.2, seTBI = 5.4)	Approximately 1 year	Mixed	To determine the sensitivity of the Gambling Test (GT) to the neurocognitive effects of TBI	Gambling Task (GT)	TBI: M = 4.1. SD = 20.4; for HC: M = 14.8, SD = 21.4	Data suggests that the GT is potentially useful in the assessment of patients with TBI. The TBI effect, however, is best seen in the patients' pattern of performance across blocks rather than in their total GT score: they shift to a functional strategy more gradually.The GT was sensitive to prefrontal lesions vs other lesions, and to patients with large lesion vs no large lesions, but not to TBI severity.

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Table 1. (Continued).

Authors (Year)	Sample descriptives	HC group	TBI meas.	TBI severity	Time from TBI	Lesional data	Aim	DM Task	ES (rater2)	Findings
Fujiwara et al., 2008	N = 58, mTBI: N = 12; W = 5; age: M = 33.92, SD = 13.64; edu: M = 13.42, SD = 2.02; moTBI: N = 27; W = 10; age: M = 32.19, SD = 11.21; edu: M = 14.81, SD = 2.22; seTBI: N = 19; W = 6; age: M = 28.21, SD = 7.35; edu M = 14.74, SD = 2.75	N = 25; W = 16; age: M = 27.72, SD = 7.93; edu: M = 15.08, SD = 1.78	MRI; GCS	GCS: mTBI: M = 14.54, SD = 0.72; moTBI: M = 11, SD = 2.11; seTBI: M = 5.68, SD = 2.16	mTBI: M = 1.10, SD = 0.31; moTBI: M = 1.12, SD = 0.39; seTBI: M = 1.02, SD = 0.23	Frontal cortex or diffuse	To examine the relationship of performance on smell identification test, object alternation, and IGT to residual structural brain integrity	IGT	IGT as assessed by the composite score (T [81] = 2.19. $p < 0.05$). N = 58 TBI, HC N = 25.	The tasks were sensitive to effects of TBI. In multivariate analyses, performance in all 3 tasks was related to gray matter loss including ventral frontal cortex, but the SIT was most sensitive, even in patients without focal lesions. OA and the IGT were associated with superior medial frontal volumes. Complex tasks, such as OA and the IGT, do not consistently localize to a single cortical region.
MacPherson et al., 2009	VMPFC(TBI): N = 13; W = 3; age: M = 27.8, SD = 11.0; (range = 17–56); edu: M = 12.1, SD = 3.4, (range = 8–18)	N = 24; W = 7; age: M = 30.2, SD = 10.9, range 17–54; education: M = 11.8, SD = 3, range 8–18	CT; MRI	NA	28.4 months, SD = 28.0, range 5–89; (VMPFC) and 24.0 months, SD = 22.8, range 6–63 (non-VMPFC).	VMPFC only right or bilateral vs nonVMPFC	To investigate whether impaired performance in individuals with frontal lobe damage is determined by the presence of VMPFC lesions	IGT	VMPFC and the non-VMPFC performed significantly more poorly on the IGT than HC ($p < .05$. $d = 0.92$ and $p < .005$. $d = 1.44$ respectively).	TBI performed poorly on the IGT in comparison with HC: patients selected more disadvantageous cards. However, there is no support that VMPFC damage is the direct cause of this trend.

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Table 1. (Continued).

Authors (Year)	Sample descriptives	HC group	TBI meas.	TBI severity	Time from TBI	Lesional data	Aim	DM Task	ES (rater2)	Findings
Van Noordt & Good, 2011	N = 43; W = 33; age: M = 19.8, SD = 2.3 (range: 17–28); edu: M = 12.9, SD = 1,3 (range 12–16); mTBI: N = 18	N = 25	Clinical interview	mTBISelf-reported symptoms	NA	NA	To investigate whether self-reported mTBI in asymptomatic students is associated with differences in sympathetic arousal during DM and if a history of mTBI contributes to DM success	IGT	MHI (N = 18) (M = 42.08. SD = 35.17) and non-MHI (N = 25) (M = 46.50. SD = 29.59) groups (t (42) = −0.48. p = 0.66).	General cognitive ability and overall choice outcomes did not differ between groups. However, self-reported MHI severity predicted DM performance: the greater the neural indices of trauma, the more disadvantageous the choices made. As expected, both groups exhibited similar base levels of autonomic arousal and physiological responses to reward and punishment; however, those reporting MHI produced lower levels of EDA during the anticipatory stages of DM.
Fonseca et al., 2012	N = 16; W = 4; age: M = 37.31, SD = 13.65, (range = 18–68); edu: M = 10.50, SD = 3.48	N = 16; gender: W = 7; age: M = 32.88, SD = 13.09; edu: M = 12.44, SD = 4.20	Outpatient records, SRq	mTBI = 6 seTBI = 10	At least 1 month after injury; range = 1–50 months	NA	sought to identify dissociations in the frequency of deficits in hot vs cold executive functions (EF)	IGT	HC N = 16; TBI N = 16; IGT total score (p = .638; t-test) between the TBI group (M = −6.88. SD = 11.95), HC (M = −3.5; SD = 25.67)	No differences were found between groups in total scores and blocks on the IGT. However, TBI patients preferred the disadvantageous decks, with no evidence of learning during the task. Authors found different performance subgroups (with mixed patients and HC).

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Table 1. (Continued).

Authors (Year)	Sample descriptives	HC group	TBI meas.	TBI severity	Time from TBI	Lesional data	Aim	DM Task	ES (rater2)	Findings
Cotrena et al., 2014	N = 55; W = 22%; age: M = 34.90, SD = 14.0 (range: 18–73); edu: M = 10.1, SD = 3.34. mTBI: N = 18 seTBI: N = 37	N = 55, W = 49%, age: M = 33.4, SD = 17.4, edu: M = 11.8, SD = 4.14	CT; GCS; SRq on LOC and amnesia	mTBI, seTBI GCS, patient self-report of loss of consciousness and duration of PTA	Within 3 weeks and 5 years post trauma	MiFR:8 No-FR:6 NL:2 SeFR:11DAI:18No-FR:6 NL:6	To use the IGT to investigate differences in DM between patients who sustained TBI and HC, while controlling for age, education and gender	IGT	HC: N = 55; TBI: N = 55; $p < 0.001$	Results indicate poor DM on the IGT in patients with TBI, regardless of lesion location and severity. The instrument proved to be equally sensitive to both frontal and extrafrontal lesions and did not differentiate between patients with mild and severe TBI.
Visser-Keizer et al., 2016	N = 49; W = 11; age: M = 44.6, SD = 13.5, (range: 20–68); Edu level: M = 5.1, SD = 1, (range: 3–7) (1 = primary school, 7 = university)	N = 59; W = 22; age: M = 43.5, SD = 1.9; edu level: M = 5.4, SD = 1.1 (range: 2–7)	CT; MRI; GCS	moTBI, seTBI (GCS from 3 to 15; PTA duration: M = 25.9, SD = 25.1 days; range 1–112 days)	M = 104.8 months (range 4–402 months)	42 patients imaging data: 27 visible lesions to the frontal lobe vs 15 = no frontal lesion	To investigate if a better ability to recognize fear would be related to a better regulation of risk behavior, with HC outperforming TBI patients	IGT	HC (N = 59) had earned M = 133 euros, while TBI (N = 49) patients M = - 290 euros; a significant difference WITH HC (t = 2.4. p = .02).	Fear is not only related to overall DM in both groups, but in particular to risky choice behavior in IGT performance. Clinically speaking, impaired DM and risk behavior after TBI can be preceded by deficits in the processing of fear. A significant relationship was found between better fear recognition, the development of an advantageous strategy across the IGT and less risk behavior in the last blocks of the IGT.

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Table 1. (Continued).

Authors (Year)	Sample descriptives	HC group	TBI meas.	TBI severity	Time from TBI	Lesional data	Aim	DM Task	ES (rater2)	Findings
Adlam et al., 2017	N = 30; W = 5; age: M = 34.73, (range: 20–55); edu: M = 13.21 (range: 12–17)	N = 39; W = 22; age: M = 38.18, (range: 18–65); edu: M = 14.20, (range: 12–18)	GCS	GCS:Se (N = 23) = 3–8; Mo (N = 2) = 9–12;Mi (N = 2) = 13+	At least 6 months (M = 51.4 months; range = 11–192 months)	NA	Characterize performances across contingencies in TBI, explore sub-groups and identify predictors of performance in a emotion- based gambling task	Bangor Gambling Task (BGT):	HC: N = 39 M = 2.41. SD = 28.54; TBI = N = 30; −14.51. 27.86	Results showed that survivors of TBI made more gamble choices than controls (total BGT score), but they do not differ when using a cutoff score for 'impaired' performance and did not significantly differ in their performance across the blocks. TBI gambled more and do not show learning effects showing their inability to prefer short-term gain to long-term profit. Different subgroups were found.

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Table 1. (Continued).

Authors (Year)	Sample descriptives	HC group	TBI meas.	TBI severity	Time from TBI	Lesional data	Aim	DM Task	ES (rater2)	Findings
Fogleman et al., 2017	N = 88; PTSD: N = 21; W = 5; age: M = 29.95, SD = 4.97; edu: M = 13.80, (range: 11–16); mTBI: N = 18; W = 0; age: M = 29.22, SD = 5.08, (range: 22–42); edu: M = 13.77, (range: 11–17) PTSD/mTBI co-occurring: N = 26; W = 3; age: M = 30.23, SD = 5.26; edu: M = 13.81, (range: 11–17)	N = 23; W = 4; age: M = 30.61, (range: 23–45); edu: M = 14.78, SD = 3, (range: 12–18)	TSI; GCS; clinical interview	mTBI (TBI with normal MRI, 0–30 min of LOC, < 24 h of altered consciousness, 0–1 day of PTA, GCS of 13–15 recorded within 24 h)	NA	vlPFC, dlPFC	To assess whether behavioral measures related to reward processing and DM were compromised and related to cortical morphometric features in Veterans with PTSD, mTBI, or co-occurring PTSD/mTBI	Modified IGT	Advantageous – disadvantageous: HC: −0.44; TBI = −0.56, p = 0.41	No behavioral differences were observed between groups. Participants with PTSD and mTBI showed more risky decision.Results indicated that gray matter morphometry in the lPFC predicted performance on the mIGT among all three groups and was significantly reduced, as compared to the control group. Although behavioral performance on the mIGT was similar for all groups, previously deployed Veterans with PTSD, mTBI, or co-occurring PTSD/mTBI exhibit increased impulsivity and reduced inhibitory control during activities that involve decision-making and reward processing.

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Table 1. (Continued).

Authors (Year)	Sample descriptives	HC group	TBI meas.	TBI severity	Time from TBI	Lesional data	Aim	DM Task	ES (rater2)	Findings
DM under risk										
Salmond et al., 2005	N = 43; W = 9; age: M = 36.4, SD = 2.1	N = 29; W = 11; age: M = 37.3, SD = 2.1	CT; GCS; GOS; ISS	GCS: mTBI (N = 2), moTBI (N = 16), seTBI (N = 25)	At least 4 months (range 4–54 months)	NA	To explore the nature of DM in TBI patients in a probability-based task	Cambridge Gambling Task (CGT)	p = 0.29	TBI survivors have specific deficits in their DM abilities: they have slowed DM, made poorer decisions when the choice was difficult and displayed impulsive responding when placing bets.
Newcombe et al., 2011	N = 42; W = 15; age: M = 36.5, SD = 14.4 (range17-69)	N = 38 MRI tested: N = 38; W = 9; age: M = 34.9, SD = 10.3; (range: 18–70) NPS tested: N = 18; W = 7; age: M = 36.0, SD = 11.3 (range: 18–64)	MRI; GCS	Median admission GCS = 7 (range 3–15); no differentiation in the analysis	M = 334 days (range171–1437); at least six months post-traumatic brain injury	Did not exhibitany significant focal lesions	To describe the correlation of DTI with performance on the CGT and characterize the neuroanatomical basis of DM deficits following TBI	Cambridge Gambling Task (CGT)	HC.:N = 18; TBI:N = 42 rational choice: t = −0.705	These patients were found to have broadly intact processing of risk adjustment and probability judgment and to bet similar amounts to controls. However, a patient's preference for consistently early bets indicated a higher level of impulsiveness.
Rzezak et al., 2012	N = 15; W = 0; age: M = 33.67, SD = 11.11, (range: 19–50); edu: M = 9.47, SD = 4.36	N = 160; W = 83; age: M = 28.99, SD = 7.22, (range: 19–52); edu: M = 16.35, SD = 3.18	NA	moTBI, seTBI	At least 6 months	Orbitofrontal/ VMPFC; frontal lobe	To translate and adapt the GDT to a Brazilian population	Game Dice Task (GDT)	HC: M = 6.18. SD = 10.01. TBI: M = −3.73. SD = 3.63 (t = 3.27. p = 0.002)	Results show that TBI patients are more impulsive than healthy volunteers and this suggests that the GDT is a valid tool to investigate decision making both in healthy and TBI subjects.

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Table 1. (Continued).

Authors (Year)	Sample descriptives	HC group	TBI meas.	TBI severity	Time from TBI	Lesional data	Aim	DM Task	ES (rater2)	Findings
DM under ambiguity vs under risk										
Bonatti et al., 2008	N = 21; W = 3; age: M = 34.5, SD = 11.8; education: M = 10.7, SD = 1.6	N = 20; W = 14; age: M = 31.9, SD = 13.1, edu: M = 11.5, SD = 1.3	CT; MRI; GOS	NA	At least 3 months (M = 34.1 months, SD = 44.8, range 3 to 118)	14 patients showed multiple lesions and atrophy	To assess DM under ambiguity and DM under risk in a group of TBI	IGT; PAG task; Counsel PAG Task	HC (N = 20): M = 2060. SD = 980; TBI (N = 21): M = 1894. SD = 1002	TBI patients performed worse on both the PAG and the IGT showing deficit both in DM under risk and under ambiguity. The Authors hypothesize that may be attributed to deficient learning from feedback and to reduced risk estimation.

papers as split in the two samples, we have calculated a pooled mean; (b) time from the lesion (mean days from lesion); (c) phase (sub-acute – less than 1 year from the trauma, or chronic – where patients had trauma more than 1 year before), no coding was entered if the patients recruited were mixed in the two categories; (d) severity (i.e., mild or moderate/severe); a missing data were left if studies considered mixed severity; (e) comparisons (healthy controls, HC vs TBI patients, VMPFC vs non-VMPFC lesions); (f) type of employed DM task (i.e., IGT, GDT, Cambridge, Bangor) and used index (total earn or composite score). The inter-rater agreement was 92% (Cohen's k from 0.66 to 0.86), while intra-class correlation coefficient (ICC) was from 0.86 to 1, 95% CI [0.57; 1]. The coding of the second coder was used for the analyses.

Data analyses

The analyses were conducted using standard meta-analytic procedures via the software ProMeta3. We calculated Hedges' *g* from the data reported in the selected papers. We decided to use such an effect size as it is less biased and thus a better measure than Cohen's *d* in cases where a meta-analysis is based on a small sample of studies (Borenstein et al., 2011). Effect sizes were calculated so that a positive value indicates that HC performed better than TBI patients, whereas a negative value indicates the opposite. Confidence intervals at 95%, standard errors, variances, and the statistical significance of each effect size were also calculated and reported. Then, the effect sizes of the individual studies were pooled into a global effect size through the inverse-variance method and a random-effect model. Such a model was selected rather than a fixed-effect model as the former accounts for both within-study and between-studies variances, thus permitting generalizing the results. Heterogeneity was also calculated and reported via two indexes: The Q-statistic and I^2. Significant Q-values indicate a lack of homogeneity between the studies, whereas I^2 provides an estimation of the proportion of variance that reflects real differences in the effect sizes. An I^2 of about 25% indicates low heterogeneity, 50% as moderate heterogeneity and 70% or more as high heterogeneity (Borenstein et al., 2011). We also reported sensitivity analyses, which provide information on the global effect size when excluding one study at a time, and publication bias analyses assessed via visual inspection of the funnel plot and by applying the trim and fill method. Publication bias is believed to be an issue if the funnel plot is asymmetrical and if there is a substantial difference between the observed effect size and the effect size that is estimated via the trim and fill method. Finally, before proceeding with the meta-analysis itself, we run two pre-analyses to assess whether the different outcomes and comparisons (see coding section) could be combined for the actual analyses (Babbage et al., 2011).

Results

Study design and main characteristics

The 13 selected articles were published from 2005 (Levine et al., 2005; Salmond et al., 2005) to 2020 (Adlam et al., 2017; Fogleman et al., 2017). A total of 434 TBI patients were involved in the studies, but they differ from each other in several different characteristics (descriptives are reported in Table 1). TBI severity ranges from mild (Van Noordt & Good, 2011) to severe, but most of the studies included mixed patients' severity (Adlam et al., 2017; Cotrena et al., 2014; Fogleman et al., 2017; Fonseca et al., 2012; Fujiwara et al., 2008; Levine et al., 2005; Newcombe et al., 2011; Rzezak et al., 2012; Salmond et al., 2005; Visser-Keizer et al., 2016); one study considered veterans with mild TBI vs patients with the co-occurrence of mild TBI and post-traumatic stress disorder (Fogleman et al., 2017). No information about severity was available in Bonatti et al. (2008) and in MacPherson et al. (2009). Patients' time from lesion ranged from 3 weeks (Cotrena et al., 2014) to 402 months (Visser-Keizer et al., 2016). Four studies did not consider lesional data (Fonseca et al., 2012; Salmond et al., 2005; Van Noordt & Good, 2011). One work reported patients without focal lesions (Newcombe et al., 2011), while others compared patients with frontal vs. non-frontal lesions (Adlam et al., 2017; Cotrena et al., 2014; Visser-Keizer et al., 2016). Others, again, enrolled only patients with specific frontal lesion OFC/VMPFC (Levine et al., 2005; Rzezak et al., 2012), compared patients with VMPFC vs. non-VMPFC lesions (MacPherson et al., 2009) or consider patients with more diffuse frontal alterations (Fogleman et al., 2017; Fujiwara et al., 2008; Rzezak et al., 2012) or with general "multiple" lesions (Bonatti et al., 2008). Finally, all the studies included employed a cross-sectional design.

Assessment methods

Nine out of 13 studies employed the Iowa Gambling Task (original version, Bechara et al., 2000a) or a modified/computerized version of this task (Bonatti et al.,

2008; Cotrena et al., 2014; Fogleman et al., 2017; Fonseca et al., 2012; Fujiwara et al., 2008; Levine et al., 2005; MacPherson et al., 2009; Van Noordt & Good, 2011; Visser-Keizer et al., 2016). IGT is probably the most famous task that assesses complex DM abilities under ambiguous conditions: the rules of winning and losing are not given explicitly, rather, participants must understand them implicitly as they perform the task. In brief, four card decks appeared on the computer screen or on a table (A–D). Participants had a starting capital, aiming to maximize it until the end of the task. Patients were asked to choose cards from one of the decks: the decks were stacked such that two of them lead to high winnings and higher losses, whereas the other two decks produced more modest winnings but also smaller losses. After each selection, the amount won appeared, followed by the amount lost, if any. Over time, the last desks described yield the highest overall winnings, but participants were neither instructed about the rules of the task nor did they know the number of trials until completion of the task and substantially, they must understand that they must inhibit short-term reward to earn more money in the long run. Different indexes can be considered and usually, the more utilized are as follows: i) the total amount won; ii) a net score is usually calculated as the number of advantageous choices (number of cards drawn from advantageous decks) minus the number of cards drawn from disadvantageous decks; iii) differences between blocks. Only Fogleman et al. (2017) used a modified version of this task, where participants made a play/pass decision about each of the four decks preselected on each trial. The authors argue that this type of modification is more sensitive to individual differences in performance because of the ability to determine the independent effects of gains and losses on subsequent card selection.

Only one study used different, but very similar, tasks to assess DM under ambiguity: the Bangor Gambling task (BGT), employed by Adlam et al. (2017). This is considered an emotion-based task and it consists of a deck of 100 playing cards to which different winning scores are assigned. For example, nine cards are labeled "win 20p," 29 "win 10p," 35 "lose 20p," and 27 "lose 10p." As with the IGT, the objective was to earn as many points as possible. Again, the participant can play and bet or not bet before turning over the card. The deck is divided into five blocks of 20 selected cards. In this task, the score is given by the number of "no-risk" decisions minus the number of "risk" decisions made for each block and total. A negative score indicates a higher number of "gamble" responses.

Finally, only four studies assessed the ability of TBI patients to make decisions under the condition of risk, that is DM under explicit rules for gains and losses: Cambridge Gamble task (CGT) was used by Salmond et al. (2005), Newcombe et al. (2011), and Rzezak et al. (2012) employed the Game Dice Task and Bonatti et al. (2008) made a direct comparison between IGT and PAG task. In the Cambridge Gamble task, subjects were presented with 10 blue and red boxes and given a series of points to bet with. The objective is to guess the color hidden in the boxes by betting part of the points. The results of the task are then coded according to these components: (i) rational choices defined by the proportion of trials in which the main color was chosen; (ii) latency time to make a choice; (iii) amount bet, the average between conditions and ratios between boxes; (iv) impulsivity index, i.e., the difference in betting percentage in descending versus ascending conditions (favorable and unfavorable, riskier). Instead, in the Game of Dice Task, subjects are asked to predict the outcome of a rolled dice by choosing between several alternatives correlated with a gain concerning the probability of winning. Finally, in the PAG computerized task, participants are asked to imagine taking part in a lottery. The task aims to earn as much money as possible; so, on each trial, the participants are asked to decide between two alternatives: whether or not to accept a certain amount of money or to take a risk and gamble. If the participant decides to gamble, two cubes are shaken inside a box that appears on the computer (one red and one blue), and one is drawn. Each time a red cube is drawn, the participant earns money. Alternatively, if a blue cube is drawn, participants lose.

DM performances overview

DM under ambiguity

Concerning a qualitative overview of the study results about performance in IGT-like tasks, it can be highlighted that some of them found that patients showed impaired total performance (Cotrena et al., 2014; Fogleman et al., 2017; Fujiwara et al., 2008; Levine et al., 2005; MacPherson et al., 2009; Van Noordt & Good, 2011), while other did not (Fonseca et al., 2012; Levine et al., 2005; Visser-Keizer et al., 2016). Moreover, observing the pattern of performance across blocks, in some studies, TBI patients seemed to shift to a functional strategy more gradually (Levine et al., 2005) and were more impulsive (Fogleman et al., 2017) than controls, showing differential acquisition slopes across the five blocks (Fujiwara et al., 2008); in contrast, other authors did not find these significant differences across the blocks (Adlam et al., 2017; Fonseca et al., 2012; MacPherson et al., 2009). However, all of the studies that have considered DM under ambiguous conditions

evidenced a propensity to the selection of disadvantageous and more risky desks/cards.

Furthermore, interestingly, many of the studies evidenced how there is marked heterogeneity of patients' performances. Some of the studies have correlated patients' performances with altered functioning both in the cold component, i.e., executive functioning (Bonatti et al., 2008; Fonseca et al., 2012; Levine et al., 2005) and hot component, e.g., lower levels of electrodermal activity during anticipatory stages (Van Noordt & Good, 2011) or emotion/face recognition abilities (Visser-Keizer et al., 2016). Some others highlighted that patients showed different cognitive profiles, with some patients that presented dissociations between deficient DM on the IGT and executive functioning, while other patients (rarer) exhibited deficits in all instruments or no deficits at all (Fonseca et al., 2012) or showed more general different profiles that are related to individual differences in the approach to these tasks (e.g., risk-taking trait; Adlam et al., 2017) which are independent from the head trauma.

DM under risk

These other studies found that TBI patients were more impulsive than the control groups, betting early in the task (Newcombe et al., 2011; Rzezak et al., 2012; Salmond et al., 2005), making more risky and less non-risky choices (Rzezak et al., 2012) and which seems to indicate a generalized aversion to delay (Salmond et al., 2005). Interestingly, Newcombe et al. (2011) evidenced that performance in specific domains of the CGT correlated inversely and specifically with the severity of diffusion tensor imaging (DTI) in specific brain areas (see next paragraph for further information).

DM under ambiguity vs risk

Finally, Bonatti et al. (2008) study is the only one that compares DM abilities under ambiguity and under risk conditions. Interestingly, TBI patients performed worse than the control group on both tasks. Even if this research is based on a limited sample (N = 21), characterized by high heterogeneity (i.e., assessment that spans between 3 and 118 months which embraces both sub-acute and chronic phases), it qualitatively highlights interesting findings. In the condition under ambiguity, patients selected the disadvantageous desk more frequently (mainly in some blocks where healthy controls started to switch their strategies) and the authors hypothesize that this might be attributed to deficient flexibility in switching between strategies (coupled with poor stability to maintain a strategy) and to learn from feedback. Instead, in the condition under risk, assessed with a different task (PAG), TBI patients gambled more frequently in the low probability conditions (and less frequently in high probability), which may be consistent with an alteration of cognitive estimation.

DM task sensitivity

Complex DM tasks, such as the one used in the selected studies (see assessment methods section), showed low sensitivity in differentiating significant patients' characteristics. DM under ambiguity performance seems to be related to gray matter loss in the ventral frontal cortex (lower reliability) and superior medial frontal volumes (Fujiwara et al., 2008), while DM under risk was associated with microstructural alterations in the white matter in different frontal areas, such as the orbitofrontal cortices, the insular, and caudate bilaterally associated with impulsivity and with increased diffusion coefficients in the bilateral ventrolateral and dorsolateral prefrontal cortices, superior frontal and orbitofrontal gyri, and left-sided medial prefrontal cortex (associated with longer deliberation times; Newcombe et al., 2011). However, this research evidenced also that DM performance impairment did not consistently localize to a single cortical region failing to prove a specific sensitivity to VMPFC alterations (Fogleman et al., 2017; Fujiwara et al., 2008; MacPherson et al., 2009), to discriminate between frontal vs non-frontal lesions (Cotrena et al., 2014; Visser-Keizer et al., 2016), between focal contusion vs diffuse injury (Fujiwara et al., 2008) or between trauma severity (Cotrena et al., 2014; Fujiwara et al., 2008; Levine et al., 2005). Finally, patients seem to show different patterns of impairments both in DM under ambiguity and under explicit rules (i.e., under risk) conditions (Bonatti et al., 2008).

Meta-analytic results

First, pre-analyses were conducted. The test of difference was not statistically significant for either the comparisons, $Q(2) = 3.85$, $p = .15$, or for the type of outcome, $Q(4) = 6.51$, $p = .16$. Thus, we decided to combine the comparisons and the outcomes for the subsequent analyses (Borenstein et al., 2011).

The meta-analysis of the 13 samples ($k = 899$) on the combined outcome variables is reported in the forest plot (see Figure 2).

The effect size showed that, as hypothesized, HC performed better than TBI, Hedges' $g = 0.47$, 95% CI [0.33; 0.62]. This was a moderate effect size, according to Cohen (1988). An evaluation of the residuals and

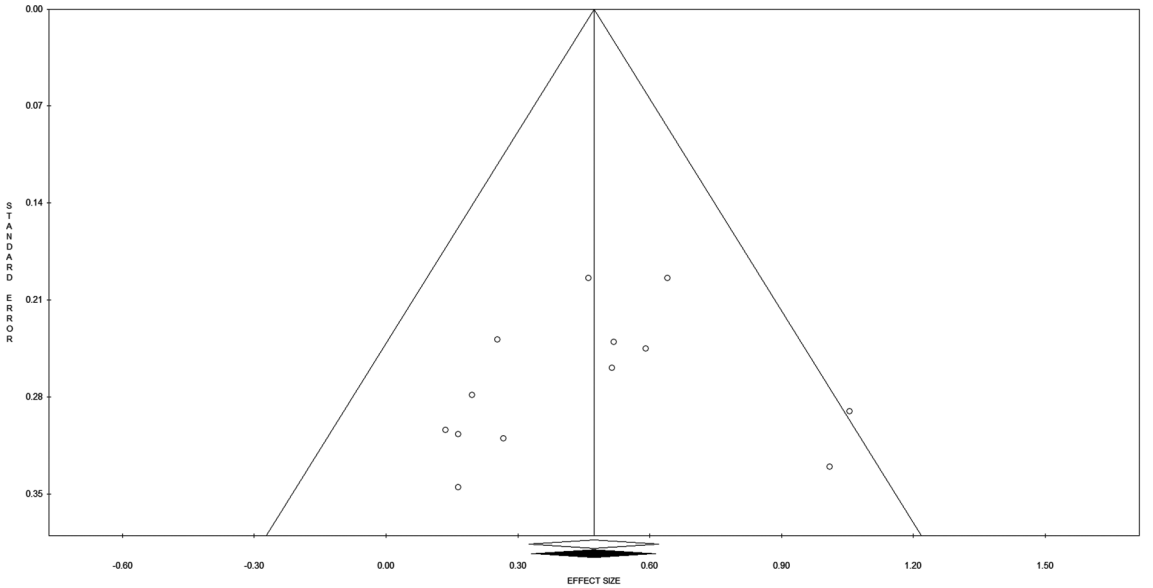

Figure 2. Funnel plot of the included research. Note. In the presented plot are graphically reported the effect size (between −0.06 and 1.5) and its standard error (between 0.00 and 0.35). Each dot represents an included study of this meta analysis.

their significance showed that Rzezak et al. (2012) was an outlier study (Hedges' $g = 1.06$, $p < .05$). A sensitivity analysis indicated that when this study was excluded, the global effect size became $g = 0.44$, 95% CI [0.29; 0.58] (showing that it did not affect the general results much) and that when excluding one study at a time the effect size ranged from $g = 0.44$ to $g = 0.49$.

Further, the studies included in the meta-analysis showed a low degree of heterogeneity, $I^2 = 7.90$, $Q(12) = 13.03$, $p = .37$. Due to the lack of evidence in support of heterogeneous results, no moderation analyses were conducted.

The funnel plot (see Figure 3) appeared to be symmetric, and indeed no study was trimmed using the trim and fill method; taken together, these two aspects indicate that there is no evidence in support of publication bias.

Discussion

The present meta-analysis aims to review and integrate data specifically focused on DM abilities in patients with a history of TBI. It is commonly accepted that patients

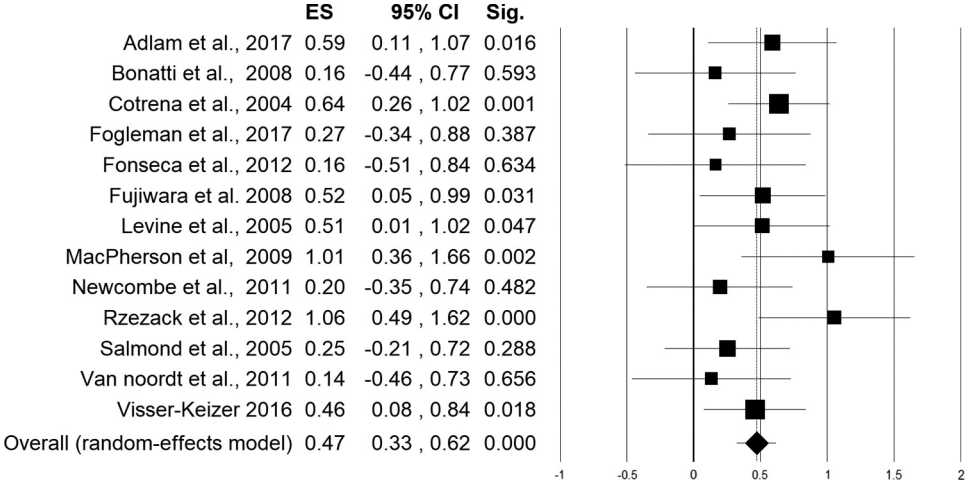

Figure 3. Forest plot of included studies. Note. The presented plot is graphically and numerically reported for the effect size (ES), the 95% confidence interval (95% CI) and statistical significance (Sig.) for each study included in this meta-analysis.

with this type of acquired brain injury suffer from different types of cognitive alterations, with a frequent impairment of DM abilities. However, sometimes, the results appear mixed and difficult to interpret: some studies found significant performance differences between TBI and healthy controls' in DM tasks (e.g., Cotrena et al., 2014; Levine et al., 2005; MacPherson et al., 2009; etc.), while others did not find any clear impaired performances (e.g., Fogleman et al., 2017; Newcombe et al., 2011; Van Noordt & Good, 2011), even if during daily complex situations patients usually showed severe difficulties in facing DM challenges (Rabinowitz & Levin, 2014). Thus, the present meta-analysis was designed to understand why such a heterogeneity exists and to try to draw a clearer picture of the DM processes' alterations in patients who have suffered head trauma.

Meta-analysis' results showed that TBI patients analyzed in the selected studies, suffered from an impairment, more or less severe, in DM abilities (g = .48, 95% CI [0.33; 0.62]), regardless of gender and age. However, the studies showed a very low heterogeneity (I^2 = 7.90, Q (12) = 13.03, p = .37) and moderating variables were not considered. Moreover, detailed evaluations, such as the distinction between frontal vs. non-frontal lesions (only one study), or the differences in the performance in DM tasks under ambiguity vs risk conditions (respectively, 10 vs. 4) have not been undertaken due to the small number of studies included.

However, on a qualitative level, patients' performance appeared poor in both tasks under risk (Bonatti et al., 2008; Newcombe et al., 2011; Rzezak et al., 2012; Salmond et al., 2005) and under ambiguity (Adlam et al., 2017; Bonatti et al., 2008; Cotrena et al., 2014; Fogleman et al., 2017; Fonseca et al., 2012; Fujiwara et al., 2008; Levine et al., 2005; MacPherson et al., 2009; Van Noordt & Good, 2011; Visser-Keizer et al., 2016). Moreover, it is worth noting that patients' performances did not differ significantly in TBI patients with frontal lesions and non-frontal lesions (Visser-Keizer et al., 2016) or between patients with frontal lesions mainly localized in VMPCF and in non-VMPFC areas (MacPherson et al., 2009) as well as these tasks seemed to be not specific for trauma severity (Cotrena et al., 2014; Fujiwara et al., 2008; Levine et al., 2005).

Taken together, these results lead us to two different considerations: 1) there is a too small number of studies in the literature that evaluate clearly and with a good statistical power (i.e., clear lesional area/network and severity of injury); 2) general DM tasks, such as IGT, are not as specific as it was believed in the past to detect alterations in DM abilities of patients with specific brain lesions (e.g., ventromedial/orbitofrontal prefrontal cortex). In addition, in the past literature, there may have been a methodological bias related to the difficulty of characterizing patients with focal brain lesions without also considering the involvement of subcortical and/or damage such as diffuse axonal injury, that is very common in the pathophysiology of TBI patients (Bigler, 2001; Levin et al., 2010; Johnson et al., 2013).

Several pioneering works on DM alterations in TBI patients have focused their attention on emotional/affect alterations that concern an impairment in somatic markers (see, e.g.,, Bechara et al., 2000a, 2000b) and hot executive functions (Brand et al., 2006). However, if TBI alterations would be only related to these components, we should expect a dissociation between DM tasks under risk (unimpaired) and under ambiguity (impaired), such as in schizophrenic patients (e.g., Lee et al., 2007). What is observed is that TBI frequently showed deficits both in DM under risk and under ambiguity (see results section), according to the fact that TBI often involves disruption in both sets of cold and hot executive functions (Wood & Worthington, 2017). Thus, in general, DM tasks show good sensitivity but low specificity.

Another interesting result concerns, from a qualitative point of view, that even if some of the included studies did not find any strong general impaired performance in TBI patients (Adlam et al., 2017; Fonseca et al., 2012; Levine et al., 2005; Newcombe et al., 2011; Salmond et al., 2005; Van Noordt & Good, 2011) computed as total or net scores (usually evaluated as advantageous-disadvantageous choices), they showed different performance in comparison with HC in several other indexes. More in detail, patients showed longer deliberation time (Newcombe et al., 2011; Salmond et al., 2005), they were more impulsive showing a clear preference for early bets (Fogleman et al., 2017; Fujiwara et al., 2008; Newcombe et al., 2011; Rzezak et al., 2012; Salmond et al., 2005), they made disadvantageous/risky/gamble choices (Adlam et al., 2017; Bonatti et al., 2008; Cotrena et al., 2014; Fonseca et al., 2012; Fujiwara et al., 2008; MacPherson et al., 2009; Visser-Keizer et al., 2016), with significant lower electrodermal activity during anticipatory stages (Van Noordt & Good, 2011), or did not show evidence of learning from feedback during the tasks – i.e., across the blocks – (Fonseca et al., 2012; Levine et al., 2005). Besides, patients have shown diverse slopes of acquisition in comparison with HC (Fujiwara et al., 2008), presenting the tendency to shift more gradually to functional strategies in comparison to healthy subjects (Levine et al., 2005). However, some studies reported alteration in the performance of TBI patients that goes beyond the slowing of the deliberation times, showing no effects of learning along the blocks

(Cotrena et al., 2014), and a higher frequency of disadvantageous choices, especially in the last blocks, compared to controls (Bonatti et al., 2008). Thus, we argue that considering the temporal dynamics (i.e., different phases) of the DM process implied in these tasks might be pivotal to unravel the specific emotional and cognitive processes and the involved brain networks in each of these different stages. It is widely recognized that in the first phase of DM (i.e., in the first blocks), especially in ambiguous situations, emotional cues (i.e., "gut feelings," Brand et al., 2006) are pivotal. In the TBI patient, the lack or, at least, a reduction in the anticipatory internal signals given from electrodermal activity seems to lead them to impulsive gambling choices and early bets because of the absence of internal signals needed to guide them (see e.g., Van Noordt & Good, 2011). However, even this explanation fails to explain all the observed results: early bets and impulsiveness were found both in tasks of both ambiguity and risk (characterized by a lower emotional involvement), and, sometimes, patients did not modify their behavior throughout the task, so much that the lack of anticipatory signals can be just a partial explanation for this behavioral evidence. As other Authors (Brand et al., 2006) have already suggested, in the last part of these tasks, emotional cues must be integrated with more top-down/control cognitive abilities such as cold EFs. According to this, no impact of EFs, such as Working Memory (WM), has been found when the general score was used as dependent variable (Adlam et al., 2017), while correlations emerged when more specific attention is moved to performance related to the different blocks (thus, on different DM phases): "cold" cognitive processes such as WM, planning, flexibility and cognitive estimation were mainly correlated to advantageous choices in the last blocks (Levine et al., 2005). Accordingly, TBI patients usually showed alterations in both sets of hot (bottom-up) and cold (top-down) executive functions (Azouvi et al., 2017; Brand et al., 2006) and this might explain why some patients continued to be more impulsive than HC and chose more disadvantageous options, failing to inhibit long-term non functional responses, even in the later stages. One tentative hypothesis, which has not yet been much explored in the literature, might be that at least some of the TBI patients can be characterized by a specific deficit in proactive inhibition. Proactive inhibition is indeed a top-down form of cognitive control (Gavazzi et al., 2021) that is described as the ability to anticipate a stop process as a result of environmental factors (Pauwels et al., 2019). It requires maintaining goal-relevant information over sustained periods and is future-oriented (Gavazzi et al., 2021), allowing subjects to detect and use environmental cues when a response might be inhibited (Meyer & Bucci, 2016) to gain long-term goals. An impairment in this type of top-down cognitive process might explain the deficit found in TBI patients who show difficulties in detecting, learning, and using environmental cues to inhibit responses/choices that are disadvantageous in the long term by learning and anticipating future consequences. This hypothesis might also be consistent with the fact that proactive inhibitory control is dependent on the integrity of the fronto-basal-ganglia network (Jahanshahi et al., 2015), and, specifically, of the inferior frontal gyrus (Cai et al., 2016; Meyer & Bucci, 2016; Pauwels et al., 2019) that is sensitive to TBI. Future studies might explore this hypothesis.

In addition to this, however, maybe the most interesting evidence emerging from the analysis of the included studies, is that TBI patients seem to show different cognitive profiles both in terms of DM abilities and in their relationships with hot and cold EFs. For example, Fonseca et al. (2012) found different dissociations between IGT performance and cognitive inhibition abilities: some patients showed deficient DM but accurate inhibition (assessed by the Trail Making test and the Hayling test), while other patients presented only partial dissociations between deficits in the IGT and an opposite performance in inhibition, and others, again, were impaired or not impaired in all the employed tests, evidencing that patients might show different cognitive profiles which can differentially impact the diverse phases of DM. Moreover, Adlam et al. (2017), through a clustering analysis, evidenced other interesting results: they found three different clusters of performance, but unexpectedly, both survivors of TBI and controls were present in each cluster. More specifically, the first cluster was characterized by the tendency to an initial gamble, followed by a reduced efficiency of the gambling choices over the blocks. Participants in Cluster 2 appeared to avoid gambling through all the blocks, suggesting a risk-avoidant strategy, while Cluster 3 showed an inability to give up short-term gains in favor of long-term profits. Therefore, individual differences in DM strategies (risk-taking or risk-avoidant) and inclinations (e.g., being sensation-seeking or prior DM style) might play a significant role and influence the performance also of TBI patients.

In conclusion, what we argue is that the clinical picture related to DM abilities in TBI patients cannot be related to the impact of a single factor (i.e., emotional or cognitive). Different factors such as the complexity of the DM process (i.e., different steps and temporal dynamics), the interplay of emotional and cognitive (executive) variables and also the heterogeneity and

individual differences of TBI patients must be considered for a better understanding of mechanisms and processes underlying this complex cognitive function. All these variables must be considered through a selective enrollment of patients and/or controlled through the help of more complex multilevel statistical analyses that are available to researchers nowadays.

Implications and future directions

Considering the complexity of DM processes, a more specific characterization of which stages and skills of the DM process are impaired in each TBI patient may be pivotal for researchers, allowing them to disentangle the role of the different EFs and the role of specific brain networks in each individual DM phase. Therefore, more specific study design and the use of more complex statistical analyses might have a huge impact on the study of DM in TBI patients.

For example, one option might be to use clustering methods in order to consider DM abilities through the different blocks and to account also for the role played by TBI patients' cognitive profiles (e.g., speed, memory, attention, working memory, reactive and proactive inhibition, planning, and flexibility abilities) and the main characteristics of the decision-maker (e.g., age, lesional areas, severity of the trauma, cognitive styles, risk perception, etc.) during the tasks (blocks). This strategy might allow to control for both the impact of the different significant variables that were cited above and to consider also the temporal dynamics among those variables within DM tasks. However, large sample sizes must be considered for these types of research.

An alternative approach would be to consider TBI performances in more specific tasks that might be able to discern alterations in targeted steps of the DM process, raising the specificity of the tasks in order to detect more targeted alterations. Indeed, if, on the one hand, the types of DM tasks considered in this meta-analysis have their strength in the fact that they showed strong ecological validity for neurological patients and other pathologies (see, e.g.,, Bechara & Van Der Linden, 2005; Jacus et al., 2018; Verdejo-Garcia et al., 2006), on the other hand, their main limitation is that they do not allow to unravel how and in which phase/step of the DM process (e.g., motivation, goal selection with value assignment and expected outcomes as sub-steps, goal selection, execution, or monitoring system) TBI patients are impaired. Therefore, possibly future studies might consider delving into more detail about possible deficits in the DM process of patients with TBI.

Finally, little evidence has been provided regarding the alteration of specific brain areas or networks and thus on the correlation of these behavioral data with the neuroanatomical substrate. In vivo neuroimaging techniques, such as DTI and fMRI, would be pivotal to study microstructural and functional integrity for a finer understanding of complex cognitive ability like DM and the interplay between hot and cold components.

This deeper knowledge can have significant practical implications by helping both clinicians and health/social workers with more targeted assessment and rehabilitation interventions, which could provide specific DM strategies and skills to these patients that hopefully will generalize to their everyday-life decisions, with an impact on their adaptation and perceived quality of life.

Limitations

Some limitations of the present meta-analysis must be considered. First, the number of studies included was limited, hence further studies and meta-analyses should be conducted to examine the generalizability of our results. Second, we have included studies that concern only domain-general DM abilities (see inclusion criteria): future studies might consider evaluating if and how general DM alterations in TBI patients highlighted by our meta-analysis generalize also to domain-specific (financial, health, social, etc.) tasks. Third, one of the included studies reported task performances of a group of "self-reported" mild TBI patients (Van Noordt & Good, 2011). We had not set exclusion criteria concerning how patients were diagnosed with TBI, but this could have had an impact on the reported results and might undermine the correctness and accuracy of the study. Fourth, we considered only published studies and the number of participants in the included studies was typically small: both these details may have resulted in an overestimation of the true effect size. As anticipated in the previous section, future studies on this topic would benefit from larger patient sample sizes with multi-center studies and projects. Last but not least, our study was not pre-registered. We made our work method as transparent as possible, but pre-registering this method could have made the review even more transparent and compliant with the rules.

Conclusions

In conclusion, the results of this meta-analysis suggest that TBI patients show clear impairments in general domain DM abilities, both in "under-risk" and "under-ambiguity" conditions; however, DM tasks seem to have good sensitivity but low specificity to detect alterations

in TBI patients. More specifically, TBI patients showed longer deliberation time and more impulsive behavior which translated into early bets, more gambling choices, and different learning curves as compared to HC. Both emotional/affective and cognitive alterations seem to play a role in the DM abilities of TBI patients: the hypothesis of an alteration of both bottom-up internal signaling (e.g., electrodermal activity) and external stimuli usage, from a cognitive top-down proactive inhibition process, has been tentatively theorized. The need to employ more specific tasks (linked to specific DM steps) and/or more complex statistical analyses to study more in-depth the processes involved in complex DM tasks and the influence of several variables related to patients' specific characteristics have been claimed. This, in turn, would have significant implications for researchers and clinical practitioners in terms of both assessment and rehabilitation strategies for TBI patients.

Data availability statement

All material and additional data (e.g., data extraction, data used for the analyses and codes) used for the present meta-analyses will be made available on requests to the corresponding Author.

Disclosure statement

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