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Effortful semantic decision-making boosts memory performance in older adults

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ABSTRACT

A major concern in age-related cognitive decline is episodic memory (EM). Previous studies indicate that both resource and binding deficits contribute to EM decline. Environmental support by task manipulations encouraging stronger cognitive effort and deeper levels of processing may facilitate compensation for these two deficits. To clarify factors that can counteract age-related EM decline, we assessed effects of cognitive effort (four levels) and level of processing (LoP, shallow/deep) during encoding on subsequent retrieval. Young (YAs, $N = 23$) and older (OAs, $N = 23$) adults performed two incidental encoding tasks, deep/semantic and shallow/perceptual. Cognitive effort was manipulated by varying decision-making demands. EM performance, indexed by d-prime, was later tested using a recognition task. Results showed that regardless of LoP, increased cognitive effort caused higher d-primes in both age groups. Compared to YAs, OAs showed a lower d-prime after shallow encoding across all cognitive effort levels, and after deep encoding with low cognitive effort. Deep encoding with higher levels of cognitive effort completely eliminated these age differences. Our findings support an environmental-compensatory account of cognitive ageing and can have important therapeutic implications.

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Given the impact of the increase in longevity on retirement age, optimal cognitive performance is increasingly important for older adults (OAs). Consequently, it is essential to develop and investigate interventions aimed to ameliorate age-related cognitive decline. One of the major age-related deficits concerns a decline in episodic memory (EM): the encoding, storage, and retrieval of personally experienced past events (Daselaar & Cabeza, 2008). Evidence from both behavioural and neuroimaging studies hypothesise age-related EM deficits in resources (i.e., reduced processing capacity and efficiency) and memory binding (i.e., difficulty in making associations spontaneously) (Daselaar & Cabeza, 2013; van Geldorp, Parra, & Kessels, 2015; Old & Naveh-Benjamin, 2008; Tromp, Dufour, Lithfous, Pebayle, & Després, 2015). Factors that might support compensatory mechanisms for these deficits have been suggested, including higher cognitive effort (Jacoby, Craik, & Begg, 1979) and deeper level of processing (LoP) (Cermak & Craik, 2014). This study aimed at investigating the effect of these two factors, especially their combined effect, in eliminating age-related EM deficits of OAs.

Resource deficits and cognitive effort

According to the resource deficit hypothesis (Craik & Byrd, 1982), age-related cognitive deficits, including EM decline, are the result of a general impairment in attentional resources resulting in ineffective cognitive processing. Consequently, OAs are less able than their younger counterparts to self-initiate appropriate mental operations (Craik & Rose, 2012). It predicts that age-related decline of EM should be reduced when the task provides greater environmental support (e.g., strategies given by instruction), resulting in a more efficient usage of attentional resources during memory encoding. Several studies have shown enhancements in EM performance when memory encoding is scaffolded by an increase in cognitive effort (Ellis, Thomas, & Rodriguez, 1984; Jacoby et al., 1979; Tyler, Hertel, McCallum, & Ellis, 1979), particularly in individuals with limited resources and inefficient processing capacity, such as patients suffering from depression (Ellis et al., 1984; Hertel, Benbow, & Geraerts, 2012). Although the theoretical framework has been addressed (Mitchell & Hunt, 1989), so far it has not been examined whether OAs' EM performance could benefit from increasing encoding effort.

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Existing research on effects of cognitive effort in young adults (YAs) has three important limitations. First, most studies used secondary tasks (e.g., simple/choice reaction time (RT) task) to assess cognitive effort (Griffith, 1976; Tyler et al., 1979), which involves the methodological issues related to dual-task paradigms (Green & Vaid, 1986); second, they often employed different types of material to manipulate variation in difficulty (McDaniel, Einstein, Dunay, & Cobb, 1986; Tyler et al., 1979). The different nature and processing of the materials might confound measurements of effort (McDaniel, Einstein, & Lollis, 1988). Third, they generally ignored the fact that cognitive effort/task difficulty is a subject-specific factor – the same task can be difficult for one participant, but not for the other (Pashler, 1998). Here, we manipulated cognitive effort during encoding by varying difficulty of decision-making which can be assessed by measuring variations in each individuals' RTs. Accordingly, trials with shorter RTs are perceived as low on cognitive effort, whereas those with longer RTs are considered high on cognitive effort (Craik & Tulving, 1975; McDaniel et al., 1986; Tyler et al., 1979). Under high cognitive effort conditions, we expect a large benefit on EM in OAs by inducing greater allocation of attentional resources to the study items, which may neutralise existing resource deficits.

Binding deficits and LoP

The binding-deficit hypothesis postulates that age-related memory deficits are the result of difficulties in binding features that constitute a coherent representation of EM (Naveh-Benjamin, 2000). Neuroimaging studies attribute these deficits to age-related reductions in medial-temporal-lobe activity during EM encoding tasks (Daselaar, Fleck, Dobbins, Madden, & Cabeza, 2006; Daselaar, Veltman, Rombouts, Raaijmakers, & Jonker, 2003; Gutchess et al., 2005). The deep/semantic encoding task employed in these studies was specifically designed to invoke semantic associations related to the study items, thereby forming durable memory traces.

According to the LoP framework (Craik, 2002; Craik & Lockhart, 1972), deep encoding concerns semantic analyses of the stimuli, associated with more elaborate, longer lasting, and stronger memory traces than shallow encoding. The latter utilises superficial analyses regarding physical or sensory features such as lines, angles, brightness, pitch, or loudness. It has been reported that deep/semantic, relative to shallow/perceptual, processing of study items improves memory performance in both YAs and OAs (Sauzeon, N'Kaoua, Lespinet, Guillem, & Claverie, 2000; Simon, 1979). Here, we included LoP as a factor as well, to find out to what extent it can compensate for age-related EM decline.

Although both cognitive effort and LoP have been well studied in the past 40 years (Craik & Byrd, 1982; Craik & Tulving, 1975), the current study combined cognitive effort and LoP to assess their effect and especially their interaction in supporting compensation for age-related EM deficits. Two incidental encoding tasks were used to manipulate LoP, a deep encoding task based on semantic relatedness between words, and a shallow encoding task based on their size. Cognitive effort was introduced by modulating decision-making demands in both encoding tasks. Here, we propose the *Environmental-Compensation view,* which states that OAs benefit most when environmental support is greatest and targeted to compensate their cognitive deficits. In this study, we expected OAs' EM performance to be as good as the YAs' in conditions combining environmental support from both LoP and cognitive effort manipulations.

Methods

Participants

Twenty-three OAs (mean age = 65.52 years, SD = 5.01; 9 females; recruited by advertisements in local newspapers) and 23 YAs (mean age = 22.41 years, SD = 2.74; 14 females; recruited from Radboud University) participated in this study. All participants were highly educated (college or higher), native Dutch speakers who presented no history of neurological or psychiatric illnesses. OAs were included in the study only when they scored higher than 27 on the Mini Mental State Examination (Folstein, Folstein, & McHugh, 1975) (M = 29.83, SD = 0.39, range: 29–30). All participants signed an informed consent and received €40 as remuneration; a bonus of €5 or €10 could be obtained depending on their performance in spotting out pseudo-words in the shallow encoding task. The study was approved by the Ethics Committee of the Faculty of Social Sciences of the Radboud University.

Materials

Deep encoding task

This task consisted of 360 trials, each beginning with a fixation cross (500 ms), followed by a word triplet. Participants indicated which of two words displayed at the bottom of the screen was more semantically related to the target word at the top by pressing appropriate buttons on the keyboard. All words and their relatedness scores were retrieved from the LSA database (lsa.colorado.edu) and matched on word length and frequency. Trials proceeded with self-pace and a 5 s response limit. In order to promote variations in *semantic* cognitive effort, each triplet was categorised to one of four difficulty levels determined by the difference between the semantic relatedness score of each top-bottom pair. These difference levels were set at 0.30 (easy, Figure 1(a)), 0.20, 0.10, or 0.05 (hard, Figure 1(b)). The smaller the difference between two scores, the more cognitive effort was assumed to be required to make the "encoding" decision. The resulting 360 triplets were translated from English to

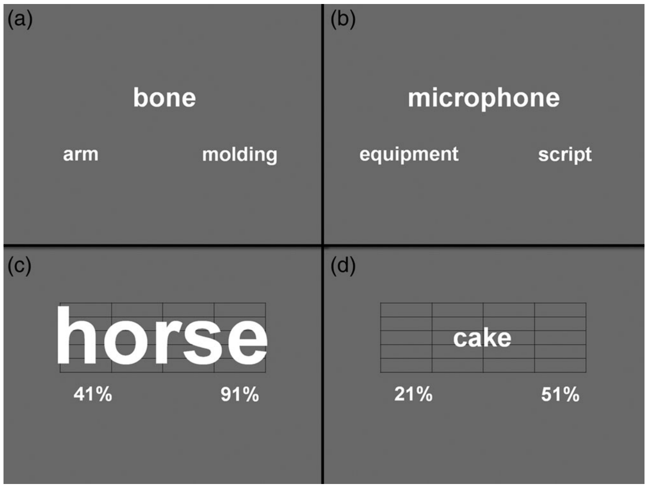

Figure 1. Sample encoding decision-making trials in easy (a, c) and difficult (b, d) deep and shallow encoding tasks, respectively. In the deep encoding task (a, b), participants indicated which of two bottom words is more semantically related to the target word at the top. In the shallow task (c, d), participants chose a value representing the correct percentage of the grid occupied by the word.

Dutch by five independent native Dutch speakers, and presented randomly for each participant.

Shallow encoding task

The shallow encoding task was similar to the deep task, but the 360 target words were now overlaid on a rectangular grid, and the bottom words were replaced with 2 percentage values. Here, participants chose a value representing the correct percentage of the grid occupied by the word. Similar to the deep encoding task, four difficulty levels were set to modulate *perceptual* cognitive effort. These levels were determined by the differences between the two bottom values, 90%, 70%, 50% (Figure 1(c)) and 30% (Figure 1(d)). Since it was necessary that participants actually read the word while making the size judgement, 36 pseudo-word trials were added as fillers. Participants could receive an extra bonus for skipping each filler by pressing the space key.

Recognition memory task

The 720 target words from the deep and shallow encoding tasks were intermixed with 360 new words and randomised for the "old/new" recognition task. Trials proceeded in a self-paced fashion with a 5 s response limit and short breaks after every 270 trials.

Procedure

The experiment comprised of two blocks of the deep encoding task followed by two blocks of the shallow encoding task with a 3 min break in between. The later recognition task had the four blocks in reverse order to counteract possible floor effects of shallow encoding. Before starting the actual experiment, participants acquainted themselves with the task using instructions and practice trials of the encoding tasks. The experiment was designed using PsychoPy (Peirce, 2009) and conducted in Radboud University research labs and lasted 2 h.

Data analysis

The data from the two encoding type blocks were collapsed for each task. Trials that were not responded to, or with an RT ± 3SD away from the mean, or with a RT < 200 ms were removed. Applied cognitive effort was measured by RTs. For each encoding task and participant, four levels of cognitive effort were established using rank-based percentile cuts (see Table 1 for means and SDs).

Memory performance at each cognitive effort level for both deep and shallow encoding tasks was calculated using d-prime (Macmillan & Creelman, 2004). A repeated-measures General Linear Model (GLM) analysis was conducted with d-prime as the dependent variable, Group (OAs vs. YAs) as between-subjects factor, and LoP (deep vs. shallow) and cognitive effort (four levels) as within-subjects factors. Post hoc tests were run to investigate interaction effects. All statistical tests used $p < .05$ as criterion for significance and effect sizes (partial eta-squared) are reported.

Results

Main effects

The repeated-measures GLM revealed three main effects: (1) Group, $F(1, 44) = 11.74$, $p = .001$, $\eta_p^2 = .21$, reflecting higher d-primes in YAs than OAs; (2) LoP, $F(1, 44) = 11.75$, $p = .001$, $\eta_p^2 = .21$, reflecting higher d-primes after the deep than the shallow encoding; (3) cognitive effort, $F(3, 42) = 32.57$, $p < .001$, $\eta_p^2 = .43$. A post hoc test with Bonferroni correction for multiple comparisons revealed that the latter represented differences at levels 1 and 2 ($p = .001$), 1 and 3 ($p < .001$), 1 and 4 ($p < .001$), 2 and 4 ($p < .001$), and 3

Table 1. Means and standard deviations of RTs for all encoding conditions for OAs and YAs.

Level of cognitive effort[a]	Deep 1	Deep 2	Deep 3	Deep 4	Shallow 1	Shallow 2	Shallow 3	Shallow 4
YAs (*M*)	1.38	1.79	2.20	2.80	1.11	1.37	1.67	2.39
YAs (sd)	*0.32*	*0.41*	*0.50*	*0.64*	*0.25*	*0.29*	*0.37*	*0.49*
OAs (*M*)	1.85	2.30	2.73	3.21	1.39	1.74	2.41	3.08
OAs (sd)	0.45	0.37	*0.41*	*0.49*	*0.29*	*0.38*	*1.42*	*1.30*

[a]Four levels of cognitive effort were established using rank-based percentile cuts of RTs of encoding tasks for each participant: Level 1: RT < 25 percentile; Level 2: 25 percentile ≤ RT < 50 percentile, Level 3: 50 percentile ≤ RT < 75 percentile; and Level 4: RT ≥ 75 percentile.

and 4 ($p = .002$). See Figure 2(a) for an illustration of the effect of cognitive effort in each group.

Interaction between Group, effort, and LoP

The interaction between Group and LoP was significant, $F(1, 45) = 4.51$, $p = .039$, $\eta_p^2 = .093$, reflecting a significantly better performance for OAs in the deep vs. shallow condition ($M_{deep} = 0.601$, $M_{shallow} = 0.320$, $F(1, 22) = 14.80$, $p = .001$, $\eta_p^2 = .40$), but not for YAs ($M_{deep} = 0.696$, $M_{shallow} = 0.630$, $F(1, 22) = 0.89$, $p = .357$, $\eta_p^2 = .04$) (Figure 2(b)). The three-way interaction between Group, LoP, and cognitive effort was also significant, $F(3, 135) = 3.00$, $p = .033$, $\eta_p^2 = .06$, which was examined further with a Group × Cognitive effort GLM for deep and shallow conditions separately.

For deep encoding, the GLM revealed a significant main effect of cognitive effort, $F(3, 42) = 17.33$, $p < .001$, $\eta_p^2 = .28$, and a significant Group × Cognitive effort interaction, $F(3, 132) = 3.10$, $p = .029$, $\eta_p^2 = .06$. Subsequent simple effect analysis showed except at the first level of cognitive effort, $F(1, 44) = 4.82$, $p = .034$, there was *no difference* in the performance of OAs vs. YAs (Figure 2(d)). For shallow encoding, the Group × Cognitive effort GLM revealed a main effect of Group, $F(1, 44) = 30.51$, $p < .001$, $\eta_p^2 = .41$, and cognitive effort, $F(3, 42) = 17.67$, $p < .001$, $\eta_p^2 = .29$, but no interaction, $F < 1$ (Figure 2(c)).

Discussion

Following the *environmental-compensation account*, encouraging different levels of processing efficiency through task manipulations, we compared the effect and interaction of different levels of cognitive effort and two levels of processing. This study revealed the following. Firstly, increased cognitive effort resulted in a better memory performance for both groups. Secondly, OAs benefited more from deep vs. shallow encoding when compared with YAs. Thirdly, in line with the *environmental-compensation account*, during deep/semantic encoding, increased cognitive effort eliminated age-related EM deficits.

Increased cognitive effort enhances memory in both old and young

Consistent with previous studies (Jacoby et al., 1979; McDaniel et al., 1986), we found that higher levels of cognitive effort

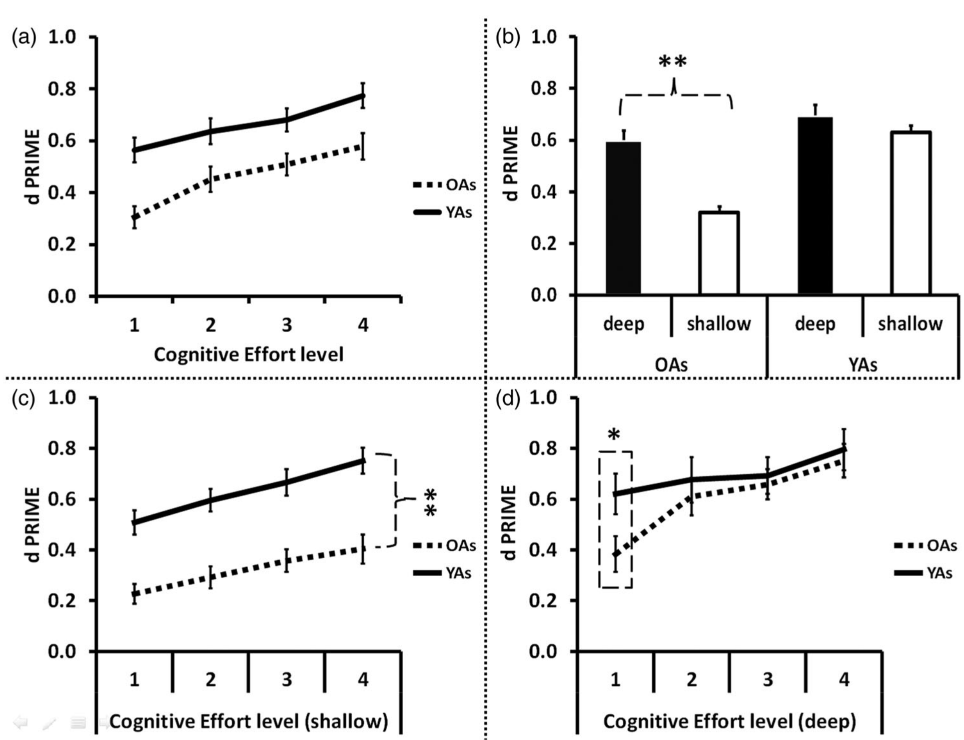

Figure 2. (a) Memory performance improved with increasing cognitive effort level in both YAs and OAs irrespective of task; (b) OAs displayed better memory performance for the deep vs. shallow encoding task; no significant difference was present in YAs; (c) YAs outperformed OAs in the shallow condition at all effort levels; (d) OAs' memory performance matched YAs' in the deep task except at effort level 1.

during encoding lead to better recognition performance in both YAs and OAs. Although some studies did not find such an effect (Green & Vaid, 1986; Tyler et al., 1979), this discrepancy could arise from methodological issues, such as the noise that may be induced in the encoding effort manipulation by using different materials or employing dual-task paradigms. To address these methodological concerns, we used RTs based on encoding performance of each individual participant as a direct index of cognitive effort, kept our tasks analogous, and materials as similar as possible. Compared to cognitive capacity, which is fixed and absolute for a given individual, cognitive effort, defined as the percentage of available resources allocated to processes required by a task, represents the efficiency of processing, relative to both task demands and to available capacity. Unfortunately, OAs with resource deficits suffer from both capacity and efficiency reduction. Although enhancing capacity is unlikely to happen at old age, OAs could take advantage of environmental support to increase efficiency (Craik, 1986; Craik & Byrd, 1982; Troyer, Hafliger, Cadieux, & Craik, 2006). As shown here, increasing encoding decision-making difficulty seems like a promising aid for memory performance.

One might argue that semantic congruency or relatedness, which has a beneficial effect on EM (Bein et al., 2015; Staresina, Gray, & Davachi, 2009), is confounded in the deep/semantic effortful encoding manipulation and that the effect of this confound was different for YAs and OAs. Indeed, due to the nature of our deep/semantic encoding task, the semantic relatedness of target word pairs was larger in easy than difficult trials. However, it is not likely that the eliminated ageing effect at higher effort levels can be explained by such differential confounder effect given evidence that OAs and YAs benefit from semantic congruency/relatedness to a similar extent (Crespo-Garcia, Cantero, & Atienza, 2012).

Semantic encoding provided environmental support for OAs

Compared with shallow processing, deep processing led to better memory for OAs. Semantic analysis of stimuli invokes associations between the stimuli and existing knowledge networks, leading to forming durable memory traces. Previous studies show that OAs with memory-binding deficits do not employ semantic-processing strategies spontaneously, but are able to use them when forced (Burke & Light, 1981; Craik & Simon, 1980). Here, when required to encode stimuli using deep processing, OAs formed stronger memory traces for later retrieval, which possibly counteracted the memory-binding deficit. However, inconsistent with other studies (Sauzeon et al., 2000; Simon, 1979), YAs did not seem to benefit from deep processing. One of the reasons might be that participants in other previous studies using a shallow condition were asked to respond to the case/font of presented words (Daselaar et al., 2003). In those cases, the words may not have been actually read or encoded. Prior to being judged on its size, we encouraged participants to read the word, by mixing in pseudo-words. Without binding deficits, we assume YAs can initiate semantic links when reading the words in both deep and shallow conditions. Moreover, by introducing a bonus payment for detecting pseudo-words in the shallow encoding task, participants were encouraged to be more involved in the shallow task. This motivation might be especially strong in YAs, additionally contributing to the lack of an LoP effect in this group.

Increasing effort in semantic encoding boosts OAs performance to match YAs

Previous studies report that OAs are less likely to spontaneously process incoming perceived events elaborately and deeply (Craik & Rose, 2012), which are the consequences of two deficits: resource deficits leading to a lack of self-initiated cognitive effort, and binding deficits reducing the likelihood of voluntarily forming deep/semantic traces during encoding. However, when adequate environmental support is provided, OAs can perform such useful operations (Kessels & de Haan, 2003), which enhance encoding and hence later memory performance. As shown here, difficult decision-making boosts the amount of effort, and deep encoding directs resources into more meaningful semantic processes. Age-related EM deficits were eliminated only in conditions where both environmental supports were provided. This suggests future therapies should combine factors that support compensation targeting both age deficits. A memory-training programme that aids OAs in forming effortful semantic traces of memory events should be developed to address this matter.

Conclusions

We studied the effects of the LoP and cognitive effort as environmental-compensatory factors for OAs' EM decline. Results reveal that the memory performance of both OAs and YAs benefit from increased cognitive effort involved during encoding. Moreover, OAs take additional advantage if encoding is deep/semantic. Interestingly, following the *environmental-compensation account*, OAs' memory performance reached the level of YAs' when environmental support was provided by effortful semantic encoding.

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Disclosure statement

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