Unconscious priming shares a common resource pool with the manipulation subsystem

Xuechen Mao[1], Anmin Li[1,*]

[1] School of Psychology, Shanghai University of Sport, Shanghai, China

[*] Corresponding author

Corresponding Author:
Anmin Li
650 Qingyuan Ring Road, Shanghai, China
Email address: anminli@sus.edu.cn

First author:
Xuechen Mao
650 Qingyuan Ring Road, Shanghai, China
Email address: Xuechenmao.asprin@outlook.com
ORCID:0000-0001-6636-6708

Abstract

Background: Working memory can be subdivided into two relatively independent subordinate systems, the maintenance subsystem and the manipulation subsystem. Although the two subsystems are quite heterogeneous, research thus far has not adequately distinguished the resource pools of the two subsystems. Additionally, previous research on the relationship between working memory and unconscious priming is paradoxical. Different subsystems leading to different effects on unconscious priming might be the reason for the paradoxical research. Therefore, the current article aimed to distinguish the resource pools among two working-memory subsystems and to investigate the relationship between the two subsystems and unconscious priming.

Methods: To address these issues, a maintenance dual-task and a manipulation dual-task program were developed. Each participant had to separately perform the two dual tasks in a balanced order. In each dual task, participants first completed a masked priming task accompanied by working-memory load. As a control, participants completed a prime identification test to confirm that the processing of the masked prime was at the unconscious level. The maintenance dual task comprised sandwich masking trials accompanied by Sternberg trials, while the manipulation dual task comprised sandwich masking trials accompanied by N-back trials.

Results: The results of the prime identification test indicated that the participants could not consciously perceive the masked prime of both dual tasks. The results of the working-memory task of both dual tasks indicated that the load manipulation was successful for both dual tasks.

36 Most importantly, the results of the masking task of both dual tasks showed that an increase in
37 working-memory load decreased the magnitude of unconscious priming in the manipulation dual
38 task, whereas an increase in working-memory load did not decrease unconscious priming in the
39 maintenance dual task. These observations demonstrate that the manipulation subsystem, rather
40 than the maintenance subsystem, interferes with unconscious priming. Together with previous
41 research, we propose a two-pool attention resource model to explain the modulation of working
42 memory on unconscious priming by dissociating the executive resource pool of the manipulation
43 system from the retention resource pool of the maintenance system. Thus, the current work
44 confirms and extends the extant literature about the dependence of unconscious processing on
45 attention resources by suggesting that unconscious priming shares a common resource pool with
46 the manipulation subsystem.

Introduction

48 According to a multicomponent model and its updates, working memory can be subdivided into
49 two relatively independent subordinate systems (Baddeley, 2012; Engle, 2018; Logie, Camos, &
50 Cowan, 2021). One is the maintenance subsystem, which is responsible for the short-term
51 maintenance of modality-specific information, and the other is the manipulation subsystem,
52 which is the central executive and responsible for online monitoring, updating, and manipulation
53 of information. Given that the limitation in working-memory resources chiefly originates in
54 limited attention resources (Chow & Conway, 2015) and that attention has a variety of resource
55 pools (Cohen et al., 2012), it is conceivable that the two working-memory subsystems share
56 various resource pools. Although the two subsystems are quite heterogeneous, research thus far
57 has not adequately distinguished the resource pools of the two subsystems (Vaughan & Laborde,
58 2021).

59   In view of the resource limitations of attention, when two tasks compete for a common
60 resource pool, an increase in the workload of the secondary task leads to a decrease in the
61 performance of the primary task (Chun, Golomb, & Turk-Browne, 2011). Therefore, the
62 resource pools of the two subsystems can be distinguished by introducing a special processing
63 type that dedicates a resource pool to one of the working-memory subsystems without occupying
64 the resource pool pf the other working-memory subsystem.

65   However, what is the suitable "special processing"? Previous research has found that
66 unconscious priming depends on temporal attention (Fabre, Lemaire, & Grainger, 2007;
67 Naccache, Blandin, & Dehaene, 2002). Furthermore, temporal attention has been confirmed to
68 be modulated only with the manipulation subsystem (Capizzi, Sanabria, & Correa, 2012) rather
69 than the maintenance subsystem (Zanto et al., 2020). The dependence degree of unconscious
70 priming on the resource pools of the two subsystems seems to be different. Therefore, whether
71 unconscious priming is the appropriate "special processing" deserves exploring. To our
72 knowledge, however, this topic has not yet been studied.

73   On the other hand, previous theories of the relationship between working memory and

74 unconscious priming are paradoxical. Despite the controversy, in contrast to controlled processes,
75 which are widely considered to be intentional, goal dependent, and conscious, automatic
76 processes are generally considered to be unintentional, uncontrolled/uncontrollable, goal
77 independent, autonomous, purely stimulus driven, unconscious, efficient, and fast (Moors & De
78 Houwer, 2006). Based on the automaticity view, unconscious priming is considered a kind of
79 automatic process and therefore is assumed not be susceptible to attention resources. Research
80 supporting this assumption reported no observation of the modulation of working-memory load
81 on unconscious priming (Bodner &Stalinski, 2008; Perea et al., 2018). Moreover, models of
82 executive control consider unconscious priming to depend on the central executive. Research
83 supporting this assumption reported that increased working-memory load decreases the
84 processing of invisible stimuli (Ansorge, Kunde, & Kiefer, 2014; Bahrami, Lavie, & Rees, 2007;
85 Hung, Wu, & Shimojo, 2020).

86 Therefore, the second topic is the real relationship between working memory and
87 unconscious priming. Bodner and Stalinski (2008) instructed one group to perform an
88 unconscious identity priming task and another group to perform an unconscious identity priming
89 task while maintaining several digits in mind. They found that there was no significant difference
90 in unconscious priming between the two groups. Additionally, instead of a between-subject
91 design, one study (Perea et al., 2018) employed a within-subject design and asked participants to
92 perform an unconscious repetition priming task while maintaining four repeated consonants (low
93 load), such as BBBB, or four different consonants (high load), such as BDKF. No changes were
94 observed in unconscious priming between low and high loads. On the other hand, Bahrami et
95 al.(2007) observed a decrease in the BOLD response elicited by invisible stimuli when
96 participants performed a rapid serial visual presentation task from a high-load condition to a low-
97 load condition. In addition, Bayramova and colleagues (2020) recently employed auditory
98 stimuli with a dual-task paradigm in which an N-back task was interleaved with a flanker task.
99 The authors found that the inhibition effect from the incongruent trials was decreased with higher
100 loads (2- and 3-back) compared to low loads (0- and 1-back). The inhibition effect is considered
101 as the relatively slower response time under incongruent trials compared with congruent trials
102 and is based on the awareness of the incongruent and congruent stimuli. Therefore, based on
103 Bayramova and colleagues (2020), the decreased inhibition effect with higher loads means the
104 decreased awareness of the incongruent and congruent stimuli with increasing working-memory
105 load.

106 Although previous findings are mixed, further analysis indicates that the load manipulation
107 tasks utilized in those studies seem to involve different working-memory subsystems; thus, this
108 could account for the paradoxical findings. The studies finding no modulation of working-
109 memory load on unconscious processing utilized the tasks that involved only maintenance
110 processes, whereas the studies finding working-memory load decreased unconscious processing
111 utilized tasks that involved manipulation processes. Thus, it is conceivable that the two
112 subsystems have different effects on unconscious priming. However, to the best of our
113 knowledge, this hypothesis has not been confirmed.

114   In this line of work, a dual-task paradigm was employed, in which an unconscious priming
115   task (the primary task) was intermixed with a working-memory task (the secondary task). The
116   sandwich masking paradigm (Geng et al., 2020; Kiefer, 2019; Kiesel, Kunde, & Hoffmann,
117   2008), which has been widely utilized to measure unconscious processes, was chosen for the
118   primary task. Typically, in this paradigm, participants are instructed to perform a target
119   discrimination task, where the target is preceded by a masked prime, which is the same
120   (congruent condition) or different from the target (incongruent condition) (Eimer &
121   Schlaghecken, 1998). The prime is presented within a very short time and is masked by a
122   forward and a backward mask; therefore, the prime remains invisible to the participants.
123   Regardless of the invisibility of the prime to the participants, the unconscious priming effect can
124   be observed. The classic unconscious priming phenomenon is manifested in the faster responses
125   to the target under congruent conditions than under incongruent conditions (Klotz & Wolff, 1995)
126   or greater accuracy under congruent conditions than under incongruent conditions (Klotz &
127   Neumann, 1999). Some studies hold that the differences in accuracy between congruent and
128   incongruent conditions with different load conditions are not significant because of the ceiling
129   effect (Kiefer, 2018, Naccache et al., 2002). Therefore, the processing of the masked prime in the
130   present study is measured by comparing the difference in response times (RTs) between
131   congruent and incongruent conditions, which is the magnitude of the unconscious priming effect
132   (Geng et al., 2020; Kiefer, 2019; Naccache et al., 2002; Perea et al., 2018).

133   According to the taxonomy of conscious, preconscious, and subliminal processing (Dehaene
134   et al., 2006), unconscious priming investigated in the present study is a type of subliminal
135   processing (etymologically 'below the threshold'), which is defined as a condition of information
136   inaccessibility because of the short presentation of the information as well as forward and
137   backward masking. Based on the relationship between the masked prime and the target,
138   unconscious priming can be divided into perceptual unconscious priming (in which the prime
139   and target are similar in appearance under congruent conditions) and semantic unconscious
140   priming (in which the prime and target are similar in semantics under congruent conditions).
141   Previous research (Fabre et al., 2007; Perea et al., 2018) held that in contrast to semantic
142   unconscious priming, which is a higher level of unconscious processes, perceptual unconscious
143   priming is a lower level of unconscious processes that do not require cognitive resources and are
144   not affected by higher levels of processes such as working memory.

145   To distinguish the resource pools among two working-memory subsystems and to
146   investigate the relationship between the two subsystems and unconscious priming, we ran two
147   dual tasks: (1) the maintenance dual task explored the effect of the maintenance system on
148   unconscious priming, and (2) the manipulation dual task explored the effect of the manipulation
149   system on unconscious priming. We therefore employed Sternberg's item-recognition task as the
150   secondary task in the maintenance dual task and deployed the N-back task as the secondary task
151   in the manipulation dual task. The Sternberg task involves maintenance processes, wherein the
152   participant is asked to retain a memory item consisting of several items during a delay and finally
153   decide whether a cue item matches a member of the memory item or not (Sternberg, 1969;
154   Sternberg, 1975). With increasing load in the Sternberg task, reaction time to the cue item

155 increases (Sternberg, 1969; Sternberg, 1975). In contrast, the N-back task involves manipulation
156 processes in addition to maintenance processes (Bayramova et al., 2021; Kattner, 2021; Miller,
157 Lundqvist, & Bastos, 2018) in presenting the participant with a sequence of memory items and
158 asking them to indicate whether the current cue matches the one presented n steps earlier.
159 Typically, the N-back task requires a stepwise increase in N (first 1-back, followed by 2-back,
160 then 3-back). Previous research has demonstrated that unconscious processing can be influenced
161 when the stimuli utilized in the unconscious priming task share a common visual representation
162 with the stimuli utilized in the working-memory task (Ozimi & Repov, 2020). To exclude this
163 additional variable, we made the stimuli in the working-memory task independent of those in the
164 sandwich masking task. That is, we selected geometrical shapes as the stimuli in the sandwich
165 masking task and chose Arabic numbers as the stimuli in the working-memory task.

166 Based on the literature, we hypothesized that unconscious processing shares a common
167 resource pool with the manipulation subsystem without consuming the resource pool of the
168 maintenance subsystem. Therefore, we expected that unconscious priming would remain
169 invariant with increasing maintenance workload in the maintenance dual task and would
170 decrease with increasing manipulation workload in the manipulation dual task. To better
171 understand the relationship between the two working-memory subsystems and unconscious
172 priming, a two-pool attention resources model for working memory was assumed. In the
173 hypothetical model, we propose the existence of a retention resource pool, which is engaged in
174 maintenance processes and is not required by unconscious priming, and we propose the existence
175 of an executive resource pool, which is engaged in manipulation processes and is required by
176 unconscious priming. Consistent with previous research finding that the two subsystems rely on
177 distinct mechanisms (Baddeley, 2012; Engle, 2018; Logie et al., 2021; Vaughan & Laborde,
178 2021), we propose that the retention resource pool is relatively independent of the executive
179 resource pool; therefore, one is required by unconscious priming, while the other is not.

Method

Participants

182 The within-subject design was deployed to increase the statistical power and control for
183 additional variables, such as individual differences, in the present study. Based on prior research
184 (Hung et al., 2020; Kiefer, 2019; Meng et al., 2019; Xia et al., 2021), power analysis (G*Power
185 3.1, α = 0.05, power = 0.80, effect size = 0.25) showed that a minimum 16 volunteers needed to
186 participate. Therefore, we included 25 students (mean age, 20.56 with a range of 18-25 years, 11
187 men) who participated in the present experiment. The Ethical Committee of Shanghai University
188 of Sport approved the present experiment (No. 102772021RT020), and all participants provided
189 written informed consent.

Materials

191   Ten Arabic numbers from zero to nine (horizontal x vertical, 0.7° x 1.0°) were adopted as stimuli
192   for the working-memory tasks. In addition, five ellipses (varying from 4.0° x 1.1° to 4.0° x 1.9°)
193   and diamonds (varying from 1.1° x 4.0° to 1.9° x 4.0°) were adopted as stimuli for the sandwich
194   masking tasks (Geng et al., 2020). Notably, one ellipse (4.0° x 1.5°) and one diamond (1.5° x
195   4.0°) were considered primes, while the remaining geometries were considered targets. All
196   stimuli were in white with a dark gray background. Two pictures with many line patterns (4.0° x
197   4.0°) were considered forward and backward masks (Meng et al., 2019). Moreover, these visual

198   stimuli, with a resolution of 1280×720 pixels, were displayed on a 19-inch color monitor

199   (refresh rate: 60 Hz, frame duration: 16.67 ms), and participants were seated at an approximately

200   60 cm viewing distance. The experimental routines were programmed in E-Prime 2.0 software

201   (Schneider, Eschman, & Zuccolotto, 2002).

202   **Procedure**

203   Each participant had to separately perform the maintenance dual task and the manipulation dual
204   task in two days. The order of performing the two dual tasks was balanced between participants.
205   That is, half of the participants performed the maintenance dual task on the first day, and the
206   others performed the manipulation dual task on the first day. On each experimental day, the
207   participants first completed three practice sessions, then completed a dual task (the maintenance
208   dual task or the manipulation dual task), and finally performed a masked prime discrimination
209   test. Three practice sessions consisted of 60 trials of the sandwich masking task, 60 trials of the
210   working-memory task (30 trials for each load block), and 6 blocks of either of the dual tasks
211   (maintenance: nine sandwich masking trials were intermixed with nine modulated Sternberg
212   trials per block; manipulation: nine sandwich masking trials were intermixed with nine N-back
213   trials per block). The maintenance dual task included 40 blocks, containing 360 Sternberg trials
214   and 360 sandwich masking trials, and the manipulation dual-task included 40 blocks, containing
215   360 N-back trials and 360 sandwich masking trials. Each dual task was divided into two load
216   conditions. The participants first performed the dual task with low load then with high load, or
217   vice versa. The order of the load conditions was counterbalanced across participants. The stimuli
218   in each task are presented in a pseudorandom order.

219   *Maintenance dual task*

220   In each trial (Fig. 1), a yellow fixation was shown for 500 ms, replaced by a memory item
221   that was presented for 2000 ms. For the low-load condition, the memory item was a random
222   number. Regarding the high-load condition, the memory item was a number sequence consisting
223   of six random numbers with no repetition from zero to nine, with no more than two numbers in
224   ascending or descending order. Based on the pilot experiment, the chosen presentation duration
225   of the memory items allowed each participant to have sufficient time to remember all the
226   numbers in the memory item. During the presentation time, the participants attempted to
227   remember the memory item because each number included in the memory item would be
228   compared with the following memory probes within one memory block.

229   Thereafter, one sandwich masking trial was presented, which started with a white fixation
230 shown for 500 ms, followed by a 200-ms forward mask, a 33-ms prime and a 33-ms backward
231 mask sequentially. Then, a target was shown, and the participants were asked to respond to the
232 target with their right hands (left arrow for diamond and right arrow for ellipse). In half of the
233 masking trials, the target was a diamond, and in the other half, the target was an ellipse.
234 Additionally, half of the masking trials were under the congruent condition, while the other half
235 were under the incongruent condition. The four diamond and four ellipse primes are shown with
236 equal frequencies. The participants were instructed to respond as correctly and quickly as
237 possible. After collecting a response, a white fixation was shown for 500 ms, followed by a
238 memory probe, which was a single number with a question mark. The participants were
239 instructed to respond to the probe with their left hands (press "yes" when the probe occurred in
240 the memory item and press "no" when the probe did not occur in the memory item). Each
241 number served equally often as the memory probe. In half of the memory trials, the probe
242 occurred in the memory item, and in the other half, the probe did not. The participants were
243 instructed to respond as correctly and quickly as possible. After collecting a response, the next
244 masking trial was initiated.

245 ***Manipulation dual task***

246 In each trial (Fig. 2) under low load, a yellow fixation was shown for 500 ms, replaced by a
247 memory item that was presented for 2000 ms. Thereafter, a white fixation was shown for 500 ms,
248 indicating a sandwich masking trial was to come. The procedure of the masking trial was similar
249 to that in the maintenance dual task. After completing the masking trial, a white fixation was
250 shown for 500 ms, replaced by a memory probe, which was a single number with a question
251 mark. The participants were instructed to respond to the probe with their left hands (press "yes"
252 when the number probe was identical to the memory item and press "no" when the number probe
253 was not identical to the memory item). Simultaneously, the participants attempted to remember
254 the number probe because it would become the new memory item and was to be compared with
255 a new number probe after completing one masking trial. Moreover, each number served equally
256 often as the memory item. After collecting a response, the next masking trial was initiated.

257   The procedure of the high-load block was similar to that of the low-load block except (1)
258 that after initial yellow fixation occurred, three memory items were presented sequentially, and
259 each memory item was presented for 2000 ms, and (2) that after the initial memory probe was
260 displayed, the participants were instructed to decide whether the memory probe was identical to
261 the first memory item and concurrently remembered this memory probe because this memory
262 probe would become the new memory item and was to be compared with a new number probe
263 after completing three masking tasks. That is, the initial first memory item leaves the set and is
264 replaced by the current memory probe. In the next trial, the previous second item is probed. In
265 summary, we employed the 3-back as the high-load condition and the 1-back as the low-load
266 condition.

267 ***Masked prime discrimination test***

268   The procedure of each masked prime discrimination test was similar to the procedure of each
269   dual task to keep the stimulation comparable (Kiefer, 2019). Only the low-load condition was
270   used in the discrimination test because previous research suggested that the visibility of the
271   masked prime was suppressed more effectively with high load than with low load (Bahrami et al.,
272   2007). We included both objective and subjective measures in the discrimination test to enhance
273   its effectiveness (Stein et al., 2021). In each trial, in the objective measure, the participants were
274   asked to identify the prime between the two masks and to perform the prime decision with the
275   same response categories as in the main task. Following the button press, a short version of the
276   4-point perceptual awareness scale (PAS) was shown, which is the subjective measure. The
277   participants had to choose one of the following options to rate the subjective visible levels of the
278   masked prime: 1 = no experience, 2 = weak glimpse, 3 = almost clear, 4 = absolutely clear.
279   Therefore, each discrimination block included objective and subjective measures for the masked
280   prime under low-load conditions. In total, the discrimination test contained 90 subjective and 90
281   objective trials, presented in 90 Sternberg trials after the maintenance dual task and 90 N-back
282   trials after the manipulation dual task, respectively.

283   **Analysis**

284   ***Masked prime discrimination test***

285   Based on previous research (Geng et al., 2020; Kiefer, 2019; Meng et al., 2019), the *d'* value was
286   adopted to examine the visibility of the masked prime by calculating the hit rates (correct
287   responses to the congruent prime) and false alarm rates (erroneous responses to the incongruent
288   prime) from each participant's performance in the objective test. One-sample t tests were
289   performed both on response accuracy (RA) of the objective test (tested against 0.5) and on *d'*
290   (tested against 0). Data from participants whose RA of the objective test was significantly larger
291   than chance (0.5) were excluded. Moreover, we compared the difference in the ratings of the
292   subjective test, the RA of the objective test and *d'* between both dual tasks by paired *t* tests.
293   Furthermore, Pearson's correlation between *d'* and unconscious priming under low load was
294   performed. Finally, a two-tailed paired *t* test was separately performed on *d'*, the objective score
295   and the subjective rating with two task conditions.

296   ***Dual task***

297   Based on prior research (Kiefer, 2019), individual responses with RTs above or below 2 standard
298   deviations from the individual cell mean RT were discarded. The mean RT of the correct
299   responses was entered into the analysis of the RT data. For the working-memory task, a two-
300   tailed paired *t* test was separately performed on mean RT and RA with two load conditions for
301   the maintenance dual task and the manipulation dual task. Furthermore, repeated-measures
302   analyses of variance (ANOVAs) on mean RT and RA with the within-subject factors working-
303   memory load (low vs. high) and working-memory subsystem (maintenance vs. manipulation)
304   were performed. For the sandwich masking task, repeated-measures ANOVAs on mean RT and
305   RA with the within-subject factors working-memory load (low vs. high) and prime congruency
306   (congruent vs. incongruent) were performed for both dual-tasks. Moreover, repeated-measures

307 ANOVAs on mean RT and RA with the within-subject factors working-memory load (low vs.
308 high), prime congruency (congruent vs. incongruent) and dual-task type (the maintenance dual

309 task vs. the manipulation dual task) were finally performed. Importantly, Greenhouse－Geisser

310 corrections were applied when sphericity assumptions were violated, although these corrections
311 did not change any inferences. Paired t-tests with LSD corrections for multiple comparisons were
312 used for posthoc analysis if ANOVA showed significant interactions among different factors.To
313 examine the order effects, the order variable was analyzed as a between-subject factor when
314 conducting repeated-measures analyses of variance (ANOVAs) on mean RT. Bayes factors with
315 JASP (JASP Team, 2018) were conducted to assess the likelihood when there was no interaction
316 on RT and RA in the sandwich masking task as well as the working-memory task.

Results

318 One participant's RA of the objective test was significantly larger than chance, which means the
319 participant had an identification rate of the masked prime exceeding the 95% confidence (CI)
320 interval of chance performance (Kiefer, 2019) and was therefore excluded from further analysis.
321 Two participants' RA of the manipulation memory task under high load was more than 2

322 standard deviations below the group average (mean ± standard error: 95.31 ± 0.8%) and

323 therefore were also excluded from further analysis. The remaining 22 participants were included
324 in further analysis, which was sufficiently powered to detect the effects of interest.

Masked prime discrimination test

326 Sandwich masking was effectual. There was no significant difference in masking effectiveness
327 between the two dual tasks (Table 1). Although it seemed that the mean objective score of the
328 maintenance dual task was better than that of the manipulation dual-task, the objective scores of
329 both dual-tasks did not show a significant difference from each other, $t(21) = 0.971$, $p = 0.343$,
330 95% CI (CI) = [-0.03, 0.08]. Moreover, there was no significant difference in subjective rating
331 and d' between both dual tasks, $t(21) = -1.496$, $p = 0.149$, 95% CI = [-0.38, 0.06] and $t(21) = -$
332 1.267, $p = 0.219$, 95% CI = [-0.36, 0.08], respectively. These results indicated that the
333 participants could not consciously perceive the masked prime of both tasks.

334 For the maintenance dual task, the RA of the objective test was distributed close to chance

335 (53.2 ± 1.98%), $t(21) = 1.616$, $p = 0.121$, 95% CI = [-0.01, 0.07]. Moreover, the subjective

336 rating was distributed close to 1 (1.24 ± 0.06). Furthermore, d' values showed no significant

337 deviation from zero (-0.06 ± 0.07), $t(21) = -0.756$, $p = .458$, 95% CI = [-0.21, 0.1]. Additionally,

338 the distribution of d' was normal (Kolmogorov－Smirnov = 0.101, $p = 0.2$); however, the

339   distribution of unconscious priming under low load was not normal (Kolmogorov – Smirnov =

340   0.283, p = 0.000). Hence, logarithmic conversion was applied to the magnitude of the

341   unconscious priming effect. The data showed that unconscious priming did not correlate with d',

342   $r(22) = -0.37, p = .09$.

343   For the manipulation dual task, the RA of the objective test was distributed close to chance

344   (50.76 ± 1.88%), $t(21) = -0.403, p = 0.691$, 95%CI = [-0.03, 0.05]. Moreover, the subjective

345   rating was distributed close to 1 (1.4 ± 0.09). Furthermore, d' values showed no significant

346   deviation from zero (0.08 ± 0.06), $t(21) = 1.306, p = 0.206$, 95%CI = [-0.05, 0.21]. Additionally,

347   the distribution of d' was normal (Kolmogorov – Smirnov = 0.118, p = 0.2); however, the

348   distribution of unconscious priming under low load was not normal (Kolmogorov – Smirnov

349   =.231, p =.004). Hence, logarithmic conversion was applied to the magnitude of the unconscious

350   priming effect. The data showed that unconscious priming did not correlate with d', $r(22)$ =

351   0.055, $p = 0.806$.

352   **Working-memory task**

353   Load manipulation was efficacious for both tasks. Regarding both dual tasks, there was a main

354   effect of load on RT (Fig. 3), $F(1,21) = 87.792, p < .000$, $\eta_p^2 = 0.807$; however, neither a main

355   effect of task nor an interaction between task and load conditions was found, $F(1,21) = 0.298, p$

356   =.591, $\eta_p^2 = 0.014$, $BF_{10} < 0.001$, and $F(1,21) = 0.028, p = 0.87$, $\eta_p^2 = 0.001$, $BF_{10} = 0.393$,

357   respectively.In addition, a corresponding ANOVA on RA revealed that there was a main effect

358   of load, $F(1,21) = 11.755, p = 0.003$, $\eta_p^2 = 0.359$; however, neither a main effect of task nor an

359   interaction between task and load conditions was found, $F(1,21) = 0.077, p = 0.784$, $\eta_p^2 = 0.004$,

360   $BF_{10} = 0.197$, and $F(1,21) = 0.19, p = 0.667$, $\eta_p^2 = 0.009$, $BF_{10} = 0.353$, respectively. These

361   results indicated that there was no significant difference in load manipulation between the two

362   tasks. Moreover, the order effects were not significant for RT and RA, $F(1,20) = .037, p = .85$,

363   $\eta_p^2 = .002$, $F(1,20) = 1.27, p = .27$, $\eta_p^2 = .059$, respectively, indicating that the order

364   manipulation was effective for the present study.

365   For the maintenance dual task, a load effect was observed on RT (outliers for low load:

366 2.93%, high: 5.03%), $t(21) = -17.734$, $p <.000$, suggesting that responses under low load (828 $\pm$
367 61.22 ms) were significantly faster than those under high load (1401.55 $\pm$ 72.36 ms).
368 Additionally, a load effect was observed on RA, $t(21) = 2.921$, $p = 0.008$, indicating that more
369 responses under low load (97.57 $\pm$ 0.84%) were correct than those under high load (95.74 $\pm$
370 0.87%).

371   For the manipulation dual task, a load effect was observed on RT (outliers for low load:
372 4.86%, high: 4.32%), $t(21) = -4.843$, $p <.000$, suggesting that responses under low load (892.18
373 $\pm$ 56.63 ms) were significantly faster than those under high load (1446.24 $\pm$ 135.93 ms).
374 Moreover, we also observed a load effect on RA, $t(21) = 2.97$, $p =.007$, indicating that more
375 responses under low load (97.45 $\pm$ 0.45%) were correct than those under high load (95.32 $\pm$
376 0.9%).

377 **Sandwich masking task**

378 Regarding both dual tasks, for the RT data, the main effect for task, $F(1,21) = 7.159$, $p =.014$,

379 $\eta_p^2 =.254$, load, $F(1,21) = 18.878$, $p <.000$, $\eta_p^2 =.473$, congruency, $F(1,21) = 14.241$, $p =.001$,

380 $\eta_p^2 =.404$, and the two-way interaction between task and load, $F(1,21) = 15.01$, $p =.001$, η_p^2

381 $=.417$, as well as between load and congruency, $F(1,21) = 10.269$, $p =.004$, $\eta_p^2 =.328$, were

382 significant. Moreover, no interaction between task and congruency was found, $F(1,21) = 0.73$, p

383 $=.403$, $\eta_p^2 =.034$, $BF_{10} < 0.001$, indicating that there was no significant difference in

384 unconscious priming between the maintenance and manipulation dual tasks. In addition, the

385 order effects were not significant, $F(1,20) = 1.93$, $p = .18$, $\eta_p^2 =.088$, indicating that the order

386 manipulation was effective for the present study. Most importantly, the three-way interaction

387 between all factors was significant, $F(1,21) = 9.291$, $p =.006$, $\eta_p^2 =.307$. Post hoc tests yielded a

388 significant decrease in unconscious priming only under a high load of the dual-task manipulation
389 but not under a high load of the dual-task maintenance (Fig. 4). Furthermore, a corresponding

390 ANOVA on RA revealed only a main effect for congruency, $F(1,21) = 5.814$, $p =.025$, η_p^2

391 $=.217$, and a two-way interaction between task and load, $F(1,21) = 7.98$, $p =.01$, $\eta_p^2 =.275$.

392 Other effects were not significant (all $Fs < 2.408$, all $ps > 0.136$). Simple effect analysis
393 indicated that the difference in RA between both loads was significant in the dual-task
394 manipulation but not in the dual-task maintenance.

395   For the maintenance dual task, a main effect of congruency was observed on RT (outliers for

396 low: 5%, high: 4.38%), indicating that responses on incongruent trials (low: 533.39 $\pm$ 17.32 ms,

397   high: 537.13 $\pm$ 18.05 ms) were always longer than those on congruent trials (low: 506.08 $\pm$

398   16.72 ms, high: 511.67 $\pm$ 16.29 ms), $F(1,21) = 12.916$, $p =.002$, $\eta_p^2 =.381$. However, we did

399   not observe a main effect of the load or an interaction between the load and congruency

400   conditions on RT, $F(1,21) = 3.09$, $p =.093$, $\eta_p^2 =.128$, $BF_{10} = 0.302$ and $F(1,21) =.577$, $p =.456$,

401    $\eta_p^2 =.027$, $BF_{10} = 0.283$, respectively. These results suggested that there was no significant

402   difference in unconscious priming between low and high loads. Additionally, a main effect of

403   congruency was observed on RA, indicating that more responses on congruent trials (low: 99.4

404    $\pm$ 0.3%, high: 99.7 $\pm$ 0.1%) were correct than those on incongruent trials (low: 99.1 $\pm$ 0.2%,

405   high: 99.3 $\pm$ 0.2%), $F(1,21) = 4.797$, $p = .04$, $\eta_p^2 =.186$. However, we did not observe a main

406   effect of the load or an interaction between the load and congruency conditions on RA, $F(1,21) =$

407   2.469, $p =.131$, $\eta_p^2 =.105$ and $F(1,21) =.104$, $p =.75$, $\eta_p^2 =.005$, respectively.

408   For the manipulation dual task, a main effect of congruency was observed on RT (outliers of
409   low and high load, 2.1% and 7.37%), indicating that responses on incongruent trials (low: 580.94

410    $\pm$ 24.9 ms, high: 687.8 $\pm$ 44.83 ms) were always longer than those on congruent trials (low:

411   548.77 $\pm$ 23.56 ms, high: 683.26 $\pm$ 48.36 ms), $F(1,21) = 5.565$, $p =.028$, $\eta_p^2 =.209$. Moreover,

412   a main effect of the load was observed on RT, $F(1,21) = 16.985$, $p <.000$, $\eta_p^2 =.447$, suggesting

413   that responses under low loads were longer than those under high loads. Importantly, an
414   interaction between congruency and load conditions was also observed, $F(1,21) = 10.577$, p

415    $=.004$, $\eta_p^2 =.335$, showing that unconscious priming under low loads was significantly larger

416   than that under high loads. Furthermore, a main effect of the load was observed on RA,

417   indicating that more responses under low loads (congruent: 99.8 $\pm$ 0.2%, incongruent: 99.8 $\pm$

418   0.1%) were correct than those under high loads (congruent: 99.3 $\pm$ 0.2%, incongruent: 99.1 $\pm$

419   0.3%), $F(1,21) = 7.751$, $p =.011$, $\eta_p^2 =.27$. Additionally, neither a main effect of congruency nor

420   an interaction between the load and congruency conditions was found on RA, $F(1,21) =.401$, p

421    $=.534$, $\eta_p^2 =.019$, $F(1,21) =.231$, $p =.636$, $\eta_p^2 =.011$, respectively.

Discussion

422

423 The current work used an experimental method to distinguish the resource pool of the
424 manipulation subsystem from that of the maintenance subsystem. It also investigated the
425 relationship between working memory and unconscious processing. To our knowledge, this is
426 the first study that focuses on distinguishing the effects of two working-memory subsystems on
427 unconscious priming. In line with our expectations, we observed that the increase in the
428 workload of the N-back task decreased the magnitude of the unconscious priming effect, whereas
429 the increase in that of the Sternberg task did not decrease the magnitude of the unconscious
430 priming effect. These observations suggested that unconscious priming shares a common
431 resource pool with the manipulation subsystem rather than the maintenance subsystem, which
432 can explain past paradoxical evidence about the relationship between working memory and
433 unconscious priming.

434 Our observations in the maintenance dual task are in accord with previous studies, which
435 found that working-memory load does not affect unconscious priming (Bodner & Stalinski, 2008;
436 Perea et al., 2018). In those studies, one masked identity priming task was interleaved with one
437 cognitive load task; the latter required only maintaining or matching stimuli. The results showed
438 that no decrease in unconscious priming was found, which is similar to the present findings.
439 However, it is worth considering that there are some differences in the adopted dual-task
440 paradigm between those studies and the present study. First, the unconscious priming elicited in
441 the present study is different from the unconscious identity priming in those studies because the
442 masked prime in the maintenance dual task was not identical to the target but was proportionally
443 enlarged or narrowed relative to the target. Therefore, the unconscious priming in the present
444 study involved more processing and required more attention resources than that in previous
445 studies (Kiesel et al., 2008). However, we did not observe a significant decrease in unconscious
446 priming with increasing maintenance workload, which was not due to the independence of
447 unconscious priming on attention resources; instead it was ascribed to the independence of
448 unconscious priming on the maintenance subsystem. Therefore, it seems inappropriate to simply
449 summarize these findings that unconscious processing did not require resources or that working
450 memory did not affect unconscious priming. Second, the difficulty of the dual-task paradigm in
451 the present study was harder than that in previous studies because nine masked priming trials
452 were intermixed with nine memory load trials in one block of the maintenance dual task.
453 Therefore, it is conceivable that an increase in task difficulty might increase the effect of
454 memory load on unconscious priming. However, a similar magnitude of unconscious priming
455 between both loads was observed in the maintenance dual task, which was convergent with
456 previous findings. Hence, the present findings in the maintenance dual task confirm and extend
457 previous findings that unconscious priming is independent of the maintenance subsystem, and
458 this independence is robust and generalizes across variations of the dual-task paradigm.

459 Our observations in the manipulation dual task are novel in that unconscious priming is
460 impaired by an increased manipulation workload. This result is reconciled with earlier findings

461 claiming that increasing executive attention load interferes with stimuli processing (Bayramova
462 et al., 2021; Fougnie & Marois, 2007; Spinks et al., 2004). In those studies, the participants were
463 engaged in a cognitive load task that required continuous updating or reordering of the target
464 while an unexpected stimulus or a distractor was presented near the target. The results showed
465 that the interference effect of the distractor dwindled or even disappeared as the executive load
466 increased. Although both earlier findings and the present findings provide evidence of the
467 modulation of the manipulation processes on stimuli processing, one important difference is
468 noteworthy: in earlier studies, unexpected stimuli or distractors were shown inside of awareness,
469 whereas in the present study, stimuli were present outside of awareness. Additionally, only one
470 study has investigated the effect of executive attention load on unconscious processing (Bahrami
471 et al., 2007). In that study, a foveal rapid serial visual presentation task was combined with
472 peripherally represented stimuli that were rendered invisible by continuous flash suppression
473 (CFS). Taking advantage of functional magnetic resonance imaging (fMRI), a decrease in the
474 BLOD response elicited by invisible stimuli was observed when the executive attention load
475 increased. Hence, the authors summarized that attention resources affect the processing of
476 unconscious stimuli. However, it should be noted that the previous study observed only the
477 neural performance of the load effect on invisible stimuli without associating any behavior
478 performance such as unconscious priming. A recently published study reported that a previously
479 performed induction task can affect the processing of stimuli suppressed by CFS (Hung et al.
480 2020). The authors concluded that different induction tasks led to different attention loads, which
481 contributed to corresponding unconscious priming interference. Although that result is quite
482 close to the present findings, two facts should be noted. First, the unconscious priming produced
483 in that study is semantic unconscious processing, which is a relatively high-level processing and
484 has been confirmed to require attention resources and to be modulated by mental workload
485 (Fabre et al. 2007). However, the unconscious priming produced in the present study belongs to
486 unconscious perceptual processing, which is a relatively low-level processing and is considered
487 an automatic process and therefore is assumed not to be affected by mental workload (Fabre et al.
488 2007; Perea et al. 2018). The present study thus contradicts previous research by arguing that
489 even low-level unconscious priming requires attention resources. Second, the so-called task-
490 induced attention load in that study was quite different from the manipulation load in the present
491 study; the latter is a subsystem of working memory. To our knowledge, the present study is
492 therefore the first to directly explore the impact of the manipulation subsystem on unconscious
493 perceptual priming at a behavioral level.

494   What is the mechanism by which the two subsystems show different effects on unconscious
495 priming? Based on the present and previous studies (Capizzi et al., 2012; Fabre et al., 2007;
496 Hung et al., 2020; Naccach et al., 2002; and Zanto et al., 2020), we propose a two-pool model of
497 attention resources to explain the moderation of attention resources on working memory and
498 unconscious priming relationships. As summarized in Fig. 5, two relatively attention-
499 independent resource pools are responsible for two working-memory subsystems: (1) the
500 retention resource pool, which is not required by unconscious processes, is responsible for the
501 maintenance subsystem, and (2) the executive resource pool, which is required by unconscious

502 processes, is responsible for the manipulation subsystem. When increasing the workload of the
503 maintenance subsystem, retention attention is fully depleted, while executive attention is spared.
504 The spare resources are available to the unseen prime; thus, unconscious priming is preserved. In
505 contrast, when increasing the workload of the manipulation subsystem, executive attention
506 consumes full resources, which leads to insufficient resources for the masked prime; therefore,
507 unconscious priming diminishes. In short, the mechanism by which working memory modulates
508 unconscious processing depends on the availability of the executive resource pool. These results
509 are in agreement with those of many studies that recommend models of central executive control
510 of unconscious priming (Ansorge et al., 2014) and demonstrate that unconscious priming
511 depends on the participants' ability to successfully allocate their attention resources to the
512 masked prime.

513   The proposed two-pool model of resources required by working memory and unconscious
514 priming can be supported by prior fMRI data. The unconscious priming elicited in the current
515 work has been found to be associated with neural activity in the bilateral inferior and medial
516 superior frontal gyri and corresponding regions (Ulrich & Kiefer, 2016), and these frontal areas
517 are specifically associated with manipulation processes but not maintenance processes (Tomasi
518 et al., 2007). Therefore, some researchers have suggested that the modulation of the
519 manipulation subsystem on unconscious processing is related to the frontal cortex because the
520 two kinds of processing compete for common neural resources (Bergström & Eriksson, 2018).
521 However, the evidence for the neural mechanism underlying this modulatory effect is mixed.
522 Some studies report that the superior frontal sulcal area is involved in the maintenance subsystem,
523 while the dorsolateral prefrontal cortex is associated with the manipulation subsystem (Glahn et
524 al., 2002); hence, the dorsolateral prefrontal cortex seems to be an essential neural basis for the
525 modulation of the manipulation subsystem on unconscious priming. On the other hand, some
526 studies report that although maintenance processes activate virtually identical neural areas with
527 manipulation processes (Veltman, Rombouts, & Dolan, 2003), their dynamic activation patterns
528 are quite different (Jolles et al., 2011), which may account for the corresponding effects on
529 unconscious priming. Considering that this line of research is relatively scarce, further
530 investigations with neuroimaging techniques or other psychophysiological methods could
531 provide deeper insights into the relation between working memory and unconscious priming at a
532 neural-based level.

533 **Limitations and future research**

534 The current work not only addresses the paradoxical evidence of the relation between working
535 memory and unconscious priming but also effectively distinguishes the resource pools of two
536 working-memory subsystems. However, the current work is not without limitations. First, to
537 avoid the effect of the content of working memory affecting unconscious priming, we utilized
538 geometries as the masked primes while utilizing unrelated Arabic numbers as the memory items.
539 Based on the attentional sensitization model, however, the previously performed induction task
540 affects subsequent unconscious priming. In this proposed model, a perceptual induction task

541 facilitates perceptual unconscious priming, whereas a semantic induction task dampens
542 perceptual unconscious priming (Kiefer, 2019). Hence, it seems rational that the decline in
543 unconscious priming with the loaded condition observed in the manipulation dual task stemmed
544 from the task set rather than the engagement of the manipulation processes. Nonetheless, it
545 should be pointed out that the stimuli we utilized in the induction task (memory task) were the
546 same between both dual tasks; therefore, if the interference effect exists, the interference effect
547 of both tasks on unconscious priming should be identical. Since both induction tasks contained
548 the maintenance processes but only the manipulation dual task contained the manipulation
549 processes, any difference in unconscious performance should originate at the engagement of the
550 manipulation subsystem. On the other hand, additional variables, such as the effect of the type of
551 induction task on the modulation of working memory on unconscious priming, deserve more
552 attention. Thus, future research should vary the type of induction task as well as the type of
553 unconscious priming to explore more possibilities associated with the modulation of working
554 memory on unconscious priming. Moreover, the present data evaluated the effect of working
555 memory on unconscious perceptual priming but not other types of unconscious processing (e.g.,
556 unconscious semantic priming). Hence, our hypothesized model needs corroborating by
557 additional studies. Additionally, we only recruited a relatively small sample of participants;
558 hence, we cannot exclude the impact of individual differences on our results. Future studies can
559 examine the present results with a larger sample size. Finally, although this paper demonstrates
560 the effect of working memory on unconscious priming at the behavioral level, the neural
561 mechanism underlying this phenomenon remains unclear and is worth exploring in the future.

Conclusion

563 The present article tested the effect of two working-memory subsystems on unconscious priming
564 and discriminated different resource pools among the two subsystems. To this end, participants
565 were engaged in the sandwich masking task while storing or updating the memory items in two
566 experimental tasks. The results indicated that unconscious priming is affected by the
567 manipulation workload rather than the maintenance workload. We then proposed a two-pool
568 attention resource model to explain the relationship between working memory and unconscious
569 priming and provided some neuro-based evidence to support the proposed model. Despite a
570 growing consensus in the literature that holds that unconscious processing depends on attention
571 resources, the current study is the first to show that unconscious priming shares a common
572 resource pool with the manipulation subsystem. By introducing unconscious priming, we are
573 capable of distinguishing the two resource pools among the two subsystems: one is needed for
574 unconscious priming, while the other is not. Additionally, by distinguishing the two resource
575 pools, we are capable of explaining previous mixed findings regarding the relationship between
576 working memory and unconscious priming. Some studies investigate the relationship between
577 maintenance processes and unconscious priming, while some studies investigate the relationship
578 between manipulation processes and unconscious priming.

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Figure 1

A schematic illustration of one block in the maintenance dual task.

(A) An example of one sandwich masking priming trial combined with a modulated Sternberg trial under low load (top) or under high load (bottom) in a maintenance dual task. (B) A schematic illustration of the key press during the dual-task paradigm.

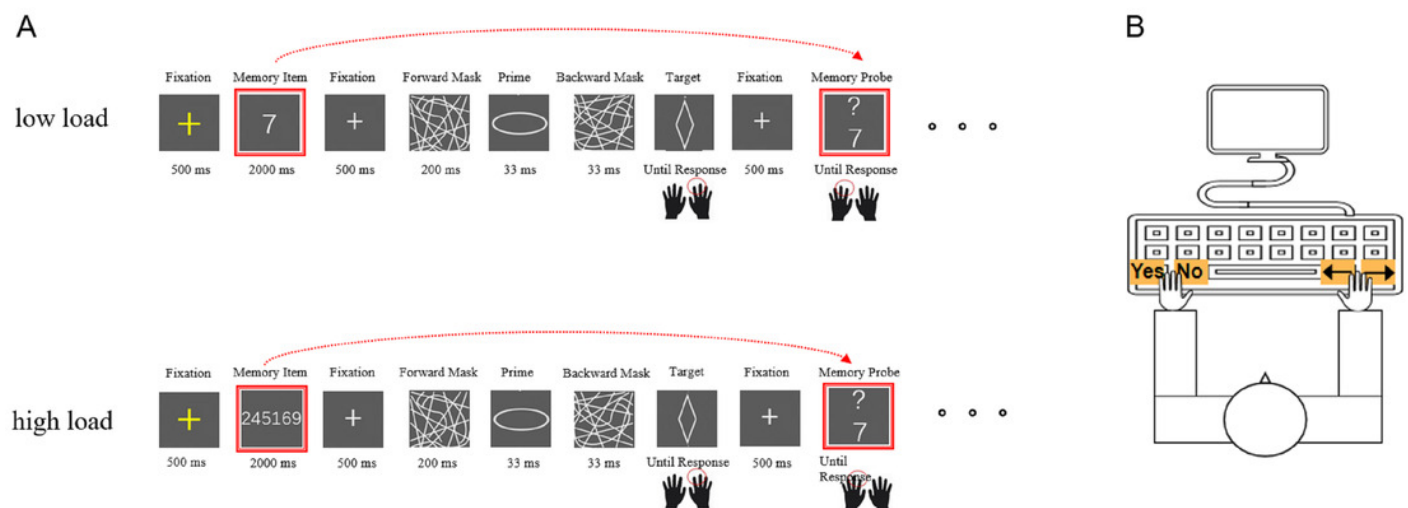



Figure 2

A schematic illustration of one sandwich masking priming trial combined with an N-back trial under low load (top) or under high load (bottom) in the manipulation dual task.

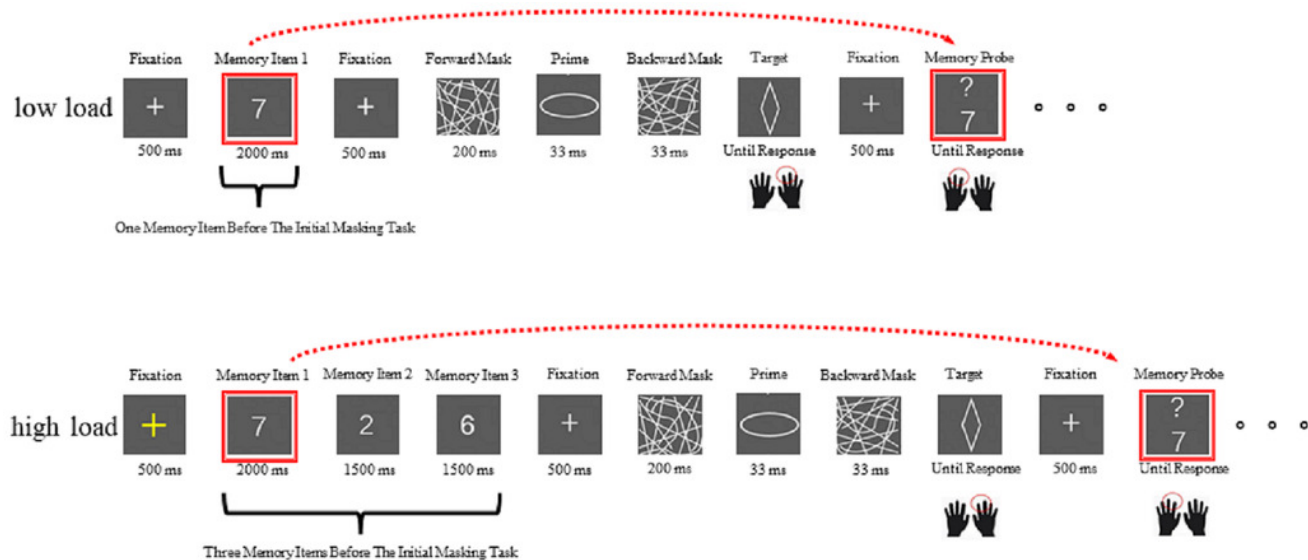



Figure 3

Mean response times as a function of working-memory load (low versus high) and experimental task type (maintenance dual task versus manipulation dual task) in the working-memory task.

Red bars represent response times under the low-load condition in the maintenance dual task, and yellow bars represent response times under the high-load condition in the manipulation dual task. Error bars reflect standard errors corrected for within-participant variation. ***p < 0.001, n.s. means no significant difference.

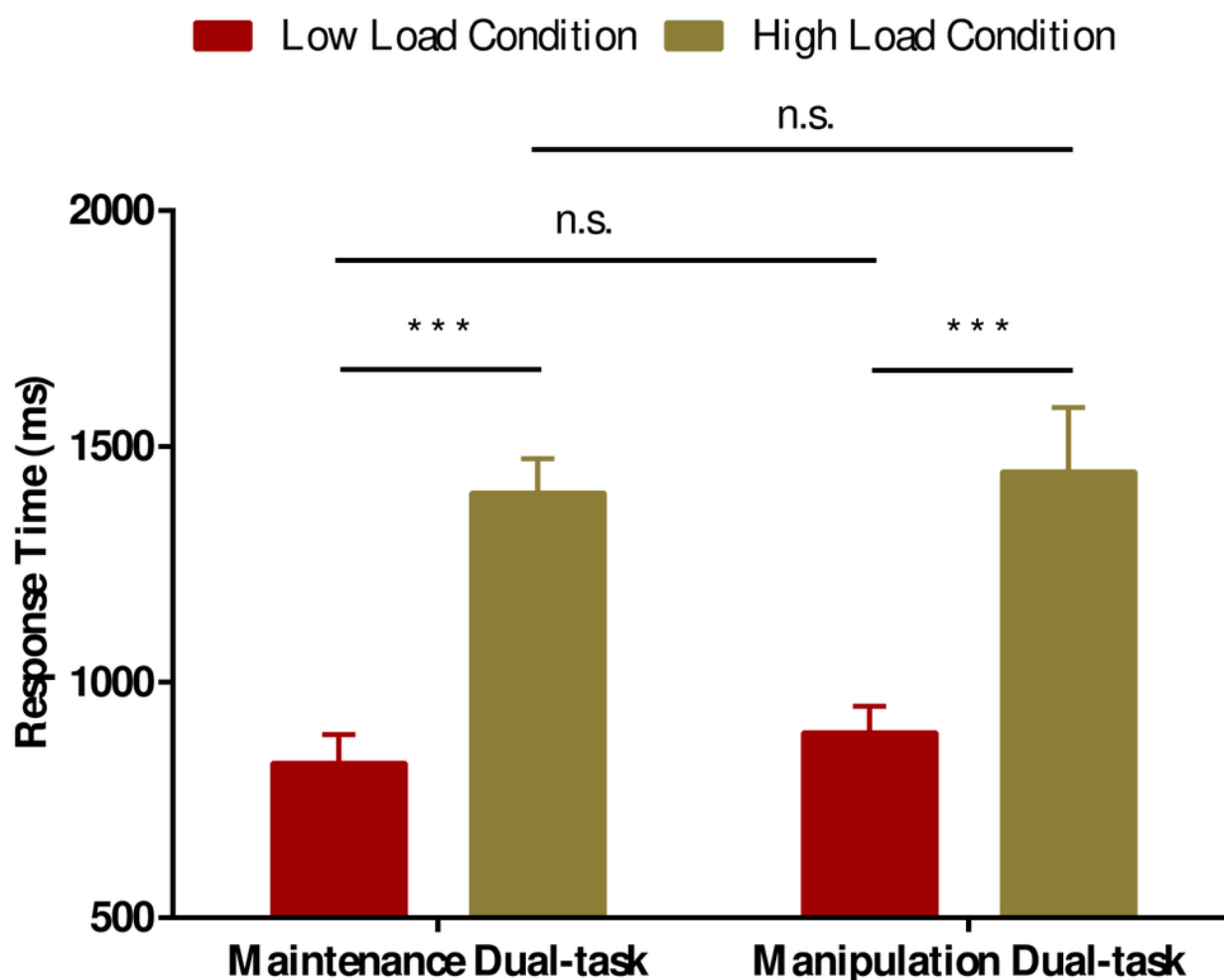



Figure 4

Mean response times as a function of working-memory load (low versus high), prime congruency (incongruent versus congruent) and experimental task type (maintenance dual task versus m anipulation dual task) in the masked priming task.

Blank bars represent response times on congruent trials, and bars with patterns represent response times on incongruent trials. Red bars represent response times under low-load conditions, and yellow bars represent response times under high-load conditions. **p < 0.01, n.s. means no significant difference.

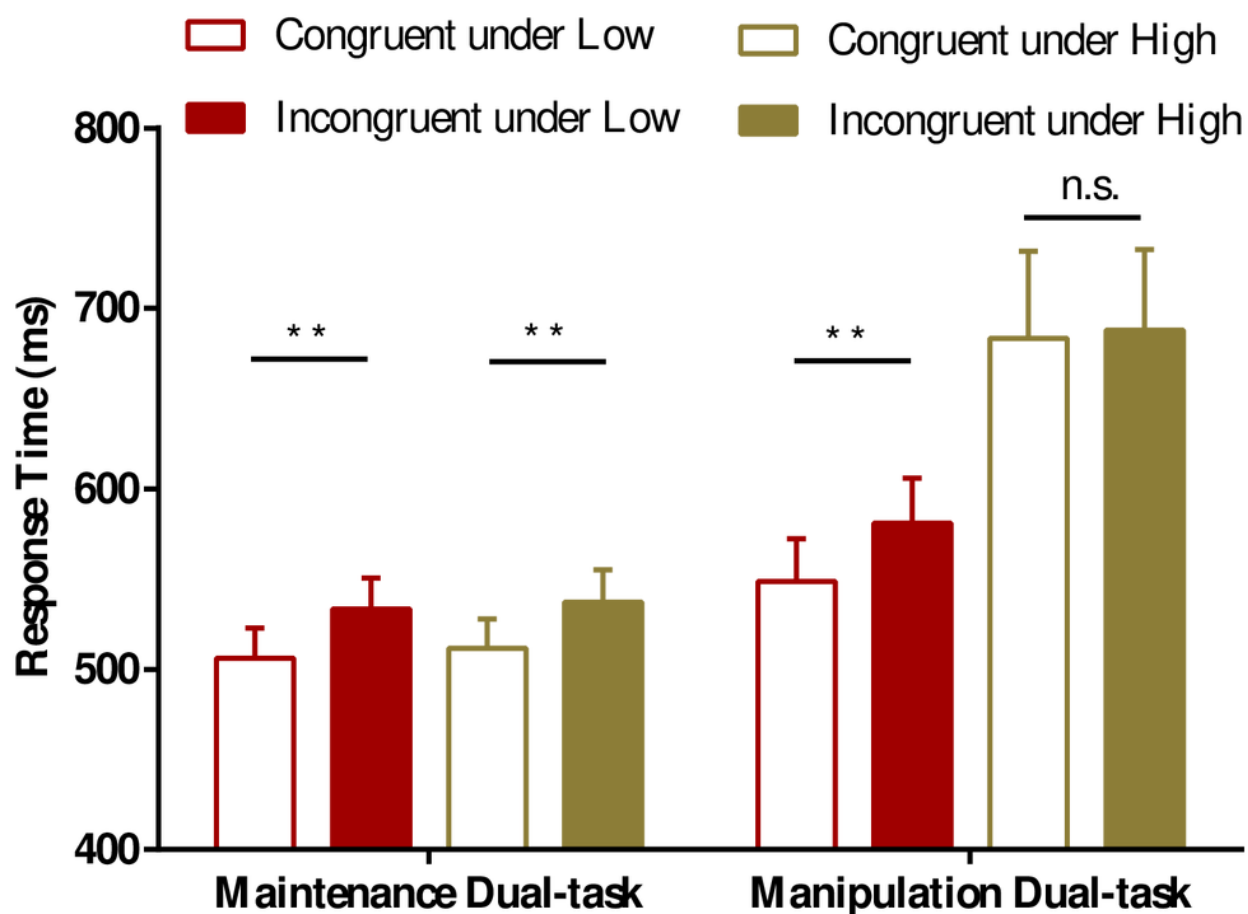
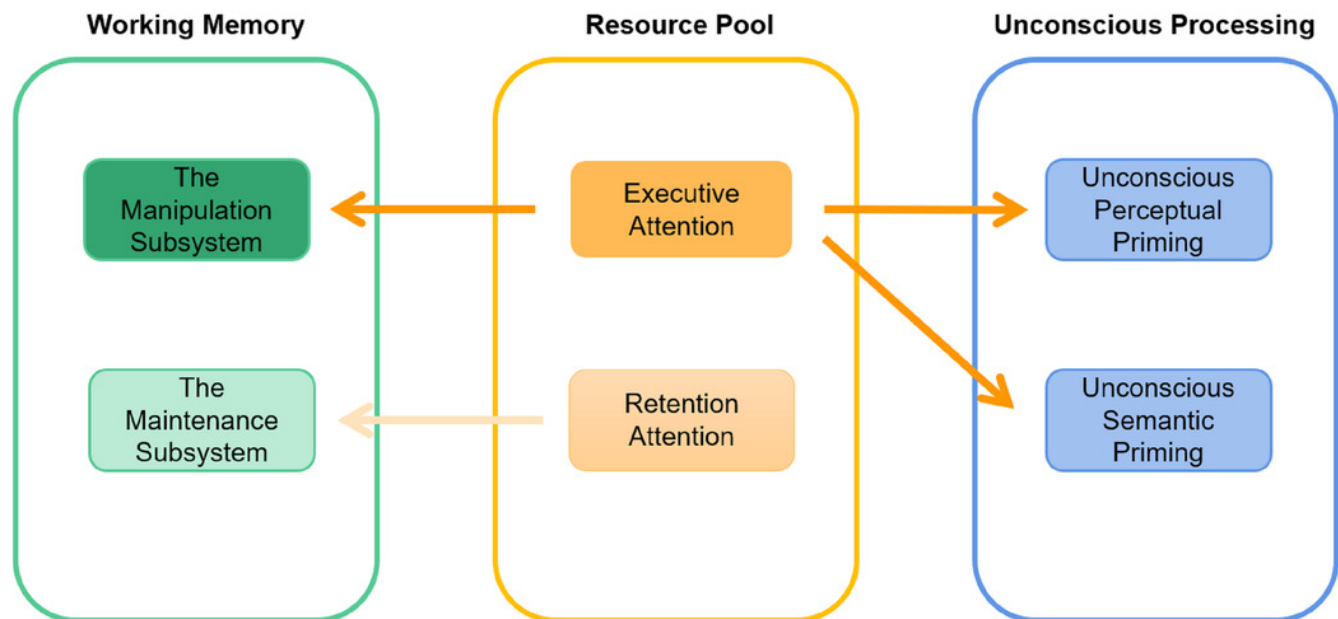



Figure 5

Proposed two-pool model of attention resources on the relationship between working memory and unconscious priming.

Performance of masked prime discrimination test in maintenance dual task and manipulation dual task. Standard error in brackets.

Masked prime discrimination test	Maintenance dual task	Manipulation dual task	90% Confidence Interval	
			Lower Limit	Upper Limit
Objective test (accuracy in percentage)	53.2 (1.98)	50.76(1.88)	-0.03	0.08
Subjective test (rating from 1 to 4)	1.24(0.06)	1.4(0.09)	-0.38	0.06
D' of the Objective test	-0.06(0.07)	0.08(0.06)	-0.36	0.08