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**Research Article**

# The impact of mild cognitive impairment on decision-making under explicit risk conditions: Evidence from the Personality and Total Health (PATH) Through Life longitudinal study

Craig Sinclair[1,2,3,4], Ranmalee Eramudugolla[1,3], Nicolas Cherbuin[2,5], Moyra E. Mortby[1,3,4] and Kaarin J. Anstey[1,3,4,5]

[1]School of Psychology, University of New South Wales, Sydney, Australia, [2]Australian Research Council Centre of Excellence in Population Ageing Research, University of New South Wales, Sydney, Australia, [3]UNSW Ageing Futures Institute, University of New South Wales, Sydney, Australia, [4]Neuroscience Research Australia (NeuRA), Sydney, Australia and [5]Centre for Research on Ageing, Health and Wellbeing, Australian National University, Canberra, Australia

## Abstract

**Objective:** Previous research has indicated that cognition and executive function are associated with decision-making, however the impact of mild cognitive impairment (MCI) on decision-making under explicit risk conditions is unclear. This cross-sectional study examined the impact of MCI, and MCI subtypes, on decision-making on the Game of Dice Task (GDT), among a cohort of older adults. **Method:** Data from 245 older adult participants (aged 72–78 years) from the fourth assessment of the Personality and Total Health Through Life study were analyzed. A diagnostic algorithm identified 103 participants with MCI, with subtypes of single-domain amnestic MCI (aMCI-single; $n = 38$), multi-domain amnestic MCI (aMCI-multi; $n = 31$), and non-amnestic MCI ($n = 33$), who were compared with an age-, sex-, education-, and income-matched sample of 142 cognitively unimpaired older adults. Decision-making scores on the GDT (net score, single number choices, and strategy changes) were compared between groups using nonparametric tests. **Results:** Participants with MCI showed impaired performance on the GDT, with higher frequencies of single number choices and strategy changes. Analyses comparing MCI subtypes indicated that the aMCI-multi subtype showed increased frequency of single number choices compared to cognitively unimpaired participants. Across the sample of participants, decision-making scores were associated with measures of executive function (cognitive flexibility and set shifting). **Conclusion:** MCI is associated with impaired decision-making performance under explicit risk conditions. Participants with impairments in multiple domains of cognition showed the clearest impairments. The GDT may have utility in discriminating between MCI subtypes.

**Keywords:** decision-making; older adults; cognitive dysfunction; mild cognitive impairment; executive function; Game of Dice Task

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Mild cognitive impairment (MCI) has been conceptualized as an intermediate stage between normal cognitive function and dementia (Winblad et al., 2004). People with MCI experience objective and sometimes subjective declines in cognition, to a greater extent than would be expected for their age and education level, while maintaining independent functioning and not meeting clinical criteria for dementia or other neurological disorders (Albert et al., 2011; Winblad et al., 2004). Although MCI diagnostic criteria require that activities of daily living are essentially unimpaired, functional impairments can be observed in more complex tasks, including bill paying (Griffith et al., 2003), driving (Anstey et al., 2017), and decision-making in health and financial contexts (Griffith et al., 2010; Martin et al., 2019; Okonkwo et al., 2008). A diagnosis of MCI confers an increased risk of conversion to dementia, estimated in the range of 5–10% annually (Mitchell & Shiri-Feshki, 2009), or 25–65% over a five-year period (Darmanthé, Tabatabaei-Jafari, & Cherbuin, 2021).

The cognitive impairments observed in MCI often involve memory (amnestic MCI, aMCI) but can also involve other cognitive domains such as executive functions, language, or visuo-construction (Albert et al., 2011). Diagnostic classifications based on the type and number of impaired domains on neuropsychological tests yield subtypes of single- and multi-domain amnestic and non-amnestic MCI, which are associated with different patterns of neuropathology (Csukly et al., 2016). Amnestic MCI is associated with higher rates of Alzheimer's disease (AD) type dementia (Reinvang, Grambaite, & Espeseth, 2012), while the non-amnestic (naMCI) subtypes are more predictive of other (non-AD) forms of dementia (Allain, Etcharry-Bouyx, & Verny, 2013; Wadley et al., 2007). Impairment in multiple domains is associated with higher rates of progression to dementia (Jung et al., 2020).

Secondary to memory impairment, impairments in attentional and executive functions are thought to be the most important and commonly affected cognitive domains in aMCI (Reinvang et al.,

**Corresponding author**: Craig Sinclair, email: c.sinclair@unsw.edu.au

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2012) and are associated with higher rates of progression to dementia (Belleville, Fouquet, Hudon, Hervé Tchala Vignon, & Croteau, 2017). Executive functions encompass a range of cognitive and functional abilities, including planning, working memory, attentional and inhibitory control, and feedback processing (Chan, Shum, Toulopoulou, & Chen, 2008). In studies which have investigated executive functions by MCI subtypes, people with multi-domain aMCI have shown the clearest impairments (Klekociuk & Summers, 2014; Pereiro, Juncos-Rabadan, & Facal, 2014). Brandt et al. (2009) used empirically derived components from 18 executive function tests to define three subdomains of executive function, which they labeled "planning/problem-solving," "working memory," and "judgement." In their study, the planning/problem-solving and working memory domains reliably discriminated between those with and without MCI, with impairments observed for all four MCI subtypes, and strongest impairments among those with multi-domain MCI. Given the established role of executive functions in deliberative decision-making processes (Schiebener & Brand, 2015a; Schiebener et al., 2014), this suggests that there may be impairment in decision-making among those with MCI, in particular among those with impairments in executive function domains.

Decision-making performance has been assessed behaviorally using tasks which vary in terms of task parameters (e.g., risk/reward contingencies), availability of information, and optimal strategies. In "ambiguous" decision-making tasks, no information is provided about task parameters or advantageous choices, and participants must learn these associations from experience (Bechara, Damasio, Tranel, & Damasio, 1997). In "explicit risk" decision-making tasks information is provided about the task parameters, enabling participants to deduce and implement optimal strategies (Schiebener & Brand, 2015a). These two types of tasks broadly map onto the conceptual heuristic of two separable "decision-making systems"; the fast, implicit and relatively effortless "impulsive" system and the slow, explicit and controlled "deliberative" system (Liebherr, Schiebener, Averbeck, & Brand, 2017; Tversky & Kahneman, 1986). Explicit risk decision-making tasks are thought to require processing within the "deliberative" system, with performance drawing on executive functions, logical reasoning, and feedback processing (Brand, Laier, Pawlikowski, & Markowitsch, 2009; Schiebener & Brand, 2015a).

The Game of Dice Task (GDT) is an important test of decision-making under explicit risk conditions, and has been used extensively, in both clinical and nonclinical samples (Brand et al., 2005). In the GDT participants make a series of gambles on the number of a rolled dice, attempting to maximize their capital. Participants can select between one and four numbers on each trial, thus enabling a conservative (e.g., four number choices have a moderate success probability along with smaller gains and losses) or risky strategy (e.g., single numbers have low success probability and larger gains and losses). Performance is typically measured by quantifying the "net score" (quantity of "safe" three or four number choices minus quantity of "risky" one or two number choices), single number choices (quantity of "riskiest" single number choices), and the number of strategy changes (changes between "safe" and "risky" response strategies on consecutive trials). The availability of task parameter information enables participants to deduce that a conservative strategy will be more profitable over time. Studies have suggested that executive functions (Brand & Schiebener, 2013; Schiebener et al., 2014), logical reasoning (Schiebener & Brand, 2015b), numerical processing (Brand, Schiebener, Pertl, & Delazer, 2014), working memory resources (Starcke, Pawlikowski, Wolf, Altstotter-Gleich, & Brand, 2011), and episodic learning (Sinclair, Eramudugolla, Brady, Cherbuin, & Anstey, 2021) underpin successful performance on the GDT. It is therefore not surprising that impaired GDT performance has been observed among clinical populations in which cognition is impaired, including people with Korsakoff's dementia (Brand et al., 2005), AD (Delazer, Sinz, Zamarian, & Benke, 2007; Sun et al., 2020), and Parkinson's disease (Euteneuer et al., 2009).

Existing studies of explicit risk decision-making among people with MCI have indicated subtle patterns of impairment, which are typically observable when decision tasks are ambiguous, complex, or draw heavily on affected domains of cognition (Pertl, Benke, Zamarian, & Delazer, 2017). Zamarian et al. (2011) found that people with MCI showed subtle impairments on a modified version of the revised Probability Assisted Gambling task (PAG-R), an explicit risk task. Studies employing the GDT have shown a mixed pattern of results among people with MCI (Fernandes, Macedo, Barbosa, & Marques-Teixeira, 2021). Jacus et al. (2013) found that people with MCI showed lower net scores on the GDT compared to older adults without cognitive impairment, along with an increased number of highest-risk "single number" choices. Sun et al. (2020) also showed this increased number of single number choices among people with MCI, but no differences on the overall net score. Pertl et al. (2015) found that people with MCI were unimpaired on basic decision tasks, but showed suboptimal decision-making on the modified "Game of Dice Task-Double" (GDT-D), which places increased demands on numerical and probability processing abilities relative to the standard GDT. These observational studies were based on smaller samples recruited in clinical settings, limiting the ability to control for potentially confounding variables between MCI and control cases. Furthermore, none of these studies were able to report data by MCI subtype, and it is not as yet known whether GDT performance varies by MCI subtype.

In the current study we aimed to better understand the impact of MCI on decision-making, through a cross-sectional investigation of decision-making performance on the GDT among older adults with and without MCI. Using a population-based sample recruited as part of a large longitudinal study enabled matching of people with MCI and cognitively unimpaired control cases on relevant confounding variables, as well as analysis of MCI subtypes. Based on the known contribution of executive function abilities to performance on the GDT (Schiebener et al., 2014), it is reasonable to propose that GDT performance may be more impacted among those with MCI subtypes in which executive functions are affected, in particular those with multi-domain aMCI. We hypothesized (H1) that compared to those without cognitive impairment, older adults with MCI would show evidence of decision-making impairment on the GDT, and (H2) that the level of impairment would be most apparent among those with multi-domain MCI. We also hypothesized (H3) that decision-making performance would be associated with measures of executive functions.

## Methods

The Personality and Total Health (PATH) Through Life study is a population-based longitudinal cohort study, which recruited participants residing in the Australian cities of Canberra and Queanbeyan and aged within narrow age cohorts (20–24, 40–44, and 60–64 years) at wave 1 (1999–2002) via random sampling from the electoral roll (Anstey et al., 2012). Electoral roll enrolment is compulsory in Australia. The current study uses data from the

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**Table 1.** Diagnostic algorithm stages and alignment with international working group criteria for mild cognitive impairment

| Screen 1. Identifying possible decline. | |
|---|---|
| Any participants with:<br>1) a previous diagnosis of dementia or mild cognitive disorder; OR<br>2) objective cognitive impairment (scoring at or below 6.7[th] percentile on one or more cognitive measures[a], or a Mini-Mental Status Examination (MMSE) score of ≤24; OR<br>3) self-reported subjective cognitive decline on the Memory Complaint Questionnaire (MAC-Q), or objective cognitive decline of >3 points since wave 3 on the MMSE. | |
| Screen 2. IWG criteria and associated diagnostic algorithm criteria | |
| **IWG criteria:** | **Algorithm criteria:** |
| 1. Does not meet criteria for dementia | Does not meet criteria for DSM-IV dementia (see Eramudugolla et al., 2017) for these algorithm criteria |
| 2. Either or both of the following (2a *and/or* 2b) | |
| 2a. Self and/or informant report of cognitive decline *and* impairment on objective cognitive tasks | MAC-Q > 24 *or* IQCODE > 3.31 *or* recent doctor's consultation about cognitive change or informant reported worsening in everyday cognition. *And* mean *z* score ≥ −2.0 and ≤ −1.0 for one or more of memory, complex attention, executive function, language and perceptual/motor domains[a] |
| 2b. Evidence of decline over time on objective cognitive tasks | Mean decline in performance between waves 3 and 4 that is > −2.0 to ≤ −1.0 standard deviations below norms on selected tests[b] |
| 3. Preserved basic activities of daily living or minimal impairment on IADLs | No difficulty with Bayer IADL items 2, 4, and 11 *or* no self-reported need for complex personal care help, *or* Bayer IADL < 3.12 |

*Note.* [a]Cognitive measures used to define objective impairment included: Symbol Digit Modalities Test, Trail Making Test Part A, Reaction Time Test (complex attention), Digit Span Backwards, Trail Making Test Part B, Stroop Color Word Test, Zoo Map Test, Game of Dice Test (executive function), California Verbal Learning Test, Benton Visual Retention Test (Administration B) (learning and memory), Letter Fluency, Boston Naming Test-15 item, Spot the Word Test (language), Purdue Pegboard, Ideomotor Apraxia Test (perceptual motor) and Reading the Mind in the Eyes.[b]Measures available to define decline over time included: California Verbal Learning Test immediate and delayed recall, Digit Span Backwards, Symbol Digit Modalities Test, Purdue Pegboard, Controlled Oral Word Association Test, Trail Making Test Part B, Simple Reaction Time, Complex Reaction Time.
IADL = Instrumental Activities of Daily Living; MAC-Q = Memory Assessment Complaint Questionnaire; IQCODE = Informant Questionnaire on Cognitive Decline in the Elderly.

older adult cohort (N = 2551 participants aged 60–66 years, with 58.3% response rate at wave 1), with a focus on outcome measures from the wave 4 data collection (2014–2015), in which 2048 participants were invited to respond, with data collected from 1644 participants aged 72–78 years (Anstey et al., 2021). The current study is reported in line with the Strengthening Reporting of OBservational studies in Epidemiology (STROBE) checklist and guidelines (von Elm et al., 2007).

### *Participants*

Of the 1644 older participants surveyed at wave 4, 1287 completed all GDT trials and were eligible for inclusion in the study. We defined a subgroup of participants meeting International Working Group (IWG) criteria for MCI (Winblad et al., 2004), using a validated diagnostic algorithm, which has been described previously in greater detail (Eramudugolla et al., 2017). The diagnostic algorithm utilized a combination of neuropsychological assessments, participant and informant survey responses, and participant medical history information for existing clinical diagnoses. Table 1 shows how DSM-IV criteria were operationalized using data collected in the PATH study, to identify participants with suspected cognitive disorders, and the subgroup with suspected MCI. We note that at the time of applying this algorithm, wave 4 GDT net scores were included in the battery of measures to screen for a cognitive disorder (Eramudugolla et al., 2017). While this raises a possibility of circularity, the GDT was just one of five measures used as part of the executive functions domain (17 tests across all domains). Participants with combined *z* scores for the measures on a domain of ≥ −2.0 and ≤ −1.0 SD below the gender- and education-standardized age group cohort mean were identified as having "objective impairment" on a domain. Other algorithmic criteria included reports of subjective cognitive changes, either by the participant on the Memory Assessment Complaint Questionnaire (Crook, Feher, & Larrabee, 1992) or by an informant on the Informant Questionnaire on Cognitive Decline in the Elderly (Jorm, 1994). Participants identified by this diagnostic algorithm were also reviewed clinically, with full case file review by a research neurologist, along with a psychiatrist for complex cases, to confirm the diagnosis (Eramudugolla et al., 2017). Among those identified as having MCI, subtyping was undertaken using standard criteria (Winblad et al., 2004). Those with evidence of impairment on the memory domain were classified as amnestic (aMCI), others without evidence of memory impairment were classed as non-amnestic (naMCI). For both aMCI and naMCI cases, those with evidence of impairment on two or more domains (either executive, language or visuo-spatial) were classed as multi-domain cases (aMCI-multi or naMCI-multi), while those without evidence of more than a single impaired domain were classed as single-domain (aMCI-single or naMCI-single). The process for classifying MCI and MCI subtypes was undertaken and published prior to the commencement of the current study (Eramudugolla et al., 2017).

Of the 1287 participants who completed the GDT, a total of 224 met the criteria for a cognitive disorder and 116 of these met IWG criteria for MCI. Among the participants with MCI, those with a self-reported history of stroke ($n = 7$), Parkinson's disease ($n = 3$), or missing data on these comorbidity flags ($n = 3$) were excluded, leaving a total of 103 participants with MCI for further analysis (see Figure 1). Of these participants, 38 were categorized as aMCI-single, 31 as aMCI-multi, 26 as naMCI-single, and 7 as naMCI-multi. Due to the small number of participants in the naMCI-single and naMCI-multi groups, these were collapsed into an overall naMCI subtype, with 33 participants. One participant with MCI had missing data relating to MCI subtype, and was excluded from analyses at the subtype level. Of the 103 included participants categorized as having MCI at wave 4, 15 (14.6%) had previously been identified as meeting IWG criteria for MCI at wave 3 (see Table 2).

The comparison group was a sample of older adults without MCI, drawn from the same cohort and wave of the PATH study, and matched on age, sex, years of education, and household income. The *MatchIt* package (version 4.3.4) was used to perform

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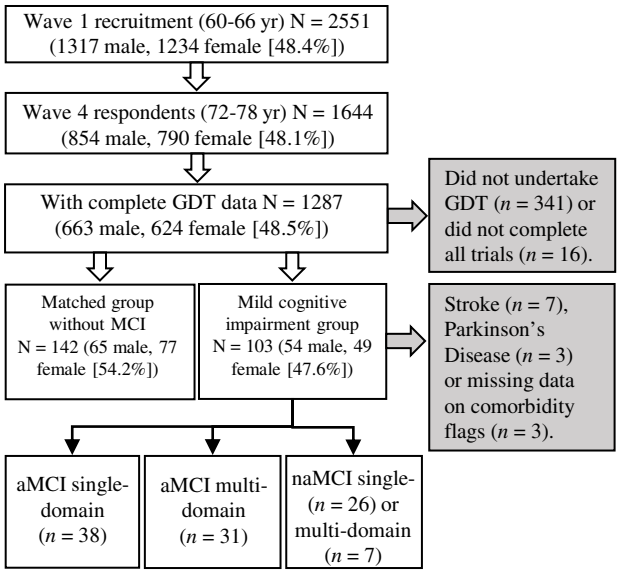


**Figure 1.** Participant flowchart showing exclusions (grey arrows and boxes) at each stage of recruitment and data processing. Gender breakdown is shown for major groups, percentages indicate the proportion of females in each wave cohort and the analytic sample.
*Note: aMCI = amnestic mild cognitive impairment; naMCI = non-amnestic cognitive impairment.*

two-to-one, nearest-neighbor, log-odds propensity score matching with replacement. The comparison group was drawn from the 1000 eligible participants with complete data on the GDT and relevant matching covariates, not meeting the criteria for MCI (or any other neurological condition or cognitive disorder) and with no self-reported history of stroke. This yielded a matched sample of 142 participants without MCI. Love Plots and Balance Plots were inspected to ensure acceptable covariate balance in the matched sample. As expected, Mini-Mental State Examination (MMSE) scores (Folstein, Folstein, & McHugh, 1975) were lower among participants with MCI than those without MCI (27.8 vs 29.2, $W = 10{,}648$, $p < .001$).

### Game of Dice Task

The GDT is a computerized decision-making task (Brand et al., 2005), in which participants commence with a hypothetical balance of $1000 AUD, and are asked to try to maximize their earnings across 18 trials. On each trial, participants choose a combination of one, two, three, or four numbers, aiming to match what appears to be a random dice roll (but is actually prespecified by software code and identical for all participants). The amount bet on each trial is specified by the combination of numbers chosen (one number = $1000 AUD bet, 16.7% chance to win; two numbers = $500 AUD bet, 33.3% chance to win; three numbers = $200 AUD bet, 50% chance to win; four numbers = $100 AUD bet, 66.7% chance to win) and is constant across the task. The gambles associated with each of the combinations are displayed on the screen, along with the participant's current balance. If the dice roll matches one of the numbers chosen by the participant on that trial, they win the gambled amount, which is added to their displayed balance. If the dice roll does not match any of the numbers chosen by the participant on that trial, they lose the gambled amount, which is subtracted from their displayed balance. Participants can continue to play even if their balance falls into a negative amount. The rewards and losses in the current task were hypothetical and participants were not compensated based on their performance or results. Based on the task reward structure and probabilities of success (which are constant across the task and always explicitly available to participants) a conservative strategy is the most optimal on this task (Brand, Heinze, Labudda, & Markowitsch, 2008). A choice of three or four numbers is classified as "low-risk," while a choice of one or two numbers is classified as "high-risk." Following previous studies (Brand et al., 2005; Pertl et al., 2015), performance on the GDT was assessed using the following measures:

1) Net score: the number of high-risk options (one or two numbers) subtracted from the number of low-risk options (three or four numbers) across the 18 trials, yielding a score between plus or minus 18, with higher scores indicating more advantageous decision-making.
2) Single number choices: the number of trials participants chose a single number option.
3) Strategy changes: the number of times participants changed between high-risk and low-risk options on consecutive trials.

### Cognitive measures

Previous studies have implicated the role of executive functions (Brand et al., 2005; Schiebener & Brand, 2015a), logical and numerical processing (Pertl, Zamarian, & Delazer, 2017), and working memory (Brand & Schiebener, 2013; Starcke et al., 2011) in behavioral tasks measuring decision-making under explicit risk, suggesting that higher-order cognitive and fluid processing abilities are of particular importance. The following measures were selected from the PATH wave 4 cognitive assessment battery, in order to i) describe levels of cognitive functioning among the participant groups, and ii) determine the cognitive abilities associated with decision-making performance for participants with MCI. The Symbol Digit Modalities Test (SDMT, Smith, 1982) was used as a measure of attention and perceptual processing speed, scored by the number of successfully completed symbols in 90 s (maximum score = 110). The Trail Making Test (TMT, Reitan & Wolfson, 1995) was used as a measure of psychomotor speed (Part A); and cognitive flexibility and set shifting (Part B). Part A and Part B completion times were used rather than a difference score, as the direct measure of Part B completion time has been shown to be more strongly predictive of GDT performance (Schiebener et al., 2014). Following the methods described by Heaton et al. (Correia et al., 2015; Heaton, Miller, Taylor, & Grant, 2004), a prorated score was calculated for the ($n = 9$) participants who did not complete all 25 circles within the maximum allowable time of 300 s, for both Part A and Part B. The Stroop Color-Word Interference Test (Spreen & Strauss, 1998; Stroop, 1935) was used as a measure of inhibitory control, by calculating an interference ratio score (color-word interference task time divided by color-dot naming task time), with higher scores reflecting an increased difficulty in inhibiting automatic responses. The first trial of the Zoo Map task (number of correct places visited minus number of errors, with broad instructions only) from the Behavioral Assessment of Dysexecutive Syndrome (Wilson, Alderman, Burgess, Emslie, & Evans, 1996) was used as a measure of planning and goal-directed behavior (Oosterman, Wijers, & Kessels, 2013). The Controlled Oral Word Association Test (COWAT, Benton, Hamsher, & Sivan, 1983) was used as a measure of phonemic verbal fluency, scored by the sum of the number of "a" words and "f" words spontaneously produced in separate trials of 60 s duration (only two of the three stimulus letters were used in

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**Table 2.** Participant demographic characteristics and cognitive measures by diagnostic grouping

| | | Cognitively unimpaired ($n = 142$) | Mild cognitive impairment ($n = 103$) | Amnestic MCI single-domain ($n = 38$) | Amnestic MCI multi-domain ($n = 31$) | Non-amnestic MCI ($n = 33$) | Test statistic | $p$ | Effect size |
|---|---|---|---|---|---|---|---|---|---|
| **Demographics** | | | | | | | | | |
| Age (years) | M (SD) | 75.1 (1.56) | 75.0 (1.63) | 75.3 (1.54) | 74.9 (1.45) | 74.9 (1.91) | $W = 7{,}561$ | .646 | – |
| Gender (female) | n (%) | 65 (45.8%) | 49 (47.5%) | 18 (47.4%) | 13 (41.9%) | 18 (54.5%) | $\chi^2$ (1, 245) = .02 | .882 | – |
| Education (years) | M (SD) | 13.3 (2.76) | 13.1 (3.08) | 14.0 (2.89) | 12.8 (2.97) | 12.3 (3.16) | $W = 7{,}393$ | .883 | – |
| Household income | | – | – | – | – | – | $\chi^2$ (2, 245) = .744 | .689 | – |
| (<$575/week) (Ref) | n (%) | 33 (23.2%) | 27 (26.2%) | 12 (31.6%) | 7 (22.6%) | 8 (24.2%) | – | – | – |
| (>=$575/week) | n (%) | 93 (65.5%) | 62 (60.2%) | 21 (55.3%) | 19 (61.3%) | 21 (63.6%) | – | – | – |
| Don't know/ Refused | n (%) | 16 (11.3%) | 14 (13.6%) | 5 (13.2%) | 5 (16.1%) | 4 (12.1%) | – | – | – |
| Pre-existing MCI (Wave 3) | n (%) | 0 (0%) | 15 (14.6%) | 5 (13.1%) | 8 (25.8%) | 2 (6.1%) | – | – | – |
| **Cognitive Measures** | | | | | | | | | |
| Mini-Mental State Examination | M (SD) | 29.2 (1.01) | 27.8 (2.00) | 28.1 (2.07) | 27.4 (2.23) | 27.8 (1.70) | $W = 10{,}648$ | <.001 | $r^2 = .40$ |
| Symbol Digit Modalities Test | M (SD) | 46.5 (8.83) | 39.1 (9.14) | 43.3 (8.62) | 35.2 (9.59) | 37.6 (7.33) | $W = 10{,}532$ | <.001 | $r^2 = .38$ |
| Trail Making Test Part A (sec.) | M (SD) | 34.6 (10.8) | 47.8 (31.5) | 39.9 (12.9) | 51.4 (27.1) | 54.2 (46.2) | $W = 3{,}944$ | <.001 | $r^2 = .39$ |
| Trail Making Test Part B (sec.) | M (SD) | 83.4 (29.5) | 125 (44.8) | 98.4 (33.2) | 148 (43.3) | 139 (42.0) | $W = 2{,}578$ | <.001 | $r^2 = .50$ |
| Zoomap Test 1 | M (SD) | 1.87 (4.84) | 0.07 (5.02) | 0.95 (4.19) | −0.59 (5.19) | −0.22 (5.72) | $W = 8{,}245$ | <.001 | $r^2 = .19$ |
| Stroop Color-Word Interference | M (SD) | 2.44 (0.70) | 2.66 (1.13) | 2.42 (0.75) | 2.77 (1.36) | 2.84 (1.24) | $W = 6{,}830$ | .43 | – |
| Controlled Oral Word Test | M (SD) | 26.2 (9.22) | 19.7 (8.74) | 21.6 (7.68) | 16.8 (8.79) | 19.6 (8.73) | $W = 10{,}038$ | <.001 | $r^2 = .33$ |
| Digit Span Backwards | M (SD) | 5.11 (2.00) | 3.88 (2.00) | 4.47 (2.39) | 3.73 (1.51) | 3.36 (1.80) | $W = 9{,}801$ | <.001 | $r^2 = .31$ |
| CVLT Immediate Recall | M (SD) | 9.71 (2.53) | 7.01 (2.59) | 6.53 (2.11) | 5.55 (2.28) | 8.94 (2.28) | $W = 11{,}334$ | <.001 | $r^2 = .47$ |
| CVLT Delayed Recall | M (SD) | 7.87 (3.21) | 4.73 (2.65) | 3.58 (1.93) | 3.68 (2.07) | 7.09 (2.36) | $W = 11{,}338$ | <.001 | $r^2 = .47$ |

*Note.* Test statistic and effect size results refer to independent paired samples tests or bivariate associations between cognitively unimpaired ($n = 142$) and mild cognitive impairment ($n = 103$) groups. For the cognitive measures higher scores reflect higher levels of performance, except for the Trail Making Test Parts A and B and Stroop Color-Word Interference ratio score. $W$ = Wilcoxon rank sum test, $\chi^2$ = chi-square test, V = Cramer's V effect size coefficient, $r^2$ = effect size coefficient ($r^2 < 0.3$ = small effect, $0.3 < r^2 < 0.5$ = medium effect), SD = standard deviation, CVLT = California Verbal Learning Test.

the PATH study). The Digit Span Backwards Test from the Wechsler Memory Scale (Wechsler, 1945, 1997) was used as a measure of verbal working memory. Immediate and delayed recall scores from the first list of the California Verbal Learning Test (CVLT, Delis et al., 1991) were used to assess episodic verbal learning and episodic verbal memory, respectively. The MMSE (Folstein et al., 1975) was used to describe global levels of cognitive function across participant groups.

### *Data analysis*

The data were analyzed using R (version 12.6.3) in the R Studio environment (version 1.3.1093). Continuous measures were inspected for normality and homogeneity of variance. Graphical inspection of GDT performance measures indicated deviations from normality, which were confirmed statistically. The GDT net scores deviated from normality and were negatively skewed (Shapiro–Wilk = .93, $p < .001$; skewness = −.45, $p < .001$; kurtosis = 2.16, $p < .001$). Single number choices (Shapiro–Wilk = .76, $p < .001$; skewness = 1.74, $p < .001$; kurtosis = 2.98, $p < .001$) and the number of strategy changes (Shapiro–Wilk = .93, $p < .001$; skewness = .31, $p < .001$; kurtosis = −.97, $p < .001$) were positively skewed and zero-inflated. Analysis used nonparametric tests, including Wilcoxon rank-sum tests and Kruskal–Wallis tests for between group differences with Benjamini–Hochberg correction (Benjamini & Hochberg, 1995) to control the false discovery rate for pairwise comparisons. Associations between continuous measures were assessed using Spearman's ρ rank order correlations.

Sensitivity analyses were undertaken for the primary hypothesis (H1), to determine whether the reported findings were dependent on i) exclusion of participants with MCI who had other neurological abnormalities, or ii) inclusion of participants with existing MCI prior to wave 4 (see Supplementary File 1).

### *Ethics approvals*

The study procedures were conducted in accordance with the Declaration of Helsinki and approved by the Australian National University Human Research Ethics Committee. All participants provided written informed consent.

## Results

Participant characteristics and cognitive test score summaries by diagnostic group are shown in Table 2. The propensity score matched sample of participants without cognitive impairment

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**Table 3.** Game of Dice Task (GDT) performance measures by diagnostic grouping

| | Cognitively unimpaired ($n = 142$) | Mild cognitive impairment ($n = 103$) | Amnestic MCI single-domain ($n = 38$) | Amnestic MCI multi-domain ($n = 31$) | Non-amnestic MCI ($n = 33$) |
|---|---|---|---|---|---|
| **Net Score** | | | | | |
| Mean (SD) | 4.27 (10.3) | 2.56 (9.97) | 3.53 (10.8) | 0.32 (8.55) | 3.15 (10.1) |
| Median | 6 | 2 | 4 | 0 | 2 |
| Test statistic, *p* value | | $W = 8{,}086$, $p$=.16 | $W = 2{,}588$, $p$=.84 | $W = 1{,}654$, $p$=.18 | $W = 2{,}508$, $p$=.79 |
| **Single number choices** | | | | | |
| Mean (SD) | 3.00 (3.74) | 3.85 (3.87) | 3.63 (4.51) | 4.35 (2.98) | 3.73 (3.92) |
| Median | 2 | 3 | 2 | 4 | 3 |
| Test statistic, *p* value | | $W = 6{,}060$, $p$=.02 | $W = 2{,}865$, $p$=.55 | $W = 2{,}934$, $p$=.02 | $W = 1{,}979$, $p$=.29 |
| **Strategy changes** | | | | | |
| Mean (SD) | 4.65 (3.27) | 5.50 (3.42) | 5.18 (3.81) | 6.32 (3.29) | 5.18 (2.99) |
| Median | 5 | 6 | 6 | 6 | 6 |
| Test statistic, *p* value | | $W = 6{,}224$, $p$=.046 | $W = 2{,}962$, $p$=.42 | $W = 2{,}812$, $p$=.09 | $W = 2{,}094$, $p$=.42 |

*Note.* Test statistic results refer to independent samples tests between cognitively unimpaired ($n = 142$) and mild cognitive impairment ($n = 103$) groups, along with pairwise tests for each MCI subtype (against the cognitively unimpaired group). For the GDT net score measure (−18 minimum to 18 maximum) higher scores reflect higher levels of performance. For the frequency of single number choices (0 minimum to 18 maximum) and strategy changes (0 minimum to 17 maximum) lower scores reflect higher levels of performance.
$W$ = Wilcoxon rank sum test, $r^2$ = effect size coefficient ($r^2 < 0.3$ = small effect), SD = standard deviation; MCI = mild cognitive impairment.

did not differ significantly from participants with MCI on age (75.1 vs 75.0 years, $W = 7{,}561$, $p = .646$), gender (45.8% vs 47.5% female $\chi^2$ (1, N = 245) = .02, $p = .882$), level of education (13.3 vs 13.1 years, $W = 7{,}393$, $p = .883$), or likelihood of reporting equal to or greater than $575 AUD per week in household income (65.5% vs 60.2%, $\chi^2$ (2, N = 245) = .744, $p = .689$) than participants with MCI. As expected, participants with MCI performed more poorly than participants without cognitive impairment on the cognitive measures ($p$'s < .001), with the exception of the Stroop Color-Word Interference ratio score (2.66 vs 2.44, $W = 6{,}830$, $p = .43$).

### *Decision-making performance scores*

Decision-making performance scores by diagnostic group are shown in Table 3. GDT net scores were not significantly lower among participants with MCI compared to participants without cognitive impairment (2.56 vs 4.27, $W = 8{,}086$, $p = .157$). The frequency of single number choices was significantly higher among participants with MCI compared to those without cognitive impairment (3.85 vs 3.00, $W = 6060$, $p = .02$, $r^2 = .15$). Participants with MCI also made more strategy changes than those without cognitive impairment (5.50 vs 4.65, $W = 6{,}224$, $p = .046$, $r^2 = .13$).

Sensitivity analyses investigated whether the reported study findings are robust to modifications in the exclusion criteria. Separate analyses tested H1 by i) including all participants categorized as having MCI at wave 4 ($n = 116$) or ii) further limiting the MCI sample to those with incident MCI at wave 4 ($n = 88$), by excluding those ($n = 15$) who had previously met MCI criteria at wave 3. In both cases the sensitivity analyses found the same pattern of results for the (H1) primary study outcomes for GDT net scores and the frequency of single number scores, but not for strategy changes (see Supplementary File 1).

Analysis at the subtype level compared the aMCI-single, aMCI-multi, naMCI, and cognitively unimpaired groups on each of the three GDT performance measures. For GDT net scores (see Figure 2) there was no significant effect of MCI subtype ($\chi^2$ (3, N = 244) = 4.72, $p = .19$). For the number of single dice choices there was a significant effect of MCI subtype ($\chi^2$ (3, N = 244) = 9.42, $p = .02$). Pairwise comparisons indicated that the only significant effect was between the cognitively unimpaired and aMCI-multi groups (3.00 vs 4.35, $p = .02$), with all other comparisons $p > .29$. For the number of strategy changes there was no significant effect of MCI subtype ($\chi^2$ (3, N = 244) = 6.24, $p = .10$). However due to the main effect of participants with MCI compared to those without cognitive impairment on this measure, pairwise comparisons were investigated, to better understand the pattern of results across MCI subtypes (see Table 3).

Spearman rank order correlation analyses were conducted to assess associations between decision-making performance and cognitive measures across the entire study sample (see Table 4). GDT net scores were significantly associated with scores on the SDMT ($\rho = .13$, $p = .046$), TMT Part B ($\rho = -.21$, $p = .001$), Zoomap Part 1 raw scores ($\rho = .17$, $p = .009$), Stroop interference scores ($\rho = -.14$, $p = .02$), and CVLT immediate recall ($\rho = .13$, $p = .04$). The number of single dice choices were significantly associated with scores on the SDMT ($\rho = -.18$, $p = .004$), TMT Part A ($\rho = .15$, $p = .02$), TMT Part B ($\rho = .26$, $p < .001$), Zoomap Part 1 raw scores ($\rho = -.19$, $p = .003$), Stroop interference scores ($\rho = .14$, $p = .03$), Digit Span Backwards ($\rho = -.15$, $p = .02$), CVLT immediate recall ($\rho = -.18$, $p = .004$), and CVLT delayed recall ($\rho = -.15$, $p = .02$). The number of strategy changes was significantly associated with scores on the TMT Part B ($\rho = .22$, $p < .001$), COWAT ($\rho = -.16$, $p = .01$), CVLT immediate recall ($\rho = -.15$, $p = .02$), and CVLT delayed recall ($\rho = -.20$, $p = .002$).

## Discussion

The current study demonstrated a pattern of less advantageous decision-making performance on the GDT among participants with MCI relative to a matched sample of older adults without cognitive impairment. While impaired decision-making was observed across two of the three outcome measures (frequency of single number choices and frequency of strategy changes), the clearest impairments were seen on the frequency of single number choices measure. In a follow-up analysis of single number choices, participants classified in the aMCI-multi group were the only subtype to show impairments in decision-making performance compared with cognitively unimpaired participants.

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**Table 4.** Correlations between Game of Dice Task (GDT) performance measures and cognitive measures among all study participants

| | Net Score | *p* | Single number choices | *p* | Strategy changes | *p* |
|---|---|---|---|---|---|---|
| Mini Mental State Examination | .11 | .09 | −.14 | .03 | .03 | .59 |
| Symbol Digit Modalities Test | .13 | .046 | −.18 | .004 | −.12 | .07 |
| Trail Making Test Part A (sec.) | −.12 | .06 | .15 | .02 | .09 | .17 |
| Trail Making Test Part B (sec.) | −.21 | .001 | .26 | <.001 | .22 | <.001 |
| Zoomap Test 1 | .17 | .009 | −.19 | .003 | −.08 | .24 |
| Stroop Color-Word Interference | −.14 | .023 | .14 | .029 | .11 | .08 |
| Controlled Oral Word Association Test | .098 | .13 | −.10 | .10 | −.16 | .01 |
| Digit Span Backwards | .12 | .06 | −.15 | .02 | −.12 | .06 |
| CVLT Immediate Recall | .13 | .04 | −.18 | .004 | −.15 | .02 |
| CVLT Delayed Recall | .10 | .10 | −.15 | .02 | −.20 | .002 |

*Note.* Correlations are expressed using Spearman's rho coefficient. For the GDT net score measure (−18 minimum to 18 maximum) higher scores reflect higher levels of performance. For the frequency of single number choices (0 minimum to 18 maximum) and strategy changes (0 minimum to 17 maximum) lower scores reflect higher levels of performance. For the cognitive measures higher scores reflect higher levels of performance, except for the Trail Making Test Parts A and B and Stroop Color-Word Interference ratio score.

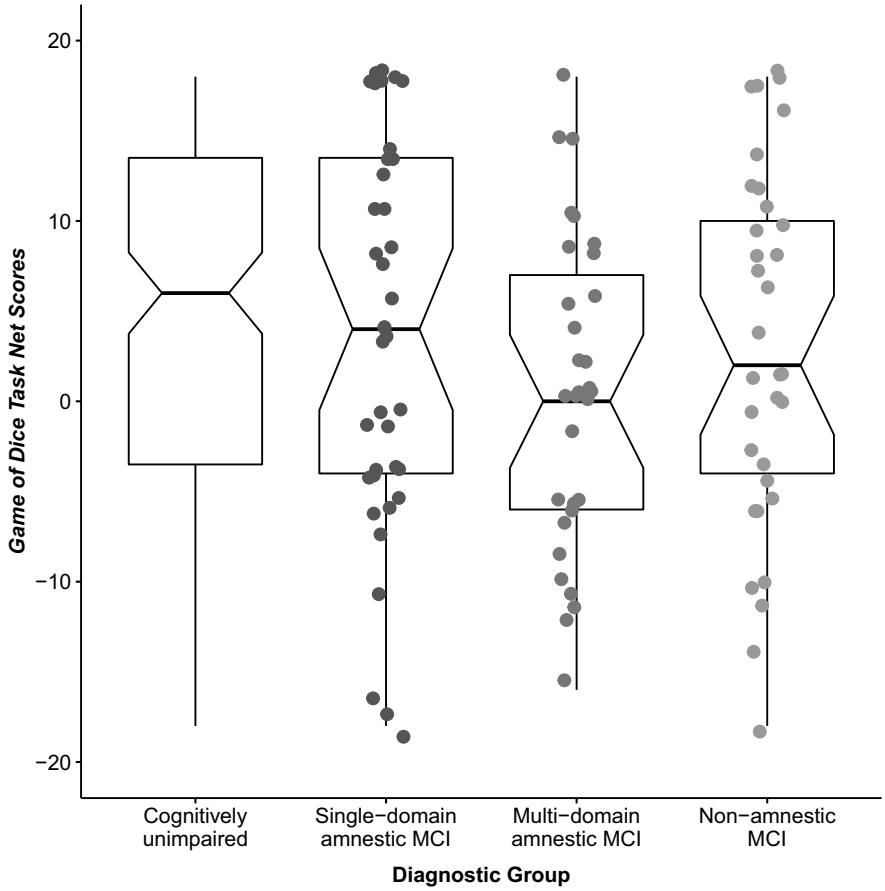


**Figure 2.** Game of Dice Task (GDT) net scores by mild cognitive impairment (MCI) subtypes, with jittered dots indicating individual participant scores within each MCI subtype. Boxplots indicate median and inter-quartile range, with notches indicating confidence intervals around the median for each group.

The current study findings are consistent with Sun et al. (2020) who showed that people with MCI chose single numbers more frequently, but did not differ from older adults without cognitive impairment on the use of negative feedback or overall GDT net score. Our observation of statistically significant differences in the frequency of single number choices and strategy changes on the GDT suggests a tendency toward more high-risk response patterns, along with a greater propensity for changing response patterns between trials, among older adults with MCI. Within existing theoretical models of decision-making under explicit risk conditions, it is proposed that "deliberative" and "impulsive" systems are activated concurrently, with a range of individual, contextual and decision-related factors influencing which is dominant for a specific decision (Schiebener & Brand, 2015a). The presence of cognitive impairment may reduce the fluid processing resources available to activate (limited capacity) deliberative decision-making systems, resulting in greater dominance of the impulsive decision-making system. This could lead to an increased tendency to choose on the basis of somatic responses activated by prospects of large rewards (e.g., high-risk responses), or to change response strategies repeatedly in response to feedback from immediately prior trials.

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Investigations by MCI subtype indicated that the only group with reliable differences in decision-making performance relative to those without cognitive impairment was the aMCI-multi group. This group showed more frequent single number choices than the cognitively unimpaired group. Executive function abilities have been consistently shown to predict performance on the GDT (Brand & Schiebener, 2013; Schiebener, Zamarian, Delazer, & Brand, 2011) and are also found to be more impaired among those with multi-domain, as opposed to single-domain MCI (Brandt et al., 2009; Klekociuk & Summers, 2014; Pereiro et al., 2014). In the current study, the aMCI-multi group also showed relatively poorer performance on a number of the included cognitive assessments, including measures of executive function abilities (TMT Part B, Zoomap test, COWAT) compared to participants without cognitive impairment or other MCI subtypes. This suggests that the aMCI-multi group included a higher proportion of participants with attentional or executive function impairments in addition to memory impairments, whose poorer executive function abilities may have contributed to their poorer performance on the GDT (Brand & Schiebener, 2013; Schiebener et al., 2014). Changes in frontal and striatal brain regions associated with the "dysexecutive" form of MCI (Grambaite et al., 2011) may result in difficulties in inhibiting impulsive responses, and difficulties activating deliberative systems to integrate task information, process feedback, and select optimal responses to maximize probabilities of success (Schiebener & Brand, 2015a). However, while the aMCI-multi group appears to include participants with attentional and/or executive impairments, we also note that other subtypes, in particular participants in the naMCI subtype, also showed evidence of executive function impairments. The absence of reliable impairment on the GDT in the naMCI group suggests that impairments in memory and/or learning may also play a role in performance on the GDT (Sinclair et al., 2021; Starcke et al., 2011). Hence the observed findings may also reflect broader impacts across multiple cognitive domains. Future work might investigate whether impairment on the GDT emerges in the context of combined amnestic and dysexecutive patterns of impairment.

Across this sample of older adult participants, and for all three of the GDT performance scores (net scores, single number choices and strategy changes) the cognitive assessment showing the strongest association with GDT performance was the TMT Part B completion time. This supports previous observations of associations between GDT performance and measures of executive functions, in particular the TMT Part B, as a measure that is correlated with GDT scores (Schiebener et al., 2014). However, additional correlations were noted between GDT performance and measures of attention, planning, inhibitory control, working memory, and episodic learning. These are consistent with previous studies, including in populations without cognitive impairment (Brand, Labudda, & Markowitsch, 2006; Sinclair et al., 2021; Starcke et al., 2011). The GDT is a multicomponent decision-making task, and optimal response has been proposed to require directing attention toward the risk-reward contingencies for the task, undertaking numerical processing to identify an optimal strategy, activating responses in line with this strategy, and integrating feedback from prior trials to refine and update the strategy (Schiebener & Brand, 2015a). The overall low magnitude of the correlations between GDT scores and all of the cognitive assessments suggest that the GDT may reflect a more complex range of cognitive abilities, albeit with an emphasis on executive functions (Gathmann, Brand, & Schiebener, 2017; Schiebener et al., 2011).

The inconsistent effects from previous studies, along with the small effect sizes observed in the current study, suggest that MCI is associated with subtle impairments in decision-making when tasks are predictable and straightforward. Clearer impairments are observed in the context of more advanced neuropathology (e.g., dementia diagnosis; Mueller et al., 2019; Sun et al., 2020) or more complex tasks, such as the GDT-D (Pertl et al., 2015) or PAG-R (Zamarian et al., 2011). Given our findings that differences between participants with and without MCI on the GDT appear to be primarily driven by the aMCI-multi subtype (at least on single number choices), it may be that the inconsistent findings in previous studies were due to differences in the (unreported) proportions of participants with different MCI subtypes.

### *Strengths and limitations*

The current study has some limitations, which should be considered in interpreting the results. Sample representativeness is impacted by prior sample attrition (e.g., loss to follow-up or death). Also, 357 potentially eligible participants (28 of whom met IWG criteria for MCI) were excluded as they did not complete the GDT. The propensity score matching achieved acceptable matching on age, sex, years of education, and level of household income between participants with MCI and those without MCI, however other unobserved variables may also contribute to the observed between group effects. On the other hand, the population-based, prospective recruitment methods employed in the current study enables more representative sampling and control for a broader range of covariates across multiple observation points, and is a strength. While the inclusion of wave 4 GDT net scores as part of the screening for cognitive disorders raises a possibility of circularity, this measure was just one of five assessments used in the executive functions domain, and those identified by the algorithm were also reviewed clinically to confirm the diagnostic classification (Eramudugolla et al., 2017). Finally, the GDT is typically thought to measure individual decision-making under explicit risk conditions, within a financial (gambling) domain, and without the prospect of real monetary gains or losses that might be associated with real-world financial decision-making. Hence, this task may lack personal relevance to participants, thus limiting its generalizability to real-world contexts. However, previous work has suggested that performance impairments on behavioral decision-making tasks are associated with real-world decision-making impairments (Pertl, Benke, et al., 2017), such as susceptibility to fraudulent advertising (Denburg et al., 2007).

### *Implications*

The current findings identified impaired decision-making performance among participants with MCI, and suggest that the GDT can discriminate between participants with and without MCI. This may have implications for clinicians who are designing or selecting measures aimed at detecting early signs of cognitive impairment or discriminating between MCI subtypes, particularly in community-based samples. The current findings also demonstrate the importance of MCI subtypes in decision-making performance, suggesting that MCI subtype categories should be reported where possible.

### *Conclusion*

The current study demonstrates impaired decision-making performance among participants with MCI, relative to older adults

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without cognitive impairment. To our knowledge, this study is the first to enable comparative analysis by MCI subtype, showing subtle decision-making impairments among participants with multi-domain amnestic MCI. Further research is required to understand the specific pattern of pathology associated with impaired decision-making performance on the GDT, and its relevance for providing supportive interventions to assist people with MCI in real-world decision-making contexts.

**Supplementary material.** To view supplementary material for this article, please visit https://doi.org/10.1017/S1355617722000765

**Data availability statement.** The data from the Personality and Total Health (PATH) Through Life study are not publicly available, however they can be accessed via an application to the Research Subcommittee http://pathstudy.org.au. Full analysis script will be made available upon request.

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**Conflicts of interest.** None.

## References

Albert, M. S., DeKosky, S. T., Dickson, D., Dubois, B., Feldman, H. H., Fox, N. C., Gamst, A., Holtzman, D. M., Jagust, W. J., Petersen, R. C., Snyder, P. J., Carrillo, M. C., Thies, B., & Phelps, C. H. (2011). The diagnosis of mild cognitive impairment due to Alzheimer's disease: Recommendations from the National Institute on Aging-Alzheimer's Association workgroups on diagnostic guidelines for Alzheimer's disease. *Alzheimer's & Dementia*, *7*, 270–279. https://doi.org/10.1016/j.jalz.2011.03.008

Allain, P., Etcharry-Bouyx, F., & Verny, C. (2013). Executive functions in clinical and preclinical Alzheimer's disease. *Revue Neurologique*, *169*, 695–708. https://doi.org/10.1016/j.neurol.2013.07.020

Anstey, K. J., Butterworth, P., Christensen, H., Easteal, S., Cherbuin, N., Leach, L., Burns, R., Kiely, K. M., Mortby, M. E., Eramudugolla, R., & Gad, I. (2021). Cohort profile update: The PATH through life project. *International Journal of Epidemiology*, *50*, 35–36. https://doi.org/10.1093/ije/dyaa179

Anstey, K. J., Christensen, H., Butterworth, P., Easteal, S., Mackinnon, A., Jacomb, T., Maxwell, K., Rodgers, B., Windsor, T., Cherbuin, N., & Jorm, A. F. (2012). Cohort profile: The PATH through life project. *International Journal of Epidemiology*, *41*, 951–960. https://doi.org/10.1093/ije/dyr025

Anstey, K. J., Eramudugolla, R., Chopra, S., Price, J., Wood, J. M., & Bondi, M. (2017). Assessment of driving safety in older adults with mild cognitive impairment. *Journal of Alzheimer's Disease*, *57*, 1197–1205. https://doi.org/10.3233/JAD-161209

Bechara, A., Damasio, H., Tranel, D., & Damasio, A. (1997). Deciding advantageously before knowing the advantageous strategy. *Science*, *275*, 1293–1295. https://doi.org/10.1126/science.275.5304.1293

Belleville, S., Fouquet, C., Hudon, C., Hervé Tchala Vignon, Z., & Croteau, J. (2017). Neuropsychological measures that predict progression from mild cognitive impairment to Alzheimer's type dementia in older adults: a systematic review and meta-analysis. *Neuropsychology Review*, *27*, 328–353. https://doi.org/10.1007/s11065-017-9361-5

Benjamini, Y., & Hochberg, Y. (1995). Controlling the false discovery rate: A practical and powerful approach to multiple testing. *Journal of the Royal Statistical Society. Series B (Methodological)*, *57*, 289–300.

Benton, A. L., Hamsher, d. S. K., & Sivan, A. B. (1983). *Multilingual aphasia examination* (2nd ed.). Iowa City, IA: AJA Associates.

Brand, M., & Schiebener, J. (2013). Interactions of age and cognitive functions in predicting decision making under risky conditions over the life span. *Journal of Clinical and Experimental Neuropsychology*, *35*, 9–23. https://doi.org/10.1080/13803395.2012.740000

Brand, M., Fujiwara, E., Borsutzky, S., Kalbe, E., Kessler, J., & Markowitsch, H. J. (2005). Decision-making deficits of Korsakoff patients in a new gambling task with explicit rules: Associations with executive functions. *Neuropsychology*, *19*, 267–277. https://doi.org/10.1037/0894-4105.19.3.267

Brand, M., Heinze, K., Labudda, K., & Markowitsch, H. J. (2008). The role of strategies in deciding advantageously in ambiguous and risky situations. *Cognitive Processing*, *9*, 159–173. https://doi.org/10.1007/s10339-008-0204-4

Brand, M., Labudda, K., & Markowitsch, H. J. (2006). Neuropsychological correlates of decision-making in ambiguous and risky situations. *Neural Networks: The Official Journal of the International Neural Network Society*, *19*, 1266. https://doi.org/10.1016/j.neunet.2006.03.001

Brand, M., Laier, C., Pawlikowski, M., & Markowitsch, H. J. (2009). Decision making with and without feedback: The role of intelligence, strategies, executive functions, and cognitive styles. *Journal of Clinical and Experimental Neuropsychology*, *31*, 984–998. https://doi.org/10.1080/13803390902776860

Brand, M., Schiebener, J., Pertl, M.-T., & Delazer, M. (2014). Know the risk, take the win: How executive functions and probability processing influence advantageous decision making under risk conditions. *Journal of Clinical and Experimental Neuropsychology*, *36*, 914–929. https://doi.org/10.1080/13803395.2014.955783

Brandt, J., Aretouli, E., Neijstrom, E., Samek, J., Manning, K., Albert, M. S., & Bandeen-Roche, K. (2009). Selectivity of executive function deficits in mild cognitive impairment. *Neuropsychology*, *23*, 607–618. https://doi.org/10.1037/a0015851

Chan, R. C. K., Shum, D., Toulopoulou, T., & Chen, E. Y. H. (2008). Assessment of executive functions: Review of instruments and identification of critical issues. *Archives of Clinical Neuropsychology*, *23*, 201–216. https://doi.org/10.1016/j.acn.2007.08.010

Correia, S., Ahern, D. C., Rabinowitz, A. R., Farrer, T. J., Watts, A. K. S., Salloway, S., Malloy, P. F., & Deoni, S. C. L. (2015). Lowering the floor on trail making test Part B: Psychometric evidence for a new scoring metric. *Archives of Clinical Neuropsychology*, *30*, 643–656. https://doi.org/10.1093/arclin/acv040

Crook, T. H., Feher, E. P., & Larrabee, G. J. (1992). Assessment of memory complaint in age-associated memory impairment: The MAC-Q. *International Psychogeriatrics*, *4*, 165–176. https://doi.org/10.1017/S1041610292000991

Csukly, G., Sirály, E., Fodor, Z., Horváth, A., Salacz, P., Hidasi, Z., Csibri, É., Rudas, G., & Szabó, Á. (2016). The differentiation of amnestic type MCI from the non-amnestic types by structural MRI. *Frontiers in Aging Neuroscience*, *8*, 52–52. https://doi.org/10.3389/fnagi.2016.00052

Darmanthé, N., Tabatabaei-Jafari, H., & Cherbuin, N. (2021). Combination of plasma neurofilament light chain and mini-mental state examination score predicts progression from mild cognitive impairment to Alzheimer's disease within 5 years. *Journal of Alzheimer's Disease*, 1–14. https://doi.org/10.3233/JAD-210092

Delazer, M., Sinz, H., Zamarian, L., & Benke, T. (2007). Decision-making with explicit and stable rules in mild Alzheimer's disease. *Neuropsychologia*, *45*, 1632–1641. https://doi.org/10.1016/j.neuropsychologia.2007.01.006

Delis, D. C., Massman, P. J., Kaplan, E., McKee, R., Kramer, J. H., & Gettman, D. (1991). Alternate form of the California verbal learning test: Development and reliability. *Clinical Neuropsychologist*, *5*, 154–162. https://doi.org/10.1080/13854049108403299

Denburg, N. L., Cole, C. A., Hernandez, M., Yamada, T. H., Tranel, D., Bechara, A., & Wallace, R. B. (2007). The orbitofrontal cortex, real-world decision making, and normal aging. *Annals of the New York Academy of Sciences*, *1121*, 480–498. https://doi.org/10.1196/annals.1401.031

Eramudugolla, R., Mortby, M. E., Sachdev, P., Meslin, C., Kumar, R., & Anstey, K. J. (2017). Evaluation of a research diagnostic algorithm for DSM-5 neurocognitive disorders in a population-based cohort of older adults. *Alzheimer's Research & Therapy*, *9*, 15. https://doi.org/10.1186/s13195-017-0246-x

Euteneuer, F., Schaefer, F., Stuermer, R., Boucsein, W., Timmermann, L., Barbe, M. T., Ebersbach, G., Otto, J., Kessler, J., & Kalbe, E. (2009). Dissociation of

decision-making under ambiguity and decision-making under risk in patients with Parkinson's disease: a neuropsychological and psychophysiological study. *Neuropsychologia*, *47*, 2882. https://doi.org/10.1016/j.neuropsychologia.2009.06.014

Fernandes, C., Macedo, I., Barbosa, F., & Marques-Teixeira, J. (2021). Economic decision-making in the continuum between healthy aging and Alzheimer's disease: A systematic review of 20 years of research. *Neuroscience and Biobehavioral Reviews*, *131*, 1243–1263. https://doi.org/10.1016/j.neubiorev.2021.10.030

Folstein, M. F., Folstein, S. E., & McHugh, P. R. (1975). "Mini-mental state": A practical method for grading the cognitive state of patients for the clinician. *Journal of Psychiatric Research*, *12*, 189–198. https://doi.org/10.1016/0022-3956(75)90026-6

Gathmann, B., Brand, M., & Schiebener, J. (2017). One executive function never comes alone: monitoring and its relation to working memory, reasoning, and different executive functions. *Cognitive Processing*, *18*, 13–29. https://doi.org/10.1007/s10339-016-0773-6

Grambaite, R., Selnes, P., Reinvang, I., Aarsland, D., Hessen, E., Gjerstad, L., & Fladby, T. (2011). Executive dysfunction in mild cognitive impairment is associated with changes in frontal and cingulate white matter tracts. *Journal of Alzheimers Disease*, *27*, 453–462. https://doi.org/10.3233/jad-2011-110290

Griffith, H. R., Belue, K., Sicola, A., Krzywanski, S., Zamrini, E., Harrell, L., & Marson, D. C. (2003). Impaired financial abilities in mild cognitive impairment: A direct assessment approach. *Neurology*, *60*, 449–457. https://doi.org/10.1212/wnl.60.3.449

Griffith, H. R., Okonkwo, O. C., den Hollander, J. A., Belue, K., Copeland, J., Harrell, L. E., Brockington, J. C., Clark, D. G., & Marson, D. C. (2010). Brain metabolic correlates of decision making in amnestic mild cognitive impairment. *Aging Neuropsychology and Cognition*, *17*, 492–504. https://doi.org/10.1080/13825581003646135

Heaton, R. K., Miller, S. W., Taylor, M. J., & Grant, J. (2004). *Revised comprehensive norms for an expanded Halstead Reitan battery: Demographically adjusted neuropsychological norms for African Americans and Caucasian adults*. Lutz, FL: Psychological Assessment Resources.

Jacus, J. P., Fau, B. S., Raffard, S., & Gély-Nargeot, M. C. (2013). Decision-making and apathy in early stage of Alzheimer's disease and in mild cognitive impairment. [Prise de décision et apathie dans la maladie d'Alzheimer débutante et le Trouble léger de la cognition.]. *Geriatrie Et Psychologie Neuropsychiatrie De Vieillissement*, *11*, 215–223. https://doi.org/10.1684/pnv.2013.0406

Jorm, A. F. (1994). A short form of the Informant Questionnaire on Cognitive Decline in the Elderly (IQCODE): development and cross-validation. *Psychological Medicine*, *24*, 145–153. https://doi.org/10.1017/S003329170002691X

Jung, Y. H., Park, S., Jang, H., Cho, S. H., Kim, S. J., Kim, J. P., Kim, S. T., Na, D. L., Seo, S. W., & Kim, H. J. (2020). Frontal-executive dysfunction affects dementia conversion in patients with amnestic mild cognitive impairment. *Scientific Reports*, *10*, 772–772. https://doi.org/10.1038/s41598-020-57525-6

Klekociuk, S. Z., & Summers, M. J. (2014). Exploring the validity of mild cognitive impairment (MCI) subtypes: Multiple-domain amnestic MCI is the only identifiable subtype at longitudinal follow-up. *Journal of Clinical and Experimental Neuropsychology*, *36*, 290–301. https://doi.org/10.1080/13803395.2014.890699

Liebherr, M., Schiebener, J., Averbeck, H., & Brand, M. (2017). Decision making under ambiguity and objective risk in higher age: A review on cognitive and emotional contributions. *Frontiers in Psychology*, *8*. https://doi.org/10.3389/fpsyg.2017.02128

Martin, R. C., Gerstenecker, A., Triebel, K. L., Falola, M., McPherson, T., Cutter, G., & Marson, D. C. (2019). Declining financial capacity in mild cognitive impairment: A six-year longitudinal study. *Archives of Clinical Neuropsychology*, *34*, 152–161. https://doi.org/10.1093/arclin/acy030

Mitchell, A. J., & Shiri-Feshki, M. (2009). Rate of progression of mild cognitive impairment to dementia meta-analysis of 41 robust inception cohort studies. *Acta Psychiatrica Scandinavica*, *119*, 252–265. https://doi.org/10.1111/j.1600-0447.2008.01326.x

Mueller, S. M., Arias, M. G., Vazquez, G. M., Schiebener, J., Brand, M., & Wegmann, E. (2019). Decision support in patients with mild Alzheimer's disease. *Journal of Clinical and Experimental Neuropsychology*, *41*, 484–496. https://doi.org/10.1080/13803395.2019.1585517

Okonkwo, O. C., Griffith, H. R., Copeland, J. N., Belue, K., Lanza, S., Zamrini, E. Y., Harrell, L. E., Brockington, J. C., Clark, D., Raman, R., & Marson, D. C. (2008). Medical decision-making capacity in mild cognitive impairment A 3-year longitudinal study. *Neurology*, *71*, 1474–1480. https://doi.org/10.1212/01.wnl.0000334301.32358.48

Oosterman, J. M., Wijers, M., & Kessels, R. P. C. (2013). Planning or something else? Examining neuropsychological predictors of zoo map performance. *Applied Neuropsychology: Adult*, *20*, 103–109. https://doi.org/10.1080/09084282.2012.670150

Pereiro, A. X., Juncos-Rabadan, O., & Facal, D. (2014). Attentional control in amnestic MCI subtypes: Insights from a Simon task. *Neuropsychology*, *28*, 261–272. https://doi.org/10.1037/neu0000047

Pertl, M. T., Benke, T., Zamarian, L., & Delazer, M. (2015). Decision making and ratio processing in patients with mild cognitive impairment. *Journal of Alzheimers Disease*, *48*, 765–779. https://doi.org/10.3233/jad-150291

Pertl, M. T., Benke, T., Zamarian, L., & Delazer, M. (2017). Effects of healthy aging and mild cognitive impairment on a real-life decision-making task. *Journal of Alzheimers Disease*, *58*, 1077–1087. https://doi.org/10.3233/jad-170119

Pertl, M. T., Zamarian, L., & Delazer, M. (2017). Reasoning and mathematical skills contribute to normatively superior decision making under risk: evidence from the game of dice task. *Cognitive Processing*, *18*, 249–260. https://doi.org/10.1007/s10339-017-0813-x

Reinvang, I., Grambaite, R., & Espeseth, T. (2012). Executive dysfunction in MCI: Subtype or early symptom. *Int J Alzheimers Dis*, *2012*, 936272–936278. https://doi.org/10.1155/2012/936272

Reitan, R. M., & Wolfson, D. (1995). Category test and trail making test as measures of frontal lobe functions. *The Clinical Neuropsychologist*, *9*, 50–56. https://doi.org/10.1080/13854049508402057

Schiebener, J., & Brand, M. (2015a). Decision making under objective risk conditions-a review of cognitive and emotional correlates, strategies, feedback processing, and external influences. *Neuropsychology Review*, *25*, 171–198. https://doi.org/10.1007/s11065-015-9285-x

Schiebener, J., & Brand, M. (2015b). Self-reported strategies in decisions under risk: role of feedback, reasoning abilities, executive functions, short-term-memory, and working memory. *Cognitive Processing*, *16*, 401–416. https://doi.org/10.1007/s10339-015-0665-1

Schiebener, J., Wegmann, E., Gathmann, B., Laier, C., Pawlikowski, M., & Brand, M. (2014). Among three different executive functions, general executive control ability is a key predictor of decision making under objective risk. *Frontiers in Psychology*, *5*. https://doi.org/10.3389/fpsyg.2014.01386

Schiebener, J., Zamarian, L., Delazer, M., & Brand, M. (2011). Executive functions, categorization of probabilities, and learning from feedback: What does really matter for decision making under explicit risk conditions? *Journal of Clinical and Experimental Neuropsychology*, *33*, 1025–1039. https://doi.org/10.1080/13803395.2011.595702

Sinclair, C., Eramudugolla, R., Brady, B., Cherbuin, N., & Anstey, K. J. (2021). The role of cognition and reinforcement sensitivity in older adult decision-making under explicit risk conditions. *Journal of Clinical and Experimental Neuropsychology* (1744-411X (Electronic)). https://doi.org/10.1080/13803395.2021.1909709

Smith, A. (1982). *Symbol Digit Modalities Test (SDMT) Manual*. Los Angeles: Western Psychological Services.

Spreen, O., & Strauss, E. (1998). *Compendium of neuropsychological tests: administration, norms and commentary*. New York: Oxford University Press.

Starcke, K., Pawlikowski, M., Wolf, O., Altstotter-Gleich, C., & Brand, M. (2011). Decision-making under risk conditions is susceptible to interference by a secondary executive task. *Cognitive Processing*, *12*, 177–182. https://doi.org/10.1007/s10339-010-0387-3

Stroop, R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology*, *18*, 643–662.

Sun, T., Xie, T., Wang, J., Zhang, L., Tian, Y., Wang, K., Yu, X., & Wang, H. (2020). Decision-making under ambiguity or risk in individuals with Alzheimer's disease and mild cognitive impairment. *Frontiers in Psychiatry*, *11*. https://doi.org/10.3389/fpsyt.2020.00218

https://doi.org/10.1017/S1355617722000765 Published online by Cambridge University Press

Tversky, A., & Kahneman, D. (1986). Rational choice and the framing of decisions. *Journal of Business*, *59*, S251–S278. https://doi.org/10.1086/296365

von Elm, E., Altman, D. F., Egger, M., Pocock, S. J., Gøtzsche, P. C., Vandenbroucke, J. P., & Vandenbroucke, J. P. (2007). The Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) statement: guidelines for reporting observational studies. *Annals of Internal Medicine*, *147*, 573–577. https://doi.org/10.7326/0003-4819-147-8-200710160-00010

Wadley, V. G., Crowe, M., Marsiske, M., Cook, S. E., Unverzagt, F. W., Rosenberg, A. L., & Rexroth, D. (2007). Changes in everyday function in individuals with psychometrically defined mild cognitive impairment in the advanced cognitive training for independent and vital elderly study. *Journal of the American Geriatrics Society*, *55*, 1192–1198. https://doi.org/10.1111/j.1532-5415.2007.01245.x

Wechsler, D. (1945). A standardized memory scale for clinical use. *The Journal of Psychology*, *19*, 87–95. https://doi.org/10.1080/00223980.1945.9917223

Wechsler, D. (1997). *Wechsler Memory Scale (WMS-III)*. Chicago: Psychological Corporation.

Wilson, B. A., Alderman, N., Burgess, P. W., Emslie, H., & Evans, J. J. (1996). *Behavioural assessment of the dysexecutive syndrome*. Edmunds England: Thames Valley Test Company.

Winblad, B., Palmer, K., Kivipelto, M., Jelic, V., Fratiglioni, L., Wahlund, L. O., Nordberg, A., Bäckman, L., Albert, M., Almkvist, O., Arai, H., Basun, H., Blennow, K., de Leon, M., DeCarli, C., Erkinjuntti, T., Giacobini, E., Graff, C., Hardy, J., Jack, C., Jorm, A., Ritchie, K., van Duijn, C., Visser, P., & Petersen, R. C. (2004). Mild cognitive impairment - Beyond controversies, towards a consensus: Report of the International Working Group on Mild Cognitive Impairment. *Journal of Internal Medicine*, *256*, 240–246. https://doi.org/10.1111/j.1365-2796.2004.01380.x

Zamarian, L., Weiss, E. M., & Delazer, M. (2011). The impact of mild cognitive impairment on decision making in two gambling tasks. *Journals of Gerontology - Series B Psychological Sciences and Social Sciences*, *66 B*, 23–31. https://doi.org/10.1093/geronb/gbq067

https://doi.org/10.1017/S1355617722000765 Published online by Cambridge University Press