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1 The role of working memory sub-components in food choice and dieting success.

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13

Abstract

14 Evidence suggests a role for self-reported working memory (WM) in self-reported food
15 intake, but it is not known which WM sub-components are involved. It is also important to
16 consider how individual differences in dietary restraint and disinhibition influence WM and
17 the impact of this on food choice. The current study assessed the relationship between WM
18 sub-components and food choice, using computerised measures of WM sub-components and
19 a direct assessment of food intake. The role of dieting success (measured by restraint and
20 disinhibition) as a distal predictor of food choice that influences food choices via WM, and
21 the role of WM more generally in dieting success were investigated. Female undergraduate
22 students (N = 117, mean age: 18.9 years, mean BMI: 21.6 kg/m²) completed computer tasks
23 assessing three components of WM (updating, phonological loop and visuospatial sketchpad)
24 and a snack food taste-test. Greater visuospatial WM span was associated with a higher
25 (lower) percentage of food intake that was low (high) energy dense. It was also found that
26 unsuccessful dieters (high restraint, high disinhibition) had poorer visuospatial WM span and
27 consumed a lower (higher) percentage of low (high) energy dense food. Visuospatial WM
28 span significantly mediated the relationship between dieting success and percentage of low
29 energy dense food intake. Further, dietary restraint was associated with poorer updating
30 ability, irrespective of disinhibition. These findings suggest that better visuospatial WM is
31 associated with a greater (reduced) preference for low (high) energy dense foods, and that
32 deficits in visuospatial WM may undermine dieting attempts. Future work should assess
33 whether the ability to deal with food cravings mediates the relationship between visuospatial
34 WM and dieting success and investigate how WM may influence the mechanisms underlying
35 behavioural control.

36 **Keywords: working memory, food intake, restraint, disinhibition, successful dieting**

37 The factors affecting food intake decisions are far-reaching and include both internal and
38 external influences (Herman & Polivy, 2008). Important internal influences include cognitive
39 functions, such as episodic memory, learning and executive functions (Higgs, Robinson, &
40 Lee, 2012). Executive functions are a set of cognitive abilities that allow individuals to
41 regulate their behaviour according to their higher-order goals or plans. They can be recruited
42 when behaviour is effortful and deliberate (Diamond, 2013), but also as part of a learned
43 reflex in the form of automatic inhibition (Verbruggen, Best, Bowditch, Stevens, & McLaren,
44 2014). Executive functions may be a key determinant of the strength of reflective processes
45 in the dual-process theories of behaviour control (Hofmann, Schmeichel, & Baddeley, 2012;
46 Strack & Deutsch, 2004). The current consensus is that there are three core executive
47 functions: inhibition, working memory and cognitive flexibility/set-shifting (Diamond, 2013;
48 Miyake et al., 2000). The importance of executive functions in controlling eating behaviour
49 has been shown repeatedly, with findings suggesting that better executive functions are
50 associated with more healthful eating habits (Allom & Mullan, 2014; Hall, Fong, Epp, &
51 Elias, 2008; Hall, 2012). Studies have shown that training inhibitory control can improve
52 eating behaviour and aid weight loss (Lawrence et al., 2015; Veling, Koningsbruggen, Aarts,
53 & Stroebe, 2014). However, the results of meta-analyses have revealed inconsistent effects,
54 and the mechanisms by which these work are varied (Allom, Mullan, & Hagger, 2015; Jones
55 et al., 2016).

56 The second of these core executive functions, working memory (WM), and its role in eating
57 behaviour has been relatively less well studied. Nonetheless, WM is now considered an
58 important executive function, alongside inhibitory control ability, that may play a role in the
59 reflective processes that influence eating behaviour (Hofmann, Friese, & Wiers, 2008).
60 Important components of WM relevant to self-regulation of behaviour include not only the
61 amount of information that can be held active at any given time, but also the ability to hold in

62 mind information stored in long-term memory and to maintain focused attention on currently
63 active information while preventing the interference of other potentially distracting
64 information (Hofmann, Gschwendner, Friese, Wiers, & Schmitt, 2008). Applied to eating
65 behaviour, WM capacity may be important in retrieving long-term memories and holding
66 these active in WM (e.g. dieting goals); resisting attending to eye-catching stimuli in the
67 environment (e.g. tempting foods); protecting active goals from distracting stimuli by
68 maintaining focused attention on the active goals; and down-regulating emotions (e.g.
69 reducing cravings in a given situation) (Hofmann et al., 2012).

70 Working memory capacity has been reported to moderate the role of impulsive processes in
71 predicting health behaviours. For example, in people with low WM capacity, impulsive
72 processes were better predictors of high energy dense (HED) food consumption than in
73 people with higher WM capacity (Hofmann, Friese, & Roefs, 2009; Hofmann, Gschwendner,
74 et al., 2008). Few studies have examined the direct relationship between WM and food
75 intake, and the findings are contradictory. Two studies found that WM negatively correlated
76 with snack food intake (Riggs, Chou, Spruijt-Metz, & Pentz, 2010; Riggs, Spruijt-Metz,
77 Sakuma, Chou, & Pentz, 2010), whereas two other studies found no association with fat
78 intake (Allom & Mullan, 2014; Limbers & Young, 2015). The former two studies assessed
79 self-reported executive functioning using the Behavioural Rating Inventory of Executive
80 Functioning (using the subscales “emotional control”, “inhibitory control”, “working
81 memory” - e.g. “I forget what I’m doing in the middle of things” and “organisation of
82 materials”) (Guy, Isquith, & Gioia, 2004). The final analysis in both studies combined scores
83 on all subscales to form a composite executive function score (Riggs, Chou, et al., 2010;
84 Riggs, Spruijt-Metz, et al., 2010). Therefore, little can be said about the role of WM in food
85 intake, because an overall composite score leaves the contribution of the WM subscale
86 unclear. Limbers and Young (2015) found that the relationship between WM and saturated

87 fat intake disappeared when controlling for demographic factors, BMI and eating styles.
88 While this study also used the BRIEF measure of executive functioning, the relationship
89 between food intake and performance on the individual subscales was assessed, increasing
90 confidence that these findings relate to WM specifically. Allom and Mullan (2014) used the
91 n-back and operation span tasks to assess WM (updating ability specifically), which are
92 validated measures of WM that do not rely on self-reports of behaviour (Diamond, 2013;
93 Miyake et al., 2000). Overall, the strength of evidence suggests that perhaps WM is not
94 important for intake of high energy dense foods.

95 Research on the relationship between WM and fruit and vegetable intake also appears to be
96 contradictory but may be explained by the differing methods used to assess WM across
97 studies. Allom and Mullan (2014) and Sabia et al. (2009) used computerised assessment of
98 WM and found a positive correlation between WM and fruit/vegetable intake. Limbers and
99 Young (2015) did not find a relationship between WM and fruit/vegetable intake, but these
100 authors assessed WM via self-report. On the other hand, Riggs, Chou et al., (2010), who also
101 used a self-report measure of WM ability, did report a positive relationship between WM and
102 fruit/vegetable intake. Theoretically, WM may play a more important role in intake of low
103 energy dense foods than high energy dense foods. Allom and Mullan (2014) based on their
104 finding that WM was associated with fruit/vegetable intake and not saturated fat intake,
105 argued that inhibitory control is not important for health improving behaviours, but rather
106 updating, or working memory is important as it directly supports activation and maintenance
107 of long-term goals (such as weight loss) that encourages low energy dense (LED) food
108 consumption.

109 Several factors limit the research conducted to date on the relationship between WM and
110 food intake. While the self-report measures of WM may provide greater ecological validity

111 due to assessment of WM performance in everyday situations, these measures are subject to
112 self-report bias. A further limiting factor is the lack of consideration of the role of WM sub-
113 components. The traditional view of WM is that there are three core components of WM: the
114 central executive is an attentional control system that allocates, divides and switches attention
115 across two slave sub-systems. The two slave sub-systems (the phonological loop and the
116 visuospatial sketchpad) deal with different information, namely verbal and acoustic
117 information and visual and spatial information, respectively (Baddeley, 2007). The three core
118 components of WM have different functions that could differentially relate to food intake.
119 For example, the slave sub-systems could be important in the processing of visual aspects of
120 food (e.g. what looks appetizing and food cravings) and the auditory aspects (e.g. the sound
121 of food cooking or unwrapping food), whereas the central executive could be important for
122 the allocation of attention to these sub-components and retrieving long-term memories about
123 health goals. More recent literature argues for retiring the central executive in favour of
124 multiple specialised skills, such as updating the contents of WM and inhibition of distraction
125 for items held in WM (Logie, 2016). Updating is one central executive function that has been
126 shown to relate to food intake (Hofmann, Gschwendner, et al., 2008; Hofmann et al., 2012).
127 A final limitation of previous studies is that food frequency questionnaires have been used to
128 measure food intake, which is subject to self-report bias and recall error. More reliable
129 measures of food intake are needed, such as a laboratory-based taste-test that measures actual
130 food consumption.

131 It is also important to consider potential moderators of the relationship between WM and
132 food intake, such as psychological eating styles that are associated with differences in WM.
133 Dieting in individuals high in cognitive restraint is related to WM deficits such as deficits in
134 sustained attention (Rogers & Green, 1993), poorer immediate recall and slower reaction
135 times compared with non-dieters (Green & Rogers, 1995; Green, Rogers, Elliman, &

136 Gatenby, 1994). Specific deficits have also been shown in sub-components of WM (Green &
137 Rogers, 1998; Green, Elliman, & Rogers, 1997), including the central executive (Green et al.,
138 2003; Kemps & Tiggemann, 2005; Kemps, Tiggemann, & Marshall, 2005) and phonological
139 loop (Green & Elliman, 2013; Shaw & Tiggemann, 2004; Vreugdenburg, Bryan, & Kemps,
140 2003), but not the visuospatial sketchpad (Green & Rogers, 1998; Kemps, Tiggemann, &
141 Marshall, 2005; Kemps & Tiggemann, 2005; Shaw & Tiggemann, 2004; Vreugdenburg et al.,
142 2003). However, evidence for deficits in phonological loop functions is somewhat
143 contradictory (see Green et al., 2003; Kemps & Tiggemann, 2005; Shaw & Tiggemann,
144 2004; Vreugdenburg et al., 2003). Overall, these data suggest a negative impact of dieting
145 behaviour on some aspects of WM, which could mediate the relationship between dieting and
146 food intake.

147 A further consideration is that studies investigating the effects of dieting on WM have
148 compared current dieters with non-dieters and have not usually distinguished between
149 successful and unsuccessful dieters (Kemps & Tiggemann, 2005; Kemps, Tiggemann, &
150 Marshall, 2005). Individuals who score high on cognitive restraint but low on the tendency
151 towards disinhibition (successful dieters) respond differently to individuals scoring high in
152 restraint and high in the tendency towards disinhibition (unsuccessful dieters) in a task
153 assessing WM guidance of attention to food cues (Higgs, Dolmans, Humphreys, & Rutters,
154 2015). Successful and unsuccessful dieters have also been shown to differ in their
155 experiences of food cravings: unsuccessful dieters reported more food cravings relating to
156 difficulties in self-control over food intake and intentions to consume food than did
157 successful dieters (Meule, Lutz, Vögele, & Kübler, 2012). Cravings are believed to be visual
158 in nature (May, Andrade, Kavanagh, & Penfound, 2008; May, Andrade, Panabokke, &
159 Kavanagh, 2004; Tiggemann & Kemps, 2005) and to consume visuospatial WM resources,
160 impairing performance on other visuospatial WM tasks (Green, Rogers, & Elliman, 2000;

161 Kemps, Tiggemann, & Grigg, 2008; Meule, Skirde, Freund, Vögele, & Kübler, 2012;
162 Tiggemann, Kemps, & Parnell, 2010). It is therefore possible that successful dieters have
163 greater visuospatial WM capacity, allowing them to deal with demands on visuospatial WM
164 more appropriately, such as food cravings.

165 In summary, there has been little investigation of the role of specific WM processes in eating
166 behaviour to date. The aim of the present study was to investigate the role of WM sub-
167 components in food choice using computerised measures of WM and a measure of actual
168 food intake (food taste-test paradigm). In addition, the role of dieting success (measured by
169 restraint and disinhibition) as a distal predictor of food intake that influences food choices via
170 WM, and the role of WM more generally in dieting success were assessed. The association
171 between WM and food choice, with dieting success as a distal predictor can be
172 conceptualised within a mediation framework, in which the effects of dieting success on food
173 choice are mediated by WM. It was therefore predicted that there would be a significant
174 relationship between WM and food choice, such that better WM would be associated with a
175 greater (lower) percentage of total food intake that was LED (HED; hypothesis 1). There is
176 currently little evidence to suggest that any one sub-component or function of WM may play
177 a more important role in food choice over other WM components, and therefore predictions
178 regarding specific WM sub-components were not made. Considering the research that has
179 found dieting to be associated with WM deficits, it was expected that dietary restraint,
180 irrespective of disinhibition, would be associated with poorer updating and phonological loop
181 functioning (but not visuospatial span, hypothesis 2). However, it was also predicted that
182 dieting success would be associated with WM (such that successful dieters would show better
183 visuospatial WM than unsuccessful dieters, hypothesis 3). It was also expected that dieting
184 success would be associated with food choice, such that successful dieters would consume a
185 greater (lower) percentage of their total food intake from LED (HED) food (hypothesis 4).

186 Finally, it was predicted that there would be a significant indirect relationship between
187 dieting success and food choice via WM (hypothesis 5). Again, no predictions about the
188 specific WM components or functions involved here were made, as current research does not
189 suggest any one specific WM component is more involved in food intake than others.

190 **Methods**

191 **Participants**

192 Female undergraduate students at the University of Birmingham received course credit for
193 taking part in this study (N=117). Only females were included because eating habits are
194 known to differ between men and women, and dieting to control weight is more common in
195 women (Kiefer, Rathmanner, & Kunze, 2005; Wardle et al., 2004). Participants were
196 required to have normal or corrected-to-normal vision, but there were no restrictions based on
197 age or BMI. One participant was excluded from the analyses as she was an outlier on a
198 number of measures, and reported that she was sad during the experiment (final N = 116).
199 There were no outliers on any of the WM outcome measures. However, one participant failed
200 twice on the lowest level of the backwards digit task, which was most likely because they did
201 not understand the instruction to reverse the sequence, and therefore this participant was
202 excluded on that task.

203 To disguise the aims, the study was advertised as investigating the relationship between
204 cognitive functioning and food taste perceptions. The sample size was decided a priori via a
205 power calculation using G Power (Faul, Erdfelder, Lang, & Buchner, 2007). With power set
206 at 0.8 and alpha 0.05, to identify a medium effect size ($f^2 = 0.15$) in a multiple linear
207 regression, a sample size of 92 participants would be needed. Previous studies assessing the
208 association between WM and food intake identified medium to large effect sizes when WM
209 was included in the models (Allom & Mullan, 2014; Limbers & Young, 2015), and hence it

210 was reasonable to expect a similar effect size. As it would not be possible to predict which
211 group participants would fall into prior to testing them (allocation to groups was based on
212 levels of restraint and disinhibition using questionnaire responses), more than 92 participants
213 were recruited to ensure there were sufficient numbers in each group. However, further
214 targeted recruitment was required towards the end of the study to obtain more balanced
215 groups. The final sample size (116) powered the study to identify a medium effect size with
216 up to 9 predictors, although a maximum of 5 were actually used in any given analysis. This
217 study was approved by the Middlesex University Psychology Ethics Sub-committee and the
218 University of Birmingham Research Ethics Committee.

219 **Measures**

220 **Demographic information.** Participants were asked to report their age, ethnicity,
221 when they last ate, whether and how often they drink alcohol and smoke, whether they have
222 any food allergies, or have past or current psychological issues. These were used to
223 characterise the sample, and anyone with food allergies were excluded (none were excluded
224 on this basis).

225 **Working memory assessments**

226 **Updating.** Updating was assessed using the validated Spatial Working Memory test
227 of the Cambridge Cognition Neuropsychological Test Automated Battery (CANTAB,
228 Cambridge Cognition, Cambridge, UK). This task required updating within the visuospatial
229 domain. Participants had to search for blue tokens hidden inside coloured boxes. Once a
230 token was found inside a box, a token would not be hidden inside that box again. Therefore,
231 participants had to remember where they had already found tokens and update the
232 information held in WM so as not to return to the same box twice. Updating ability is
233 considered an important component of WM for self-regulation of behaviour (Hofmann et al.,

234 2012). The task started with 4 boxes and 4 tokens to find, and increased to 6, 8 and finally 10
235 boxes and 10 tokens. The key outcome measure for updating ability was the degree to which
236 participants used a strategy to perform the task (Goghari et al., 2014; Owen, Downes,
237 Sahakian, Polkey, & Robbins, 1990). The best strategy for this task was to search the boxes
238 in the same order every time a new search commenced. The number of times a participant
239 started the search from a different box was counted, and a higher score therefore indicated
240 poorer use of this strategy.

241 **Phonological loop.** The phonological loop component of WM was assessed using the
242 backwards digit span task. Participants were shown a sequence of numbers on screen and had
243 to recall the sequence in reverse order, using the on-screen number pad. The first sequence
244 contained 3 items and increased by one after two consecutive correct answers. The task
245 finished when two consecutive incorrect answers were given. The longest sequence of
246 numbers remembered correctly was taken as a measure of the participant's phonological loop
247 capacity. The digit span task is a validated measure of short-term memory, specifically
248 phonological loop capacity (Baddeley, Gathercole, & Papagno, 1998) and has previously
249 been used to identify poorer phonological loop capacity in unsuccessful dieters compared to
250 non-dieters (Kemps, Tiggemann, & Marshall, 2005).

251 **Visuospatial sketchpad.** The visuospatial sketchpad component of WM was assessed
252 using the Spatial Span Task from the Cambridge Cognition Neuropsychological Test
253 Automated Battery (CANTAB, Cambridge Cognition, Cambridge, UK), which is a
254 computerised version of the Corsi blocks task (a validated measure of visuospatial sketchpad
255 capacity; Hanley, Young, & Pearson, 1991). White squares were shown on screen, and
256 several of these briefly changed colour. Participants had to touch the squares in the correct
257 order in which they changed colour (on a touch screen monitor). The first sequence contained

258 2 square colour changes, and increased by one after every correctly recalled sequence. The
259 task finished when three consecutive sequences were recalled incorrectly. Visuospatial WM
260 capacity was taken as the highest level of this task successfully completed.

261 **Taste test**

262 Eating behaviour was assessed in the laboratory using a bogus taste-test paradigm (Houben,
263 2011). Participants were presented with a snack buffet box containing 4 high energy dense
264 (HED) foods (chocolate chip cookies ~65g, ~323 kcal; cheese and onion rolls ~65g, ~201
265 kcal; MnM's, ~165g, 799 kcal; and ready salted crisps, ~25g, ~133 kcal) and 4 low energy
266 dense (LED) foods (carrot sticks ~110g, ~44 kcal; plum tomatoes ~139g, ~28 kcal; grapes,
267 ~153g, ~101 kcal; and salt and vinegar rice cakes, ~10.5g, ~40 kcal). All food was
268 manufactured by Sainsbury's UK, except for the M&Ms (Mars, France) and rice cakes
269 (Snack a Jacks, UK). These foods were chosen to provide a range of high and low energy
270 dense foods from both sweet and savoury categories to account for different preferences. To
271 bolster the cover story, participants were given 10 minutes to taste each of the foods and rate
272 them on three 100mm visual analogue scales, with the questions above "How pleasant was
273 the taste of the...?"; "how bitter was the taste of the...?" and "how sweet was the taste of
274 the...?", with anchors "not at all" and "extremely". Participants were told they could eat as
275 much or as little of the foods as they wished, as any remaining food would be thrown away
276 afterwards. To create an outcome measure that reflected the healthiness of food choices when
277 participants were offered both low and high energy dense food options (our primary interest
278 in this study), the percentage of total food intake that was LED was calculated. Specifically,
279 the amount consumed by each participant was first calculated by subtracting the post taste-
280 test weight from the pre taste-test weight for each of the food items. This was then totalled
281 separately for the HED and LED foods. Total LED intake (grams) was divided by the total

282 amount eaten (HED + LED grams), and multiplied by 100 to give the percentage of total
283 snack intake that was LED food.

284 **Dieting behaviour**

285 The cognitive restraint and disinhibition subscales of the Three Factor Eating Questionnaire
286 (TFEQ) were used to identify successful and unsuccessful dieters (Stunkard & Messick,
287 1985). In the majority of our analyses restraint and disinhibition remain as continuous
288 variables. However, for the categorical analyses to identify baseline group differences those
289 who scored ≥ 9 on the restraint subscale and ≥ 7 on the disinhibition subscale were classified
290 as unsuccessful dieters (Higgs et al., 2015). Those scoring ≥ 9 and < 7 on these subscales
291 (respectively) were classified as successful dieters. Classification of dieting status took place
292 after participants had taken part in the study, therefore reducing any experimenter-induced
293 expectancy effects as the researcher was blind to dieting status during the testing sessions.
294 Appended to the end of the TFEQ was the question “are you currently dieting to lose
295 weight?” to characterize the sample.

296 **Procedure**

297 Testing sessions took place between 9:30am-12pm and 1:30pm-5pm, and participants were
298 tested individually in a cubicle. Upon arrival, participants provided informed consent,
299 completed the medical history and food allergies screening questionnaire, and rated their
300 baseline hunger and fullness on 100mm VAS scales asking “how hungry/full do you feel
301 right now?” with the anchors “not at all hungry/full” and “extremely hungry/full”. As a
302 further distraction to the aims of the study, participants completed a number of 100mm VAS
303 scales asking about their mood. These consisted of the question “How do you feel right
304 now?”, with various emotions inserted, for example, happy, sad, nervous and irritable.
305 Anchors were “not at all” and “extremely”. The participant then completed the WM tests and

306 repeated the hunger and mood questions. Then the participant completed the snack food
307 taste-test and another set of hunger and mood questions. The questionnaire pack that
308 contained questions on demographics and the TFEQ was then completed. To probe
309 awareness of the study aims, participants were asked the following open ended questions: 1)
310 “what do you think was the purpose of the study?” and 2) “in the snack buffet, what do you
311 think the researchers were interested in?” Height and weight were measured using a
312 stadiometer and body weight scales (heavy clothing and shoes removed) in order to calculate
313 BMI (kg/m^2). Participants were then debriefed. The first participant did not eat until 10am,
314 and the last participant ate at 4:30pm, as these are considered normal snacking times.

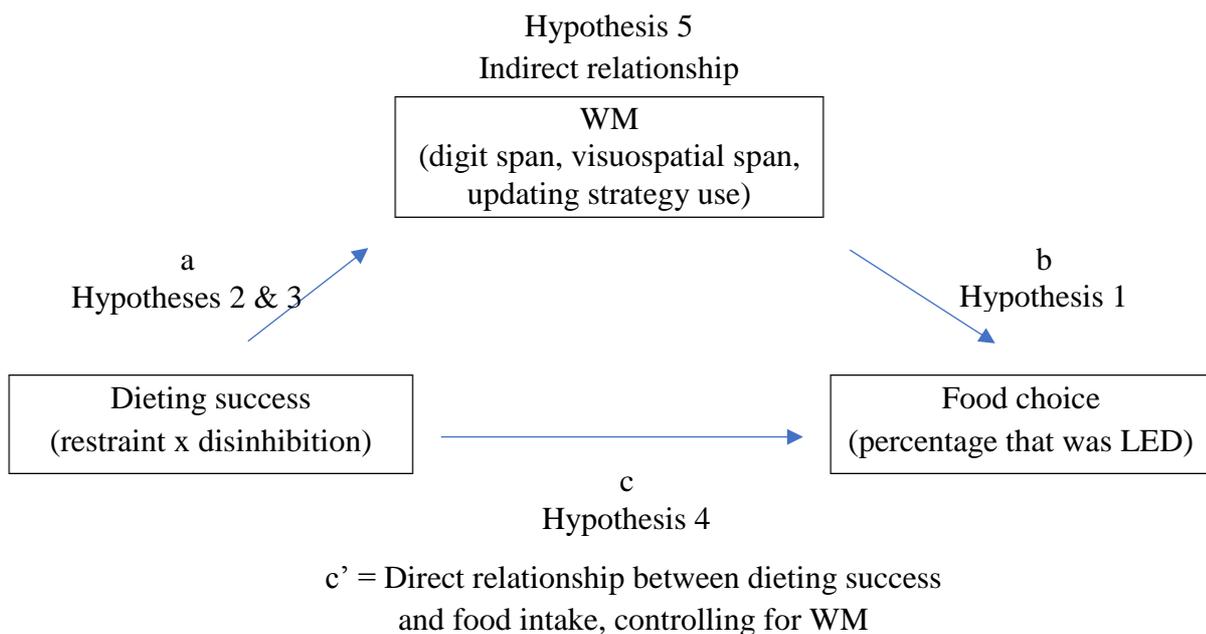
315 **Data analysis**

316 Group differences on baseline characteristics were checked with a multivariate ANOVA with
317 restraint (high, low) and disinhibition (high, low) as factors and BMI, age and baseline
318 hunger as outcomes. Correlations were also conducted to identify if food intake correlated
319 with baseline characteristics (e.g. age, BMI, hunger, when last ate, and liking of each food).

320 Mediation analysis was conducted using model 4 of the PROCESS macro for SPSS (Hayes,
321 2013), entering the interaction between restraint and disinhibition (mean centred) as the
322 independent variable, WM performance (digit span, visuospatial span and updating strategy
323 use) as the mediator, and percentage of food consumed that was LED as the dependent
324 variable. Bayesian linear regressions were conducted to identify the strength of evidence
325 supporting the alternative and null hypotheses regarding the relationship between WM
326 components and food choice. A Bayes factors close to 1 represents evidence that is
327 insensitive and inconclusive, a Bayes factor much greater than 1 reflects strong evidence of
328 the alternative hypothesis, whereas closer to 0 represents strong evidence of the null
329 hypothesis (Dienes, 2014). More specific cut-offs have been suggested, whereby a value of 3

330 or higher is substantial evidence of the alternative hypothesis and less than 0.3 is substantial
331 evidence for the null hypothesis (Dienes, 2016; Jeffreys, 1961). Values between 0.3 and 3 are
332 considered anecdotal evidence.

333 In order to understand associations between dieting success and WM/food choice, regressions
334 were run with restraint, disinhibition and the interaction between the two as independent
335 variables and WM performance (digit span, visuospatial span and updating strategy use) and
336 percentage of food consumed that was LED as the dependent variables. Simple slopes
337 analyses were used to visualise interaction effects. Bias-corrected and accelerated
338 bootstrapping (based on 1000 bootstrap samples) was applied to overcome any issues with
339 bias. The regression results for the interaction between restraint and disinhibition replicated
340 the effects found in the mediation analyses, and so to avoid repeating results, only the simple
341 slopes analyses for significant interaction effects are reported. Main effects of restraint and
342 disinhibition are also only reported where significant. Figure 1 shows a model of how we
343 expected WM to be associated with food choice and dieting success, and how WM was



344 expected to mediate the relationship between dieting success and food choice.

345 **Figure 1. Model of dieting success as a predictor of food choice, mediated by WM.**

346 **Results**

347 **Participant characteristics**

348 Mean age of the sample was 18.9 years ($SD = 1.0$, range = 18-24 years) with a mean BMI of
349 21.6 kg/m^2 ($SD = 2.6$, range = 16.9-30.6). Seventy-nine participants self-reported as being
350 white, 21 Asian/Asian British, 8 Black/African/Caribbean/Black British; 7 mixed/multiple
351 ethnic group, and 1 as “other”. Twenty-three participants reported that they were currently
352 dieting to lose weight. A small number of participants (5.2%) were self-reported light
353 smokers or had past or current psychological health problems (11.2%), and 92.2% said that
354 they drink the government guideline of 14 units of alcohol per week or less (Department of
355 Health UK, 2016). Participants last ate on average 364 minutes prior to participating in the
356 study (range = 80-1440 minutes), indicating that in general they had complied with the
357 instruction to not eat for at least 2 hours before taking part. However, one person ate 80
358 minutes and two ate 90 minutes prior to the study. Excluding these from the analyses did not
359 alter the results, and so their data were included in the analyses. Mean hunger and fullness
360 ratings at the beginning of the study were 48.4 ($SD = 20.2$) and 29.9 ($SD = 20.3$),
361 respectively. Mean restraint, disinhibition and hunger on the TFEQ were 8.7 ($SD = 6.0$), 7.0
362 ($SD = 3.4$) and 6.8 ($SD = 3.3$), respectively. Participant’s characteristics grouped by restraint
363 and disinhibition scores are in Table 1.

364 **Baseline group differences**

365 BMI differed according to restraint scores ($F(1,113) = 5.92$, $p = 0.02$), and there was a
366 marginally significant effect on age ($F(1,113) = 3.81$, $p = 0.05$), but no effect of group on

367 baseline hunger (smallest $p = 0.28$). High restraint participants tended to be older and have a
 368 higher BMI. There were significant correlations between baseline hunger and food intake and
 369 between rated liking and intake of the foods, therefore baseline hunger and average liking of
 370 the foods were included as covariates in the analyses (and as nuisance variables in the
 371 Bayesian linear regressions).

372 **Table 1. Participant characteristics grouped by restraint and disinhibition scores.**

	LRLD	LRHD	HRLD	HRHD
N	30	26	24	36
Age (years)	18.73 (0.94)	18.77 (0.71)	19.33 (1.40)	18.89 (0.82)
BMI (kg/m ²)	20.71 (3.14)	21.34 (2.05)	22.14 (2.80)	22.32 (2.28)
Hunger VAS (mm)	44.80 (19.44)	52.73 (21.27)	48.58 (17.43)	48.22 (21.78)

373 *Note.* LRLD = low restraint, low disinhibition; LRHD = low restraint high disinhibition;
 374 HRLD = high restraint low disinhibition; HRHD = high restraint high disinhibition. High
 375 restraint ≥ 9 on restraint subscale; high disinhibition ≥ 7 on the disinhibition subscale.

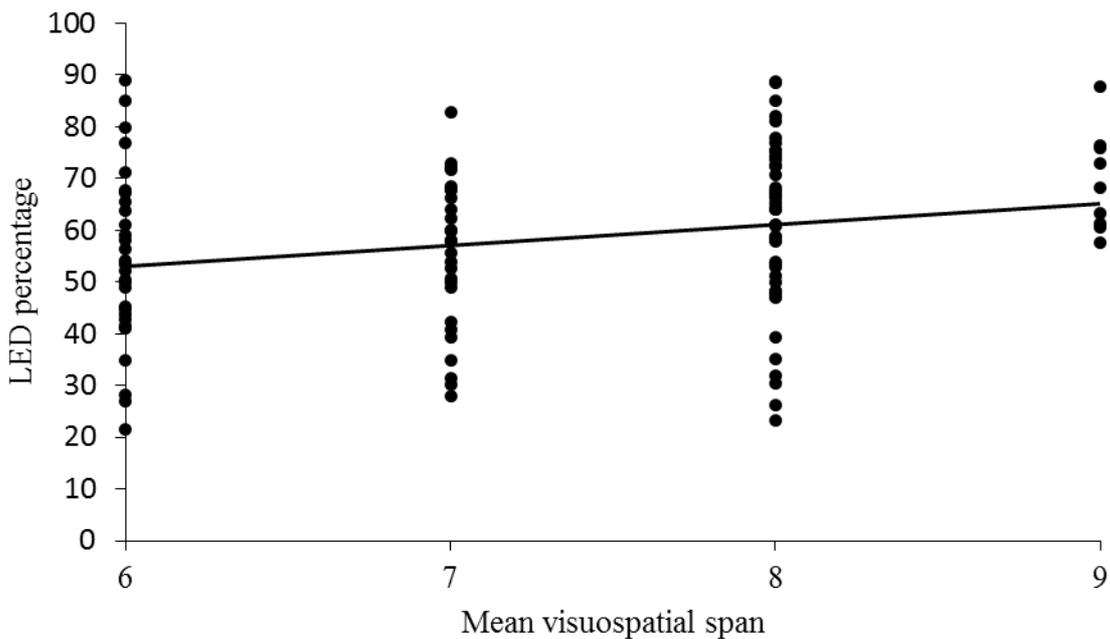
376 Awareness of study aims

377 None of the participants guessed the exact purpose of the study, although 18% guessed the
 378 broad purpose (e.g. “the relationship between cognitive functioning and food intake”).

379 **Working memory as a mediator of the relationship between dieting success and food**
 380 **choice**

381 Better visuospatial span was associated with a greater (lower) percentage of total food intake
382 that was LED (HED, hypothesis 1). See Table 2 for the results and Figure 2 for a scatterplot
383 of this relationship.

384 **Figure 2. Percentage of food intake that was LED plotted against visuospatial WM span**
385 **(with a regression line).**



386
387 Dieting success (the interaction between restraint and disinhibition) was significantly
388 associated with visuospatial span (hypothesis 3), and was directly associated with percentage
389 of total food intake that was LED (hypothesis 4). The direct relationship between dieting
390 success and LED percentage intake was no longer significant when controlling for
391 visuospatial span, and the indirect effect via WM was significant (hypothesis 5). See Table 2
392 for the results of all the mediation analyses and Figure 3 for a model of the results involving
393 just visuospatial span.

394

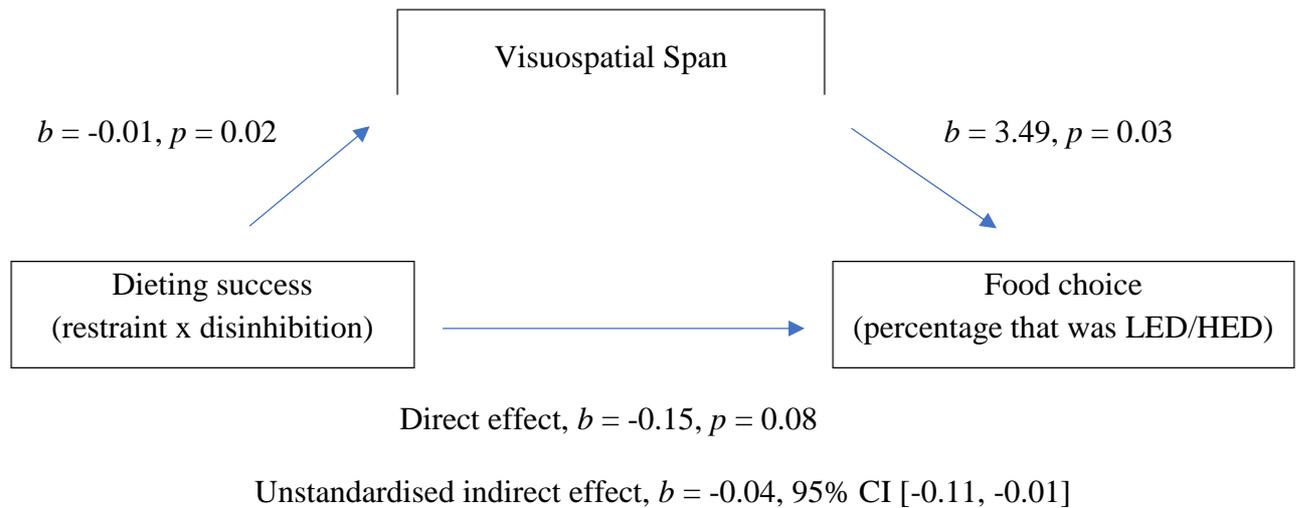
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396

397 **Table 2. The relationships between WM, food choice and dieting success (restraint x**
398 **disinhibition) in a mediation model.**

Path	Digit span (<i>b</i> , <i>p</i>)	Visuospatial span (<i>b</i> , <i>p</i>)	Updating strategy use (<i>b</i> , <i>p</i>)
a	-0.01 (0.27)	-0.01 (0.02)	-0.02 (0.55)
b	1.77 (0.18)	3.49 (0.03)	-0.13 (0.63)
c	-0.19 (0.03)	-0.19 (0.03)	-0.19 (0.03)
c'	-0.18 (0.04)	-0.15 (0.08)	-0.19 (0.03)
Standardised indirect effect of dieting success on food intake (bootstrapped 95% CIs)	-0.02 (-0.08, 0.01)	-0.04 (-0.12, -0.01)	0.003 (-0.01, 0.05)

399 **Note.** a = association between dieting success and WM; b = association between WM and
400 percentage of intake that was LED food; c = association between dieting success and
401 percentage of intake that was LED food; c' = direct association between dieting success and
402 percentage of intake that was LED food when controlling for WM.

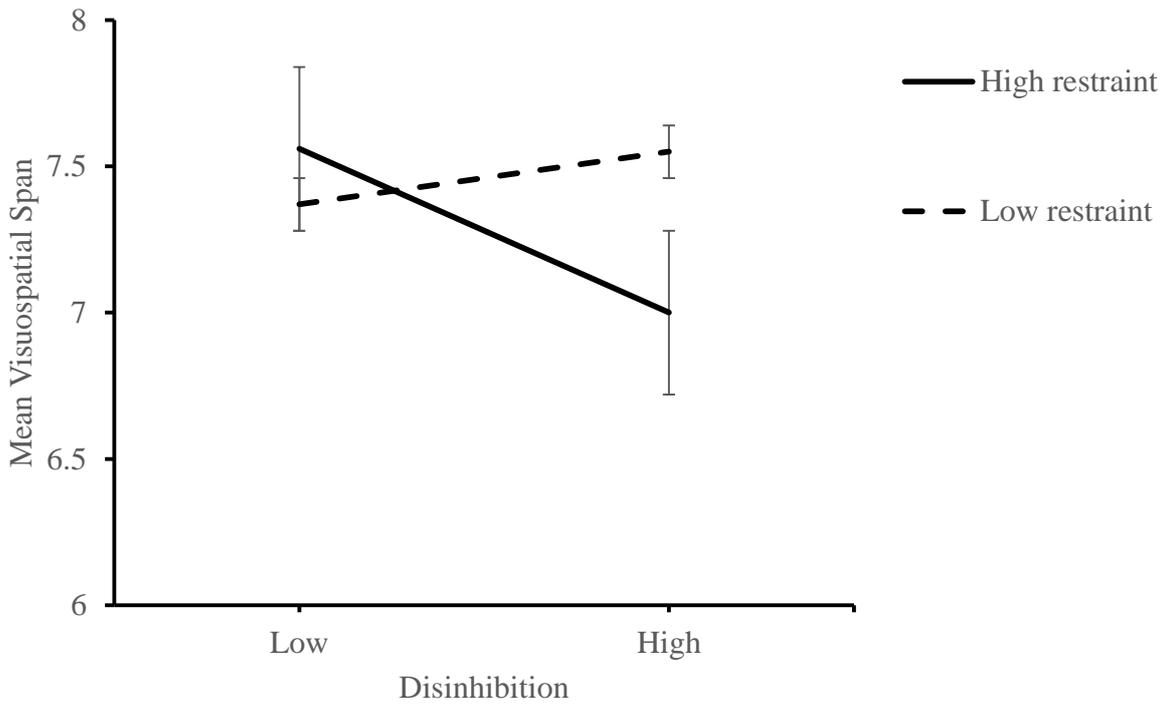


403 **Figure 3. Model of dieting success as a predictor of food choice, mediated by**
 404 **visuospatial span.**

405 Bayesian linear regressions showed moderate evidence for the association between
 406 visuospatial span and greater LED (lower HED) percentage intake when controlling for
 407 baseline hunger and liking of the LED foods ($BF_{10} = 7.75$). Bayes factors for updating
 408 strategy use and digit span reflect anecdotal evidence for the null hypotheses ($BF_{10} = 0.34$
 409 and 1.06, respectively).

410 **Dieting success and working memory**

411 As plotted in Figure 4, simple slopes analysis showed that at high levels of restraint,
412 visuospatial WM span decreased as disinhibition increased, $b = -.08$, $t(112) = -2.47$, $p = 0.01$
413 (relating to hypothesis 3).



414 **Figure 4. Mean visuospatial span as a function of restraint and disinhibition (with**
415 **standard error bars).**

417 There was also a significant positive relationship between restraint and updating strategy use
418 score, $b = 0.23$, $t(112) = 2.38$, $p = 0.02$ (hypothesis 2). A higher score means poorer use of
419 the strategy, suggesting that those high in restraint used the strategy less than those low in
420 restraint. There were no main effects of restraint or disinhibition on any other WM outcomes.

421 **Dieting success and food intake**

422 Simple slopes analysis showed that those high in restraint, and low in disinhibition
 423 (successful dieters) ate a higher (lower) percentage of LED (HED) foods than those high in
 424 disinhibition (unsuccessful dieters), $b = -1.70$, $t(105) = -2.49$, $p = 0.01$ (hypothesis 4).

425 **Post-hoc examination of food intake**

426 Consumption data split by restraint and disinhibition (dieting status) for LED grams, HED
 427 grams and total intake (kcal) are provided in Table 3. The pattern of data presented here
 428 suggests that successful dieters (HRLD) ate less HED food and total kcal, but ate a similar
 429 amount of LED food, compared to unsuccessful dieters (HRHD).

430 Table 3. Descriptive statistics for food intake measures grouped by restraint and disinhibition
 431 scores.

	LRLD	LRHD	HRLD	HRHD
LED percentage	62.3 (15.9)	57.02 (12.2)	60.4 (18.8)	54.7 (15.7)
LED (grams)	101.2 (66.9)	88.9 (52.1)	89.6 (56.8)	87.0 (49.1)
HED (grams)	53.6 (30.7)	60.0 (27.5)	49.0 (25.3)	66.2 (36.2)
Total (kcal)	270.1 (143.0)	294.0 (136.5)	246.7 (118.6)	322.4 (173.1)

432 *Note.* LRLD = low restraint, low disinhibition; LRHD = low restraint high disinhibition;
 433 HRLD = high restraint low disinhibition; HRHD = high restraint high disinhibition. High
 434 restraint ≥ 9 on restraint subscale; high disinhibition ≥ 7 on the disinhibition subscale.

435 **Discussion**

436 The aim of this study was to investigate the relationship between WM components and food
437 intake, using computerised non self-report measures of WM and a measure of actual food
438 intake (food taste-test paradigm). In addition, the role of dieting success (measured by
439 restraint and disinhibition) as a distal predictor of food intake that influences food choices via
440 WM, and the role of WM more generally in dieting success were assessed. Our first
441 prediction, that there would be a significant relationship between WM and food choice, such
442 that better WM would be associated with a greater (lower) percentage of total food intake that
443 was from LED (HED) food (hypothesis 1), was partially supported. Greater visuospatial WM
444 span was associated with a higher (lower) percentage of food intake that was LED (HED).
445 Specifically, for every 1 item increase in visuospatial span, the percentage of food consumed
446 that was LED (HED) increased (decreased) by 3.49%. In someone with the highest
447 visuospatial span in the current study (9 items), this represents 10.47% more (less) LED
448 (HED) food than those with the poorest visuospatial span (6 items). The Bayes factor for the
449 association between visuospatial span and LED percentage intake (when controlling for
450 baseline hunger and liking of LED food) showed moderate evidence for this effect. However,
451 the Bayes factors for no involvement of updating strategy use and digit span were anecdotal,
452 preventing a conclusion that these components of WM are not related to food choice. Future
453 research can address this by applying a stopping rule whereby recruitment continues until
454 there is strong evidence for either the null or alternative hypotheses using Bayesian statistics
455 (Dienes, 2016). These findings are in line with studies showing that WM is related to food
456 intake (Allom & Mullan, 2014; Riggs, Chou, et al., 2010; Sabia et al., 2009), and extend this
457 to suggest that visuospatial WM in particular is important. Better visuospatial WM may
458 enable people to deal with demands on visuospatial WM such as cravings (Green et al., 2000;

459 Kemps et al., 2008; Meule, Skirde, et al., 2012; Tiggemann et al., 2010), ultimately changing
460 food preferences if these can be dealt with appropriately.

461 This study also investigated the role of WM in dieting success. It was predicted that dieting
462 success would be associated with better visuospatial WM and a higher (lower) percentage of
463 food intake that was LED (HED; hypotheses 3 and 4, respectively). It was also expected that
464 the relationship between dieting success would be mediated by WM (hypothesis 5).

465 Supporting hypotheses 3 and 4, those high in restraint and low in disinhibition (successful
466 dieters) showed better visuospatial WM span and ate a higher (lower) percentage of LED
467 (HED) food than those high in restraint and high in disinhibition (unsuccessful dieters). The
468 former effect represents a decrease of 0.08 items recalled for every 1 point increase in
469 disinhibition (at high levels of restraint). Therefore, visuospatial span in a person scoring 16
470 on tendency towards disinhibition (the maximum score) would be 1.28 items less than
471 someone scoring 0 on the disinhibition subscale. Considering the relatively small range of
472 visuospatial working memory found in the present study (6-9 items), we argue that this is not
473 a small effect and could have clinical relevance. Another study published since this study was
474 conducted also found dieting success to be associated with WM (Meule, 2016). Specifically,
475 Meule found that dieting success was associated with fewer omission errors on a food versus
476 a neutral block in an n-back task in current dieters (Meule, 2016). The association between
477 dieting success and percentage intake reflects a 1.7% decrease (increase) in percentage of
478 LED (HED) intake for every 1 point increase in disinhibition (in those high in dietary
479 restraint). This means that in someone with a score of 16 on tendency towards disinhibition,
480 percentage of LED (HED) food intake would be 27.2% less (more) than some scoring 0 on
481 this subscale. This is a strong effect.

482 Visuospatial WM span was found to significantly mediate the relationship between dieting
483 success and percentage of food intake that was LED, supporting hypothesis 5. This suggests
484 that poorer visuospatial WM may undermine dieting success. The pattern of the data for
485 consumption of LED and HED food (grams) and total intake (kcal) in successful compared to
486 unsuccessful dieters, suggests that better WM processes may facilitate the ability to resist and
487 inhibit HED seeking behaviour (influencing total kilocalorie intake), but may not facilitate
488 LED seeking behaviour. Considering the evidence that food cravings are associated with
489 visuospatial WM deficits (Kemps, Tiggemann, & Hart, 2005; Tiggemann et al., 2010), and
490 differences between successful and unsuccessful dieters in their experiences of cravings
491 (Meule, Lutz, et al., 2012), better visuospatial WM functioning in successful dieters may
492 better enable them to deal with demands on visuospatial WM, such as preoccupying thoughts
493 about food and advertising. Specifically, elaboration intrusion theory argues that it is
494 elaboration of intrusive thoughts about food in WM that guide overt behaviour (Kavanagh,
495 Andrade, & May, 2005; May, Kavanagh, & Andrade, 2015). Better visuospatial WM in
496 successful dieters may, therefore, enable these people to prevent elaboration of food thoughts
497 into cravings (e.g. imagining smelling and consuming food), or to activate and retrieve
498 alternative thoughts, such as health or dieting goals. Indeed, studies have found that food cues
499 elicit health goals in successful dieters and not in unsuccessful dieters (Papies, Stroebe, &
500 Aarts, 2008a; Papies, Stroebe, & Aarts, 2008b). Alternatively, it is possible that successful
501 dieters experience fewer food cravings, leaving them with greater capacity to deal with other
502 visuospatial WM demands. To better understand the mechanism underlying this finding,
503 future research should compare experiences of cravings between successful and unsuccessful
504 dieters, how successful dieters deal with induced food cravings, and examine whether
505 visuospatial WM mediates the relationship between food cravings and food intake/dieting

506 success. Initial research on this has found that slower reaction times on a food-specific n-back
507 task mediated the effect of current dieting status on food cravings (Meule, 2016).

508 Finally, it was predicted that restraint would be associated with impairments in updating
509 ability and phonological loop WM functioning irrespective of tendency towards disinhibition
510 (hypothesis 2). This hypothesis was partially supported, as higher levels of restraint were
511 associated with poorer updating (strategy use), irrespective of levels of disinhibition. This
512 suggests that the negative effect of dieting on central executive functioning that has
513 previously been found, is independent of tendency towards disinhibition (Green et al., 1997;
514 Shaw & Tiggemann, 2004). There was no effect of restraint on phonological loop
515 functioning. This is in line with some research (Green et al., 2003; Kemps & Tiggemann,
516 2005), but not others (Green & Elliman, 2013; Shaw & Tiggemann, 2004; Vreugdenburg et
517 al., 2003). It could be that assessing overall phonological loop functioning masked the effects
518 of the two components of the phonological loop, since previous studies have found a
519 relationship between dieting and articulatory control processes and not the phonological store
520 (Shaw & Tiggemann, 2004) or vice versa (Vreugdenburg et al., 2003).

521 The current study assessed associations between WM and food choice, and so no claims can
522 be made about causality. Indeed, there is evidence to support the suggestion that food intake
523 influences WM as well as vice versa (Crichton, Murphy, Howe, Buckley, & Bryan, 2012). It
524 will be important in future studies to investigate the effectiveness of WM training to improve
525 food intake and measures of dieting success, such as weight loss and maintenance of weight
526 loss. Initial evidence suggests that WM training in overweight/obese adults reduces food
527 intake in individuals scoring high on a measure of dietary restraint (Houben, Dassen &
528 Jansen, 2016). The current sample was a group of undergraduate women with a low BMI
529 (although BMI was still within the normal range). It would be interesting to see if the effects

530 reported here would be replicated in higher BMI men and women, who may also have greater
531 experience of dieting success and failure. The present study utilised computerised measures
532 of WM as a way of measuring basic WM capacity. However, it is possible that participants'
533 WM was already taxed in some way, impairing their performance on these tasks. It is
534 therefore important that future research tries to identify and control for such potential
535 influences on WM, such as food cravings.

536 The conclusions that can be drawn from the current findings may be limited to the specific
537 tasks used. For example, the backwards digit span task used in this study required
538 memorizing a sequence of verbal information and manipulating this sequence in order to
539 recall it in the reverse order, therefore using both the phonological loop and the central
540 executive sub-components of WM. Similarly, the Spatial Working Memory Task used to
541 assess updating ability required remembering visuospatial information as well as updating of
542 this information, and so engaged both the visuospatial sketchpad and central executive sub-
543 components of WM. The present findings may therefore be limited to phonological loop
544 functioning that also involves manipulation, and updating ability that also involves the
545 visuospatial sketchpad. The use of tasks that assess WM sub-components both independently
546 and in conjunction, such as simple span and complex span tasks (Daneman & Carpenter,
547 1980) is recommended in future research.

548 Future research should explore the specific role of working memory processes in behavioural
549 control. Verbruggen, McLaren, and Chambers (2014) argue that three processes underlie
550 behavioural control: signal detection, action selection and action execution. Importantly, the
551 retrieval of goals and task rules (that is, how goals can be achieved) from long-term memory,
552 and maintenance of these in WM, are likely to modulate signal detection, action selection and
553 action execution. For example, if health goals are not retrieved from long-term memory and

554 activated, then task rules and actions associated with achieving these goals cannot be
555 selected. Difficulties maintaining task rules in mind may hamper continued action execution
556 (e.g. remembering to not over eat during a meal throughout the meal). The three processes,
557 signal detection, action selection and action execution are also continually monitored and
558 updated. WM is likely to play a key role here, where new information must be incorporated
559 into subsequent action selection and execution. For example, when finding out about a price
560 reduction on deserts (signal detection), this information needs to be incorporated into goals
561 currently held in WM, which will influence activation of task rules and ultimately action
562 selection and execution (choosing to order desert or not). This is where shielding goals from
563 interference may also be important, such as by preventing distracting information (e.g. signal
564 detection in the form of a price reduction on deserts) from being incorporated into goals and
565 task rules that could then influence action selection and execution. Future research should
566 therefore investigate the specific processes that explain how working memory functions
567 influence the processes underlying behavioural control. Focusing on mechanisms and
568 processes may better inform interventions for behavioural control. For example, people who
569 struggle to activate and retrieve long-term health goals in the presence of food (food being
570 the signal that requires detection) may benefit from training in this area, such as via
571 implementation intentions to think of their health/dieting goals when they see palatable food
572 (Van Koningsbruggen, Stroebe, Papiés, & Aarts, 2011). This is likely to facilitate appropriate
573 action selection and execution. In people who struggle to maintain such health/dieting goals
574 in mind once initially activated, training to improve this (such as via rehearsal) may facilitate
575 continued appropriate action execution.

576 In summary, the present results provide new insights into the specific components of WM
577 that play an important role in determining food choices. Specifically, it appears that
578 visuospatial WM span is associated with the healthiness of food choices, and may play a role

579 in a person's ability to choose LED food and resist HED food when both options are
580 available. The finding that visuospatial WM mediated the relationship between dieting
581 success and percentage of food intake that was LED suggests that poorer visuospatial WM
582 may undermine dieting attempts. Previous findings that dietary restraint is associated with
583 deficits in central executive functioning were also clarified, by supporting that this effect is
584 independent of tendency towards disinhibition.

585

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591 Declaration of interest

592 The authors have no conflicts of interest.

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