Executive control is shared between sentence processing and digit maintenance: Evidence from a strictly timed dual-task paradigm

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Abstract

We investigated whether the comprehension of syntactically difficult sentences taxes the executive control component of working memory more than the comprehension of their easier counterparts. To that end, we tested the effect of sharing executive control between sentence comprehension and the maintenance of a digit load in two dual-task experiments with strictly controlled timing (Barrouillet, Bernardin, & Camos, 2004). Recall was worse after participants had processed one (Experiment 2) or two (Experiment 1) difficult sentences than after they had processed one or two easy sentences, respectively. This finding suggests that sentence processing and the maintenance of a digit load share executive control. Processing syntactically difficult sentences seems to occupy executive control for a longer time than processing their easy counterparts, thereby blocking refreshments of the memory traces of the digits so that these traces decay more and recall is worse. There was no effect of the size of the digit load on sentence processing performance (Experiment 2), suggesting that sentence processing completely occupied executive control until processing was complete.

Keywords

sentence processing, working memory, executive control, dual-task paradigm, time-based resource-sharing model

Working memory is generally viewed as a limited-capacity system in which information is temporarily stored and manipulated (e.g., Baddeley & Hitch, 1974; Baddeley, 1986). Most theories of working memory assume a central, domain-general executive control system, also called ‘attention’ (Barrouillet, Bernardin, Portrat, Vergauwe & Camos, 2007) ‘controlled attention’ (Engle, Kane & Tuholski, 1999), the ‘focus of attention’ (Cowan, 2000; Oberauer, 2009), or the updated version of the ‘central executive’ in the model of Baddeley (Repovš & Baddeley, 2006). This central system is assumed to be involved in both processing and storage tasks. Evidence for this dual involvement has been found in numerous dual-task experiments (e.g., Baddeley & Hitch, 1974; Rohrer & Pashler, 2003), in which a storage task and a processing task had to be performed simultaneously. It was observed that performance on either or both tasks was impaired compared to a single-task setup. Apart from this executive control system, a number of working memory theories also postulates the existence of additional, passive, domain-specific storage systems that function without executive control (Repovš & Baddeley, 2006). For example, Baddeley (1986) suggested that the phonological loop and the visuo-spatial sketchpad are responsible for the short-term storage of a limited amount of verbal and visual or spatial information respectively.

In the present article, we study the role of working memory in sentence comprehension. Sentence comprehension involves a number of subprocesses, like word recognition, retrieval of the pronunciation, meaning and grammatical features of the words, building the syntactic structure of the sentence, assignment of the thematic roles to the noun phrases, and integrating the meaning of the sentence into the wider discourse context. In the present article, we investigate the role of working memory in *the syntactic processes* involved in sentence comprehension and we will use the terms "sentence comprehension" and "sentence processing" in that sense.

It is well-established that some sentences are easier to process than others. For example, a sentence with a subject-extracted relative clause like (1a) is generally easier to process than a sentence with an object-extracted relative clause like (1b).

(1a) The reporter who attacked the senator admitted the error.

(1b) The reporter who the senator attacked admitted the error.

The difference in sentence-processing difficulty is reflected in longer reading times and more comprehension errors on difficult sentences than on easy sentences (e.g., Frazier, 1987; Frazier & Flores d'Arcais, 1989; Mak, Vonk, & Schriefers, 2002). There can be numerous reasons, of course, why one sentence is more difficult than another one, but many theories of language comprehension have directly or indirectly hypothesised that these behavioural data reflect the fact that processing difficult sentences taxes working memory more than processing easy sentences (e.g., Frazier, 1987; Gibson, 1998; Just & Carpenter, 1992; Miller & Chomsky, 1963; but see MacDonald & Christiansen, 2002; and MacWhinney, 1977 for alternative explanations).

When considering the processes involved in sentence comprehension, it is indeed easy to imagine a role for working memory. Sentence processing is considered to be an incremental process (Reichle, Rayner, & Pollatsek, 2003; Tanenhaus, Spivey-Knowlton, Eberhard, & Sedivy, 1995), in which each new, incoming word has to be assigned a syntactic function and has to be integrated into the syntactic structure that has been processed so far. This process is thought to be computationally demanding and is therefore assumed to rely on working memory (e.g., Gibson, 1998). Beside these processing demands, sentence comprehension is also assumed to involve storage demands. More specifically, in order to be able to integrate an incoming word with the part of the sentence processed so far, either these previously processed elements or the to-be-expected upcoming elements (e.g., Chomsky & Miller, 1963; Gibson, 1998) have to be kept in short-term memory. Given that most working memory theories (e.g., Barrouillet et al, 2004; Repovš & Baddeley, 2006) assume that executive control is needed for processing as well as for the active maintenance of items in short-term memory, we investigated the hypothesis that executive control is involved in sentence comprehension.

More specifically, we hypothesised that processing syntactically difficult sentences (e.g., object-extracted relative clauses) taxes executive control for a longer time than processing their syntactically easier counterparts (e.g., subject-extracted relative clauses). To test this hypothesis, we set up two dual-task experiments in which participants had to maintain an extra-sentential memory load while processing either a syntactically difficult or a syntactically easy sentence. In Experiment 1, we manipulated sentence-processing difficulty but kept the memory load size constant, whereas in Experiment 2 both factors were manipulated. As we will explain below, we hypothesised that executive control is needed for the active maintenance of an extra-sentential digit load as well as for the sentence comprehension task. Therefore, we expected the recall of the digit load to be worse after processing syntactically difficult sentence than after processing syntactically easier sentences.

Our expectations were based on the recent work of Barrouillet and colleagues (e.g., Barrouillet et al., 2004; Barrouillet, et al., 2007; Portrat, Barrouillet, & Camos, 2008). These authors extensively studied the way in which executive control is shared between a storage and a processing task in a dual-task situation. In a series of dual-task experiments, they observed that the maintenance of a memory load suffered from the presence of a simultaneous processing task, and that the amount of impairment increased with the difficulty of the intervening processing task. This observation led them to formulate the *time-based resource sharing* theory, in which they assume that executive control can be shared among processing and storage tasks, but only in a strictly *serial* fashion, namely one task at a time. The sharing of executive control is then realised by alternating between controlled processing of the intervening task on the one hand and refreshment and reconstruction of the memory representations of the items of the storage task on the other hand. Also, the more difficult the processing task is, the longer it will occupy the executive control system before it becomes available again for the storage task. As a consequence, less time will be left for reactivation of the memory load through executive control, thus leading to *passive decay* of the memory load and thus to poorer recall performance.

Applying these assumptions to the dual-task experiments in the present study, we expected that the processing of a syntactically more difficult sentence would occupy executive control for a longer time than the processing of its easier counterpart, thereby blocking the refreshment of the memory items of the extra-sentential memory load for a longer time. As a consequence, we expected the recall of that load to be worse after processing difficult compared to easy sentences. This effect would suggest that executive control is needed for the processing of the syntactic difficulty in syntactically difficult sentences.

However, we had to take care to select the appropriate extra-sentential memory load to test this hypothesis. As discussed, one mechanism of forgetting in short-term memory is the *passive decay* of the storage items when executive control is switched away, for example, to the processing task (Barrouillet et al., 2007). However, still another mechanism of forgetting in short-term memory has been proposed: *similarity-based interference* (Nairne, 1990; Lange & Oberauer, 2005; Oberauer, Lange, & Engle, 2004). It has been observed that the recall of items that are similar to each other in terms of certain features (phonological, semantic etc., see further) is worse than the recall of dissimilar items. It is therefore assumed that the representations of similar items can interfere in short-term memory. In the present study, we wanted to make sure that forgetting of the extra-sentential load is due to passive decay of the load through the sharing of executive control with sentence processing and not to interference between the memory representations of the load and those of the material in the sentence in short-term memory (Saito & Miyake, 2004). Therefore, we selected an extra-sentential load that is dissimilar to the material in the sentence, at least in terms of those linguistic features in which the sentence material is represented in short-term memory during the incremental process of sentence comprehension.

Considerable evidence suggests that the sentence material is temporally stored in terms of its semantic features and not in terms of its phonological features. For example, some brain-damaged patients with severely reduced phonological short-term memory (one to two items) have been reported to have a normal ability to process both easy and difficult sentences (e.g., Baddeley, 2000; Martin, 2006; Waters, Caplan, & Hildebrandt, 1991). Also, when disturbing the articulatory rehearsal process of phonological material with a concurrent articulation task, Waters, Caplan and Hildebrandt (1987) did not find worse plausibility judgments to syntactically difficult object-extracted relative clauses than to syntactically easier subject-extracted relative clauses. Thus, sentence comprehension appears not to rely on the maintenance of the phonological representations of the sentence material.

Rather, more recent studies suggest that the material in the sentence is encoded, stored and/or retrieved in terms of its semantic features (e.g., Lewis, Vasishth, & Van Dyke, 2006; McElree, Foraker, Dyer, 2003; Martin, 2006). For example, Fedorenko, Gibson, and Rohde (2006) found that the self-paced reading times of an English object-extracted relative clause like "who the parents liked" in the sentence "The babysitter who the parents liked planned a trip [...]" were longer when a load that was semantically similar to the NPs in the sentence ("the babysitter" and "the parents") had to be maintained than when a semantically dissimilar load had to be maintained. On the other hand, the reading times of the subject-extracted relative clause "who liked the parents" in that same sentence were unaffected by the similarity of the extra-sentential load (see Gordon, Hendrick & Levine, 2002; Potter & Lombardi, 1990; and Van Dyke & McElree, 2006 for related evidence). These results can be explained by the fact that in the object-extracted relative clause, the embedded subject "the parents" intervenes between "the babysitter" and "liked". Thus, to integrate the embedded verb "liked" with its object "the babysitter", this last element has to be retrieved from memory. When semantically similar items (the extra-sentential word load) are also stored in memory, the to-be-retrieved item can suffer from similarity-based interference (Lewis et al., 2006; Van Dyke & Lewis, 2003; Lewis & Vasishth, 2005). In contrast, in subject-extracted relative clauses, "the babysitter" can immediately be integrated with "liked". Hence, no interference of the extra-sentential word load can occur. In summary, this line of research suggests that sentence material is temporally stored in terms of its semantic features. To exclude forgetting due to similarity-based interference between the extra-sentential load and the material in the sentence in the present study, we selected a maintenance task in which the load is *semantically dissimilar* to the material in the sentence: a digit load maintenance task.

The dual-task effect between sentence processing and the maintenance of an extra-sentential digit load has been tested in a number of previous studies, but the results seem, at first sight, unclear (for an overview, see Waters, Caplan & Yampolsky, 2003). For example, Waters and colleagues (1987) found a larger effect of the concurrent articulation of a random six-digit load versus that of a familiar six-digit load (i.e., the sequence 1, 2, 3, 4, 5, 6) on semantic acceptability judgments to sentences. Moreover, the maintenance of the random digit load was more detrimental for judgments about difficult, object-relativized sentences than for those about the easier, subject-relativized sentences. This interaction suggests that the processing of syntactic difficulty and the maintenance of a random digit sequence compete for executive control. On the other hand, in a sentence-picture matching task, Waters, Caplan and Rochon (1995) found that patients with dementia of the Alzheimer's type as well as their controls recalled a random sequence of digits equally well after processing a difficult sentence (in terms of syntactic complexity) than after processing a simple sentence, suggesting that the tasks do not share executive control. The pattern of results from previous studies thus does not provide a conclusive answer to the question whether the processing of syntactic difficulty and the maintenance of a random digit sequence compete for executive control. One of the reasons for this mixed pattern of results might be that previous studies all used a self-paced paradigm, in which it is more difficult to capture the subtle effects of a trade-off between both tasks. In the present study, we therefore controlled the time within which both tasks had to be performed over conditions.

The importance of applying the same strictly controlled temporal boundaries across conditions has been advocated by the authors of the time-based resource sharing model (e.g., Barrouillet et al., 2007). As explained above, this model assumes that executive control is shared *serially* between a storage and a processing task. A methodological consequence of this assumption is the importance to strictly control the time within which two tasks in a dual-task paradigm have to serially share executive control, in order to be able to capture the subtle effects of a trade-off of executive control between both tasks.

In the present study, we applied this time-controlling methodology to test the hypothesis that processing a sentence for comprehension is a controlled process which requires executive control. As illustrated in Figure 1, we predicted that when fixing the time window between digit presentation and digit recall and consequently fixing the time within which a sentence has to be processed while maintaining a previously presented digit load, processing of a difficult sentence will occupy executive control for a longer time than processing of its easy counterpart. As a consequence, the maintenance of a digit load will be impaired more after a difficult sentence than after its easier counterpart.

(Figure 1 about here)

We performed two experiments. In the first experiment, we tested the effect of sentence-processing difficulty on digit recall. Participants had to maintain a digit load while processing two easy or two difficult sentences for comprehension. In the second experiment, we tested the same effect and additionally tested the effect of the size of the digit load on sentence-processing performance. In this experiment, only one easy or difficult sentence had to be processed during maintenance of a smaller or a larger digit load. In both experiments, the same strictly controlled temporal boundaries were applied across conditions.

Many studies on the involvement of working memory in sentence processing have investigated the difference between subject- and object-extracted relative clauses (e.g., Gordon et al., 2002; Fedorenko et al., 2006; King & Just, 1991). However, other minimal sentence pairs differ in syntactic difficulty (see the method section of Experiment 1 for more details). The difficult sentences in these pairs are read slower and less accurately than their easy counterparts (e.g., Chomsky & Miller, 1963). We hypothesise that processing of the syntactic difficulty in these difficult sentences requires the engagement of executive control, leading to longer overall processing times for difficult sentences than for their easier counterparts. To be able to generalise our findings beyond the traditionally studied subject- and object-extracted relative clauses, the present study investigates the involvement of executive control in five different sentence types. As a consequence, we will be able to extend our findings beyond subject- and object-extracted relative clauses.

Experiment 1

Experiment 1 investigated whether sentence processing captures executive control, thus impairing the maintenance of digits. We designed an experiment using the time-based resource-sharing procedure in which a sequence of digits had to be maintained in memory during performance of a sentence-processing task. The time within which these two tasks had to be performed was the same for the easy and difficult variant of a sentence. If performance of both tasks requires executive control and if difficult sentences occupy executive control for a longer time than easy sentences, we expect to find worse digit recall after processing of difficult sentences than after processing of easy sentences.

Each trial started with the presentation of six digits, which had to be kept in memory and had to be recalled after a fixed time interval. During this retention interval either two easy or two difficult sentence sequences were presented. The duration of the interval depended on the length of the intervening sentences but was the same for the easy and the difficult variant of a sentence. We presented two sentence sequences instead of one in order to maximise the chances of finding an effect of sentence-processing difficulty on digit recall. Each sentence sequence consisted of a sentence, a comprehension question, feedback to the answer on that question, and a blank screen. First, a sentence was presented that had to be read in silence before a tight time-out. Participants thus had to ensure to process the sentence before it disappeared. Sentence reading was self-paced, so if participants processed the sentence before the tight time-out, they could immediately pace themselves to the yes-no comprehension question about the sentence. In this way, the processed representation of the sentence did not have to be kept in memory during an extra time-interval. As a consequence, digit-recall performance would not be affected by the maintenance of this extra memory load, and would merely be affected by the amount of executive control used for sentence processing itself. The total duration of each sequence was fixed by introducing a blank screen with variable duration at the end of the sequence (see procedure for details). A trial was thus built up as in Figure 2.

(Figure 2 about here)

Method

Participants

Twenty-four students (18 female, 6 male) from Ghent University were paid for their participation. The mean age was 21.6 (SD=2.1). All participants were native speakers of Dutch, had normal or corrected to normal vision, had normal reading skills and were naive to the purposes of the study.

Design and materials

We selected five sentence types that have been shown to differ in sentence-processing difficulty. In the following list of the used sentence types, the first-mentioned structure is generally easier to process than the second-mentioned one, also in Dutch: (1) sentences with a subject-extracted relative clause versus sentences with an object-extracted relative clause (Frazier, 1987; Frazier & Flores d'Arcais, 1989; Mak, et al., 2002), (2) active versus passive sentences (Ferreira, 2003), (3) sentences with a non-nested relative clause versus sentences with a nested or centre-embedded relative clause (Chomsky, 1957, 1965; Yngve, 1960; Chomsky & Miller, 1963; Miller & Chomsky, 1963; Miller & Isard, 1964), (4) sentences with an unambiguous anaphoric pronoun versus those with an ambiguous anaphoric pronoun (Stewart, Holler, & Kidd, 2007), and (5) sentences in which the direct object (DO) is placed before a heavy indirect object (IO) and sentences in which the DO is placed after the heavy IO (Staub, Clifton, & Frazier, 2006). A further description of the five sentence types and an example of an easy-difficult sentence pair within each of these sentence types can be found in the Appendix. The complete list of sentences can be found on http://users.ugent.be/~mloncke/materials.html.

Within each sentence type, we constructed 20 sentence pairs each containing an easy sentence and its difficult counterpart. Sentences within a pair were built up from the same lexical items and were thus automatically matched in length. Only active and passive constructions intrinsically differ in length (e.g., the active verb phrase “verjaagt [chases]” vs. the passive one “wordt verjaagd door [is chased by]”). The length of these sentence pairs was matched in number of syllables, by selecting longer, but semantically very similar lexical items for the agent and/or patient in the active sentence than in its passive counterpart. For example, in the active sentence “De tovenaar verjaagt de reus. [The wizard chases the giant.]”, the longer word “tovenaar [wizard]” was used, whereas in its passive counterpart “De reus wordt door de heks verjaagd. [The giant is chased by the witch.]”, the shorter, but semantically related word “heks [witch]” was used. Each participant only saw one sentence of a pair. Thus, each participant saw 50 easy and 50 difficult sentences (10 of each of the 5 sentence types) and each sentence was presented to only half of the participants.

Each sentence was followed by a comprehension question, to check whether participants fully and correctly processed the sentences. The question concerned the interpretation of the meaning generated by the specific manipulation of the syntactic structure. For example, the question for the subject-extracted relative clause sentence “Ze praat met de patiënten die de dokter bezocht hebben. [She talks to the patients who visited the doctor.]” and for the object-extracted relative clause sentence “Ze praat met de dokter die de patiënten bezocht hebben. [She talks to the doctor who the patients visited.]” was “Hebben de patiënten de dokter bezocht? [Did the patients visit the doctor?]”. The question was presented immediately after the sentence. Questions were the same for the easy and difficult sentence within a pair. Half of the comprehension questions required a yes-answer and half of them a no-answer.

The validity of the operationalisation of sentence-processing difficulty was tested in a pilot study with 18 further participants (11 female, 7 male; mean age = 25.8, *SD* = 3.0), who read the sentences as quickly as possible and answered the comprehension question immediately after reading the sentence. Both tasks were performed in the absence of any memory load. Reading times were longer for difficult sentences (*M* = 4335 ms, *SD* = 1068 ms) than for easy sentences (*M* = 3933 ms, *SD* = 993 ms), $F(1,17) = 40.05$, $p < .001$, $\eta_p^2 = .70$, and questions were answered less accurately for difficult sentences (*M* = 70%, *SD* = 11%) than for easy sentences (*M* = 89%, *SD* = 9%), $F(1,17) = 40.85$, $p < .001$, $\eta_p^2 = .71$, in all sentence types.

Procedure and apparatus

At the beginning of the experiment, the instructions were presented on screen. To accustom to the procedure, participants first performed 5 practice trials. Then, the 50 critical trials were presented, with a self-paced pause after each trial.

On each trial, participants performed two tasks: they were presented 6 digits which they had to maintain while they processed two sentence sequences consecutively. Each sentence sequence consisted of the presentation of the sentence itself, followed by a comprehension question which had to be answered, feedback to that answer, and a blank screen. The two sentences presented in a trial were always of a different syntactic type, to prevent as much as possible that participants would notice the recurring sentence structures and thus would be able to use processing strategies. On the other hand, the two sentences in a trial were always of the same sentence-processing difficulty (either both were difficult or both were easy), to be able to test the effect of sentence-processing difficulty on digit recall. At the end of the trial, participants had to recall the 6 digits in the correct order.

To go into more detail, a trial was built up as follows: Each trial started with a fixation cross of 1000 ms. A new set of 6 different digits ranging from 0 to 9 was sampled for each trial. To discourage chunking (Miller, 1956), each single digit was presented on a separate screen for 1500 ms, followed by a blank screen of 200 ms.

After this sequence of digits and blank screens, the first sentence sequence was presented.

A trial thus started with a fixation cross, presented for 1000 ms. Then, the sentence was presented in its full form. To avoid that participants strategically postponed reading in order to rehearse the digits, the sentence was presented during a rather tight time interval. More precisely, the maximum presentation duration varied with sentence length. It was calculated by multiplying the number of characters (spaces included) in the sentence by 65 ms. This measure was defined on the basis of the data of the pilot study in which participants had to read the experimental sentences as quickly as possible without a time-out or secondary load. The number of characters in the sentences was highly correlated with the reading times ($r = .549$, $N = 1710$, $p < .001$). Moreover, two thirds of all reading times were lower than 65ms times the number of characters. Basing the presentation duration of the sentences on this measure thus provided us with a tight interval, which forced participants to switch to sentence processing immediately upon presentation of the sentence, in order to be able to process the full sentence completely before the presentation timed out. Duration varied over pairs but not within pairs, as the two sentences within a pair consisted of the same number of characters. There was one exception: the active and passive sentence within a pair consisted of the same number of syllables, not characters. The presentation durations for this sentence type were therefore based on the number of characters in the passive sentence in the pair.

Participants were instructed to press the spacebar on the keyboard as soon as they had completely processed the sentence. After either the registration of this self-paced spacebar press or at the time-out, the comprehension question appeared. Answers to questions were given by pressing a predefined “yes”- or “no”-button on the keyboard. Answers were self-paced, but had to be performed within 2500 ms. Immediately after detection of the answer, feedback to the answer was presented for 500 ms. Feedback could either be “juist [correct]” for correct answers, “fout [incorrect]” for incorrect answers, and “te laat [too late]” if no answer had been given, encouraging participants to answer more quickly. At the end of the sentence sequence, a blank screen was shown for minimally 1500 ms. However, if the participant had responded to the sentence and/or the question before the respective time-outs of the provided intervals, the time between the actual response and the time-out was added to the duration of the blank screen. That way, the total duration of each sequence was the same for the easy and the difficult sentence within a pair.

After this blank screen, the second sentence sequence was presented in the same way starting with a fixation cross for 500 ms. After the blank screen at the end of the second sentence sequence, a rectangle was shown in the centre of the screen to cue participants to start recalling the digits. Digits had to be typed in within 10,000 ms on the numerical keyboard in the order in which they had been presented.

Participants were instructed to remember the digits in the order in which they were presented, to read the sentences quickly, but also to ensure that they understood them completely, and to answer the comprehension questions as quickly and accurately as possible. They were instructed not to concentrate on one task (digit recall or sentence processing) more than the other.

Participants were tested individually by means of a Pentium 4 personal computer with a 17-inch monitor running the E-prime experimentation software (Schneider, Eschman, & Zuccolotto, 2002). All items were presented in white on a black screen. Digits and the preceding fixation cross were presented in the centre of the screen. Digits were presented in bold Courier New 18 font. Sentences, the preceding fixation crosses, and comprehension questions were aligned left on the horizontal axis and in the centre on the vertical axis. Sentences and questions were presented in bold Arial 7 font, so that they would all fit on one line. All fixation crosses were presented in non-bold Arial 14 font.

Results

Participants constituted the only random factor in the design of the present experiment. Items (or sentences) were not a random factor, as the easy and the difficult sentences within a pair were matched (see above) and only differed in sentence-processing difficulty (Erdfelder, 2010; Raaijmakers, Schrijnemakers, & Gremmen, 1999). Therefore, we calculated the effect of sentence-processing difficulty (difficult vs. easy sentences) on digit recall and on sentence-processing performance respectively with repeated measures analyses of variance on the means for participants. Since the two sentences within a trial always belonged to a different sentence type, the effect of sentence type could not be analysed.

Digit-recall performance

Digit-recall performance was calculated using a transformation of Kendall's rank correlation coefficient tau (τ'), which reflects the proportion of digits recalled in correct relative order. Values range between 0 and 1. Higher values reflect many recalled items in correct order, whereas low values reflect strongly violated order or few recalled items (for details see Szmalec & Vandierendonck, 2007). In practice, a value of 0.5 corresponds to a recall of the digits in random order. This τ'-measure contrasts with traditional measures of recall (e.g., span), which reflect the proportion of items recalled in correct *absolute* order. If a sequence like "1 2 3 4 5 6" is recalled as "1 3 4 5 6" (some items recalled in correct relative order, but in incorrect absolute order) or as "1 3 2 5 4 6" (items recalled correctly, but some in incorrect order), a traditional span measure would consider this as one item recalled correctly, namely only “1”. The τ’-measure we used attributes to these examples the scores 0.81 and 0.76 respectively by using the rank correlation of the recalled digits with the presented order, weighted by the proportion of digits recalled, and rescaled to the range 0-1.

Recall was better when easy sentences had been processed (*M* = 0.80, *SD* = 0.08) than when difficult sentences had been processed (*M* = 0.78, *SD* = 0.07), $F(1,23) = 4.36$, $p = .048$, $\eta_p^2 = .16$. Although this difference in recall performance seems small when expressed by the τ’-measure, the effect size (η_p^2) points at a substantial effect of sentence-processing difficulty on recall performance.

Sentence-processing performance

Sentence-processing performance was measured by (1) sentence reading times, (2) accuracy[1] and (3) response times to the comprehension questions. There were 12.8 % time-outs in the sentence reading times and 5.5 % in the response times to the comprehension questions. The time-out times were included in the analyses of the sentence reading times and of the response times to the comprehension times respectively.

There was a main effect of sentence-processing difficulty on all measures. Sentence reading times were longer for difficult sentences (*M* = 3626 ms, *SD* = 804 ms) than for easy sentences (*M* = 3357 ms, *SD* = 758 ms), $F(1,23) = 38.48$, $p < .001$, $\eta_p^2 = .63$. Answers to comprehension questions were less accurate for difficult sentences (*M* = 67%, *SD* = 11%) than for easy sentences (*M* = 82%, *SD* = 9%), $F(1,23) = 119.68$, $p < .001$, $\eta_p^2 = .84$. Response times to comprehension questions were longer for difficult sentences (*M* = 1601 ms, *SD* = 177 ms) than for easy sentences (*M* = 1524 ms, *SD* = 175 ms), $F(1,23) = 22.47$, $p < .001$, $\eta_p^2 = .49$.

Discussion

Using a time-controlled dual-task paradigm, we found an effect of sentence-processing difficulty on digit-recall performance: recall performance was worse after processing syntactically difficult sentences than after processing syntactically easy sentences. This suggests that processing difficult sentences taxes executive control for a longer time than processing easy sentences. As a consequence, refreshment of the digit sequence is blocked for a longer time and the memory traces of the digits (or the memory traces of the links between the digits and their respective positions in the sequence) decay more. This leads to poorer recall performance after difficult than after easy sentences. We thus found support for the hypothesis that one of the causes for the well-established finding that syntactically difficult sentences are processed slower and less accurately than their easy counterparts, a finding that was replicated in the present study, is the fact that processing difficult sentences occupies executive control for a longer time than processing easy sentences.

Experiment 2

In Experiment 1, we presented two sentence sequences instead of one in order to maximise the chances of finding an effect of sentence-processing difficulty on digit recall. In Experiment 2, we investigated whether it is possible to replicate the effect of sentence-processing difficulty on digit recall with only one sentence sequence instead of two. Moreover, apart from manipulating the difficulty of the sentence processing task (easy vs. difficult sentences, as in Experiment 1), we also manipulated the difficulty of the digit maintenance task (load size of 5 vs. 6 digits). In short, on the basis of the assumptions of the time-based resource sharing model (e.g., Barrouillet et al., 2007), we expected a main effect of sentence processing difficulty as well as a main effect of digit load size on digit recall performance. On sentence-processing performance, we expected either an additive effect of both factors, or an effect of sentence processing difficulty but no effect of digit load size. Crucially, we expected no interaction between both factors on any of the two dependent variables (digit recall or sentence processing performance).

To explain this in more detail, in working memory theories, components like the phonological loop (Baddeley, 1986) or the direct access area of verbal working memory (Cowan, 2000; Oberauer, 2002) are assumed to have a limited capacity that is shared continuously among the competing processes or tasks. As a consequence, if two tasks tax such a limited capacity component, an increase in the amount of capacity consumed by one task leads to a continuous decrease in capacity available for the other task and thus capacity is traded off between the two tasks, resulting in an interaction of the difficulty of these tasks.

Executive control, on the other hand, is hypothesised to be shared serially on an all-or-none basis and thus not continuously (Barrouillet et al., 2007). There is a considerable amount of evidence that many of the elementary cognitive steps involved in both processing and maintenance tasks can take place only one at a time (through a bottleneck mechanism, Pashler, 1998; Rohrer & Pashler, 2003; Rohrer, Pashler, & Etchegaray, 1998; or through a limited focus of attention, Garavan, 1998; Oberauer, 2002, 2005). Therefore, it is assumed that executive control is shared by switching between tasks (Barrouillet et al., 2007). This also implies that when executive control is available to one task, it is fully available for that task (and not partly, like when it would be shared in parallel) and unavailable for the other task (cf. evidence from task-switching research, Vandierendonck, Liefooghe & Verbruggen, 2010).

Therefore, as the results of Experiment 1 already suggested that digit maintenance and sentence processing both require executive control, no interaction of the difficulty of these tasks on sentence-processing performance is expected. At most an additive effect of both factors is expected. If participants switch to the refreshment of the digits during sentence processing at all and if the refreshment of memory traces of longer series of digits occupies executive control for a longer time, executive control will be unavailable for sentence comprehension during a longer period when refreshing a higher instead of a lower digit load. In the case of a higher digit load, refreshing operations of the digit load will continue while the sentence is presented, resulting in a shift such that sentence processing starts later but will also end at a later time. This will lead either to longer sentence reading times as measured from the start of sentence presentation, or to exceeding the available reading time (time-out of sentence reading) resulting in a lower answering accuracy to the comprehension questions. However, this effect of digit-load size is only expected if, during the retention interval, participants prefer to use time for the refreshment of the digits rather than for sentence processing. The alternative for the participants is to give priority to the sentence-processing task and use only the remaining time to refresh the digit load. In the latter case, no effect of the digit-load size on sentence-processing performance is expected.

To wrap up, no interaction of digit-load size and sentence difficulty is expected, and whether there is an effect of digit-load size on sentence-processing performance depends on which of the two tasks is given priority in accessing the serially shared executive control. Finding an interaction between both factors would suggest that executive control (or some other resource) is shared in parallel between sentence processing and digit maintenance.

In Experiment 2, we thus tested the effect of digit-load size on sentence-processing performance. In contrast to Experiment 1, where the load always consisted of 6 digits, in Experiment 2 we presented two load conditions: either 5 or 6 digits had to be recalled. The choice for these load sizes was based on a number of considerations. First, it was important that the load sizes were not too high. In a pilot study, we observed that with a load size of 8 digits, participants just gave up on executing one of both tasks, indicating that the maintenance of a load of 8 digits probably demands the permanent involvement of executive control, leaving no room for dual-tasking. As seen in Experiment 1, the execution of both tasks was still possible with a load size of 6 digits. We therefore selected this load size as the highest one in the present experiment. Second, it was important that the load sizes were not too low. Both a load of 5 digits and one of 6 digits are close to the span of the average participant and exceed the capacity of the direct access area (4 items, cf. Cowan, 2000). It is thus very likely that executive control is required to maintain them. A model like that of Baddeley and Hitch (1974), for example, assumes that lower load sizes can be passively maintained by the phonological loop and thus place little or no demands on executive control. In that case, no dual-task effects are expected with lower load sizes (but see Camos, Lagner & Barrouillet, 2009). Third, although the load difference of 5 vs. 6 digits is numerically minimal, it has proven to lead to clear effects. For example, Liefooghe, Barrouillet, Vandierendonck and Camos (2008) showed that the maintenance of 6 consonants was impaired more by task switching than the maintenance of 5 consonants. All these considerations led us to choose a load size manipulation of 5 vs. 6 digits.

In the present experiment, we also explored the effect of sentence type. Trials in Experiment 1 contained two sentences of a different sentence type. It was thus not possible to assess the individual effects of the various sentence types there. In Experiment 2, we presented only one sentence sequence per trial. This allowed us to explore whether the general effect of sentence-processing difficulty on digit recall is due to some specific sentence types, or whether executive control is involved in the processing of each of the 5 tested sentence types. This investigation is rather explorative, as we were limited to 20 sentences per sentence type (10 difficult vs. 10 easy sentences), in order to keep testing, which was very demanding for the participants, within the limits of one hour. Our sample size might thus not be large enough to yield significant effects.

Everything else in the present experiment was the same as in Experiment 1. Importantly, also here, the time within which the maintenance task and the sentence-processing task had to be performed was kept constant over sentence-processing difficulty and digit-load size conditions, in order to be able to test the subtle effects of the serial sharing of executive control between both tasks (e.g., Barrouillet, Bernardin, & Camos, 2004).

Method

Design and materials

The experiment had a 2 x 2 x 5 mixed design, crossing memory load (5 vs. 6 single digits) with sentence-processing difficulty (easy vs. difficult sentences) with sentence type (5 types of syntactic structures). The sentences and questions were the same as in Experiment 1.

Participants

Twenty-eight further students (22 female, 6 male) from Ghent University were paid for their participation. The mean age was 20.2 (SD=1.8). All participants were native speakers of Dutch, had normal or corrected vision, had normal reading skills and were naive to the purposes of the study.

Apparatus and procedure

The apparatus and procedure were the same as in Experiment 1, except where indicated otherwise. Participants performed 4 practice trials and 100 critical trials. Each trial consisted of the presentation of the digits, one sentence sequence, and time for recall of the digits.

The first screen of each trial announced during 1000 ms in words whether “vijf cijfers” (five digits) or “zes cijfers” (six digits) would be presented. We informed the participants about the number of digits that would appear so as not to increase task difficulty by having to keep track of the number of digits. Then, the digits were presented one by one (as in Experiment 1). Subsequently, a fixation cross of 1000 ms announced the sentence sequence. This sequence was built up in the same way as in Experiment 1, except that only one sentence sequence was presented per trial, instead of two. Responses to the sentences and questions were registered by means of a button box.

After the blank screen at the end of the sentence sequence, 5 or 6 underscores (according to the number of digits that had to be recalled) were presented in the centre of the screen to cue participants to start recalling the digits. Digits had to be recalled orally in the order in which they had been presented. They were noted down by the experimenter.

Results

Digit-recall performance and sentence-processing performance (i.e., reading times of the sentences, and response times and accuracy on the comprehension questions) were analysed in 2 (sentence-processing difficulty: easy versus difficult sentences) x 2 (memory load: 5 versus 6 digits) x 5 (sentence types) analyses of variance. Sentence-processing difficulty and memory load were treated as within-participants and within-items factors, and sentence type was treated as a within-participants and between-items factor. We report the analyses on the means for participants (F) for the within-items factors, and we report min F' (as computed with the online tool of Pallier, 1996) for the between-items factor (Clark, 1973; Raaijmakers et al., 1999).

Digit-recall performance

Digit-recall performance was calculated in the same way as in Experiment 1. Recall was significantly better when an easy sentence had been processed ($M = 0.78$, $SD = 0.10$) than when a difficult sentence had been processed ($M = 0.76$, $SD = 0.10$), $F(1,27) = 5.06$, $p = .033$, $\eta_p^2 = .16$. As expected, recall of 5 digits ($M = 0.80$, $SD = 0.10$) was significantly better than recall of 6 digits ($M = 0.75$, $SD = 0.11$), $F(1,27) = 20.35$, $p < .001$, $\eta_p^2 =.43$. There was a main effect of sentence type (see Figure 3 for means), *min F'*(4,200) = 4.87, p < .001, $\eta_p^2 =.09$. However, when introducing sentence length as a covariate in the by-item analysis, the effect of sentence type on digit-recall performance disappeared, *F2* < 1. Also, the proportion of time the sentence processing task (sentence reading times and response times to the comprehension questions) occupied the total retention interval correlated negatively with digit-recall performance ($r = -.168$, $N = 2800$, $p < .001$). There were no interactions between any of the factors on recall performance (all *F*s and *min F'*s < 1).

(Figure 3 about here)

Sentence-processing performance

Sentence-processing performance was assessed as in Experiment 1. There were 23.4 % time-outs in the sentence reading times and 4.5 % in the response times to the comprehension questions. The time-out times were included in the analyses of the sentence reading times and of the response times to the comprehension times respectively.

Sentence-processing difficulty affected all measures of sentence-processing performance. More specifically, reading times on difficult sentences (*M* = 3465 ms, *SD* = 633 ms) were longer than those on easy sentences (*M* = 3357 ms, *SD* = 658 ms), $F(1,27) = 19.32$, $p < .001$, $\eta_p^2 = .42$. Answers to questions concerning difficult sentences were less accurate (*M* = 69%, *SD* = 8%) than answers to questions concerning easy sentences (*M* = 81%, *SD* = 8%), $F(1,27) = 121.09$, $p < .001$, $\eta_p^2 = .82$. Response times to the comprehension questions were longer for difficult sentences (*M* = 1560 ms, *SD* = 458 ms) than for easy sentences (*M* = 1500 ms, *SD* = 438 ms), $F(1,27) = 14.28$, $p < .001$, $\eta_p^2 = .35$.

The size of the memory load did not influence sentence-processing performance: neither reading times (load 5: *M* = 3430 ms, *SD* = 662 ms; load 6: *M* = 3394 ms, *SD* = 632 ms), $F < 1$; nor the accuracy on the comprehension questions (load 5: *M* = 76%, *SD* = 7%; load 6: *M* = 74%, *SD* = 8%), $F(1,27) = 2.16$, $p = .153$, $\eta_p^2 = .07$; nor response times to the comprehension questions (load 5: *M* = 1533 ms, *SD* = 449; load 6: *M* = 1527 ms, *SD* = 449 ms), $F < 1$.

There was a main effect of sentence type on the sentence reading times (see Figure 4), *min* $F'(4,187) = 85.95$, $p < .001$, $\eta_p^2 = .65$, and in the response times to the questions (see Figure 6), *min* $F'(4,114) = 5.45$, $p < .001$, $\eta_p^2 = .16$. The length of the sentences correlated positively with both the sentence reading times ($r = .717$, $N = 2800$, $p < .001$) and response times ($r = .181$, $N = 2800$, $p < .001$). Sentence length also correlated positively with the proportion of time the sentence processing task (sentence reading times and response times to the comprehension questions) occupied the total retention interval (r = .167, N = 2800, p < .001). In the accuracy of the answers to the questions, there was also a main effect of sentence type (see Figure 5), *min F'*(3,115) = 6.53, p < .001, η_p^2 =.15, but this factor interacted with sentence-processing difficulty, *min F'*(3,157) = 9.87, p < .001, η_p^2 =.16. Pairwise comparisons of the effect of sentence-processing difficulty on answer accuracy within the different sentence types (see Figure 5) revealed that questions on active sentences were answered more accurately than questions on passive sentences, *min F'*(1,89) = 24.62, p < .001, η_p^2 =.22, and accuracy on subject-extracted relative clauses was higher than on object-extracted relative clauses, *min F'*(1,61) = 42.66, p < .001, η_p^2 =.41. Accuracy on the object-extracted relative clauses was even below chance level, t(1,27) = -4.16, p < .001. There was no effect of sentence-processing difficulty on (non-)nested sentences, nor on heavy IO sentences (*min F'*s < 1.6).

(Figure 4, 5 and 6 about here)

There were no interactions between any of the other factors on sentence reading times, accuracy or response times on the comprehension questions (all *F*s and *min F'*s < 1.5).

Discussion

As in Experiment 1, we observed an effect of sentence-processing difficulty on sentence-processing performance: processing syntactically difficult sentences was slower and less accurate than processing easy sentences. We hypothesised that these effects reflect the fact that processing difficult sentences occupies executive control for a longer time. Hence, we expected that processing difficult sentences would impede the maintenance of the digit loads more than processing easy sentences. Our hypothesis was confirmed by the finding that digit recall was worse after processing of a difficult sentence than after processing of an easy sentence. This trade-off effect replicates the one found in Experiment 1.

Digit-load size had a clear effect on digit-recall performance: recall of 5 digits was better than recall of 6 digits. As expected, the load size difference between 5 and 6 digits thus proved to be large enough to observe effects. Still, digit-load size did not affect sentence-processing performance. First and foremost, as explained in the introduction of this experiment, this finding is in line with the hypothesis that sentence processing and digit maintenance serially share executive control. As explained in the introduction, no interaction between sentence-processing difficulty and digit-load size on sentence-processing performance was predicted. Rather, either an additive effect of load size or no effect at all was predicted. That last prediction was indeed confirmed by the data: whereas sentence-processing difficulty affected digit-recall performance, the size of the digit load did not affect sentence-processing performance. This asymmetrical trade-off effect suggests that as long as the sentence-processing task captured executive control, processes needed for the maintenance of the digit load (e.g., refreshment or reconstruction of the memory traces) were blocked and hence executive control was switched to the digit maintenance task only after processing was complete. As a consequence, load size could not affect sentence-processing performance.

Besides the effect of digit-load size, we also explored the effect of sentence type in this experiment by presenting only one sentence sequence per trial. First, there was no interaction between sentence-processing difficulty and sentence type on digit recall performance. This suggests that the difficult sentences in each of the five sentence types captured executive control for a longer time than their easy counterparts and that the finding that difficult sentences occupy executive control for a longer time than easy sentences can be generalised beyond the traditionally studied subject- and object-extracted relative clauses.

Second, sentence reading times as well as response times to the comprehension questions correlated positively with sentence length. Processing of longer sentences thus took longer and might hence have occupied executive control for a bigger proportion of the retention time. Indeed, this proportion was larger for longer sentences than for shorter sentences. When following the logic of the TBRS model, it is predicted that when the proportion of time the sentence processing task occupies the retention interval becomes larger, performance on the digit maintenance task should decrease. This is indeed what is suggested by digit-recall performance, which correlated negatively with the proportion of time the sentence processing task occupied the total retention interval.

Third, in the accuracy data, there was an effect of sentence-processing difficulty that interacted with sentence type: Accuracy on passive sentences was lower than on active sentences, and accuracy on object-extracted relative clauses was lower than on subject-extracted relative clauses. In the other sentence types, no effect of sentence-processing difficulty was observed on the accuracy data. It has been hypothesised that under a memory load or under tight time limits, two conditions that applied in the present experiment, readers do not always process all information present in the syntax, but apply heuristics instead (e.g., the Garden Path model of Frazier, 1979, or the Good Enough Comprehension model of Ferreira and Patson, 2007). This might have been more detrimental for the understanding of those sentences where the syntactic structure changes the meaning of the sentence, viz. sentences with a subject-extracted vs. object-extracted relative clause and active vs. passive sentences, as opposed to (non-)nested sentences and heavy IO sentences. The load and time pressure might have led participants to interpret these sentences according to their canonical word order (as a subject-extracted instead of an object-extracted relative clause sentence and as an active instead of a passive).

General discussion

We investigated whether sentence comprehension requires executive control. To this end, we examined whether there is a dual-task trade-off between sentence processing and the maintenance of a digit load, which is semantically dissimilar to the material in the sentence. Recently, Barrouillet and colleagues (Barrouillet et al., 2004; Barrouillet et al., 2007; Portrat et al., 2008) demonstrated that in order to be able to capture the subtle effects of a trade-off of executive control between two simultaneously performed tasks in a dual-task paradigm, it is important to strictly control the time within which these tasks have to serially share executive control. Therefore, in our experiments, we applied the same strictly controlled temporal boundaries across conditions. In Experiment 1, we tested the effect of sentence-processing difficulty on digit recall with two sentences per trial. In Experiment 2, we tested the same effect with only one sentence per trial and additionally tested the effect of the size of the digit load on sentence-processing performance.

In both experiments, we observed an effect of sentence-processing difficulty on digit recall. Recall was worse after participants had processed one (Experiment 2) or two (Experiment 1) difficult sentences than after they had processed one or two easy sentences, respectively. At first sight, this effect seems to resemble the findings of Savin and Perchonock (1965). These authors auditorily presented their participants with a sentence followed by a list of words. Their design was different from ours, as their participants had to first recall the sentence and then recall as many words from the list as possible. Savin and Perchonock found that sentence difficulty affected the number of recalled words. In a follow-up study, however, Epstein (1969) showed that the effect of sentence difficulty on word recall performance in this former study has to be attributed to the sentence recall phase rather than to the sentence processing phase per se. More specifically, Epstein demonstrated that when participants had to recall only the word list and not the sentence or when they had to recall first the word list and then the sentence, sentence difficulty did not affect word recall performance. Also Foss and Cairns (1970) found evidence that more difficult sentences are more difficult to store or rehearse than their easier counterparts, but not for the hypothesis that they would also be more difficult to process. These early studies thus did not demonstrate a trade-off between the maintenance of verbal material and sentence processing per se (but rather with sentence recall).

The effect of sentence-processing difficulty on digit recall in the present study suggests that processing syntactically difficult sentences captures executive control for a longer time than processing easy sentences, thereby blocking refreshments of the memory traces of the digits so that these traces decay more and recall is worse. Moreover, the effect suggests that executive control is needed to analyse the syntactic difficulty in the difficult sentences. Whereas Waters et al. (1995) did not find an effect of sentence-processing difficulty on digit recall in a self-paced paradigm, we were able to capture this trade-off effect in two dual-task experiments with strictly controlled timing.

The time-controlling methodology of the time-based resource sharing model (e.g., Barrouillet et al., 2007) is thus able to uncover trade-off effects that are left invisible in a self-paced paradigm. Still, a possible drawback of the methodology in the present study is that sentence comprehension may not always have been performed through a full parse of the sentence, but may sometimes have been based on heuristics (e.g., the Garden Path model of Frazier, 1979, or the Good Enough Comprehension model of Ferreira and Patson, 2007). The finding in Experiment 2 that accuracy on passive sentences was lower than on active sentences, and accuracy on object-extracted relative clauses was lower than on subject-extracted relative clauses may be an indication that under time constraints or memory load participants sometimes strategically choose to not fully parse a difficult sentence, but to apply heuristics instead. This may then lead to an incorrect interpretation of the sentence. If anything, however, the use of heuristics will have reduced the chances of finding an effect of the sharing of executive control between both tasks. Nevertheless, in both experiments, we found an effect of sentence processing difficulty on digit recall, suggesting that sentence processing – although probably sometimes performed through less-demanding heuristics – competes for executive control with the digit maintenance task.

We varied sentence-processing difficulty in five different sentence types. Experiment 2 showed that the effect of difficulty on recall did not differ between these sentence types. The lack of an interaction suggests that the results are not due to the peculiarities of the traditionally tested contrast between object-extracted and subject-extracted relative clauses and can be generalised to a large range of syntactic difficulties. Apparently, the analysis of the syntactic difficulty in the difficult sentences in all tested sentence types occupied executive control for a longer time than their easy counterparts.

Also in line with the hypothesis that sentence processing and digit maintenance *serially* share executive control, we found no effect of digit-load size (5 vs. 6 digits) on sentence-processing performance in Experiment 2. This asymmetrical trade-off effect suggests that as long as the sentence-processing task captured executive control, processes needed for the maintenance of the digit load (e.g., refreshment or reconstruction of the memory traces) were blocked and hence executive control was switched to the digit maintenance task only after processing was complete. As a consequence, load size could not affect sentence-processing performance.

It is indeed very plausible that executive control was not switched away until sentence processing was complete (cf. Hitch & Baddeley, 1976). Sentence comprehension is a highly cognitively demanding task. Caplan and Waters (1999) argued that in a dual-task procedure where the presentation of the sentence is interrupted with the presentation of the load (e.g., Wanner & Maratsos, 1978), the attentional shifts associated with these interruptions could interfere with sentence processing. As attention or executive control is hypothesised to be shared serially and thus has to be switched between tasks (Barrouillet et al., 2007), this logic could in fact apply to all dual-task situations where executive control needs to be shared. Interrupting sentence comprehension to refresh the digit load would imply that the intermediate processing results of sentence comprehension so far need to be kept in memory, introducing an extra memory load on top of the digit load. Such a strategy would thus hold the risk that the sentence part that was already processed would be (partly) lost, forcing reanalysis. Given the tight computer-paced time-out on the sentence-processing task, such a strategy would presumably lead to a time-out of the presentation of the sentence before sentence processing was completed.

Note that a similar asymmetric pattern of results was observed in the experiments of Liefooghe and colleagues (2008) in the same strictly timed dual-task paradigm. Liefooghe et al. tested the effect of loads of 3 to 8 consonants on task switching performance and found that recall performance decreased as a function of the number of task switches, but that the task-switching cost remained unaffected by the concurrent memory load. Also these data are in line with the assumption that executive control is shared serially between a storage and a processing task.

The present study thus suggests that at least some processes in sentence comprehension involve the domain-general executive control system. Of course, we cannot speak to the question whether sentence comprehension *also* relies on a specialised working memory component, like the one suggested by Caplan and Waters (1999). These authors made a distinction between interpretive processes, viz. processes that extract meaning from the linguistic signal, and post-interpretive processes, viz. processes that require the use of the extracted meaning, like reasoning, planning actions, etc. According to their theory, interpretive processing is a largely unconscious process, which relies on a specialised sentence-processing component of working memory, whereas post-interpretive processing is a controlled process, which relies on a more general (but still verbal) working memory (Baddeley, 1986). One of the pieces of evidence for Caplan and Waters (1999) to assume that interpretive processing is an unconscious process, was the lack of a trade-off between sentence comprehension and digit maintenance in the self-paced study of Waters et al. (1995). Crucially, in the present study with time-controlled experiments, we showed that such a trade-off does exist. We thus proved that at least some part of interpretive processing relies on the domain-general executive control system and is a controlled process.

The finding that executive control is required for sentence comprehension is in line with existing evidence. For example, in an individual-differences study, Swets, Desmet, Hambrick, and Ferreira (2007) found that syntactic ambiguity resolution is affected by memory components that are both unique to language and shared with other parts of the cognitive architecture. The present experiments demonstrate that sentence processing indeed captures a domain-general executive control system. A challenge for future research is to pinpoint exactly which processes at what exact moments in the sentences require executive control for a longer time.

To conclude, we found an effect of sentence-processing difficulty on the recall of digits. An effect of digit-load size on sentence-processing performance was not observed. These findings suggest that both sentence processing and the maintenance of a digit load, a load which is semantically dissimilar to the material in the sentence, require executive control. Difficult sentences seem to occupy executive control for a longer time than their easy counterparts, leading to more decay of the memory traces of the digit load.

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This research was made possible by grant G.0052.08 of the Research Foundation-Flanders to André Vandierendonck, Timothy Desmet and Robert J. Hartsuiker.

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Footnotes

Footnote 1 - Answers to comprehension questions on (un)ambiguous pronoun sentences were left out of the analyses of the accuracy data. Questions on this type of sentences checked whether participants had correctly interpreted the pronoun and knew to which of the two persons in the head clause it referred. As the pronoun in sentences with an ambiguous pronoun could refer to either person in the head clause, it could never be misinterpreted and answers to comprehension questions were always correct. On the other hand, the pronoun in sentences with an unambiguous pronoun could only refer to one of the two persons in the head clause and could consequently be misinterpreted. An analysis on the accuracy data for these sentences would thus not be a fair test of performance differences.

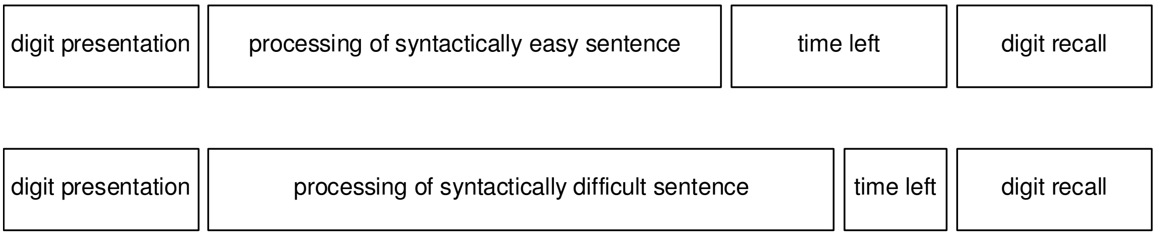

Figure 1. Illustration of the hypothesis that processing of a syntactically difficult sentence occupies executive control for a longer time than processing its easier counterpart.

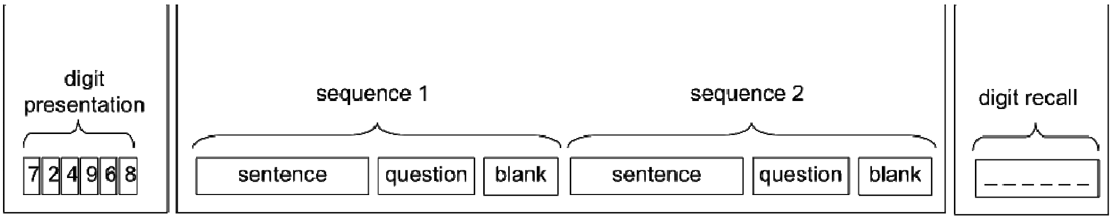

Figure 2. Design of the trials in Experiment 1. Separate boxes symbolise separate screens.

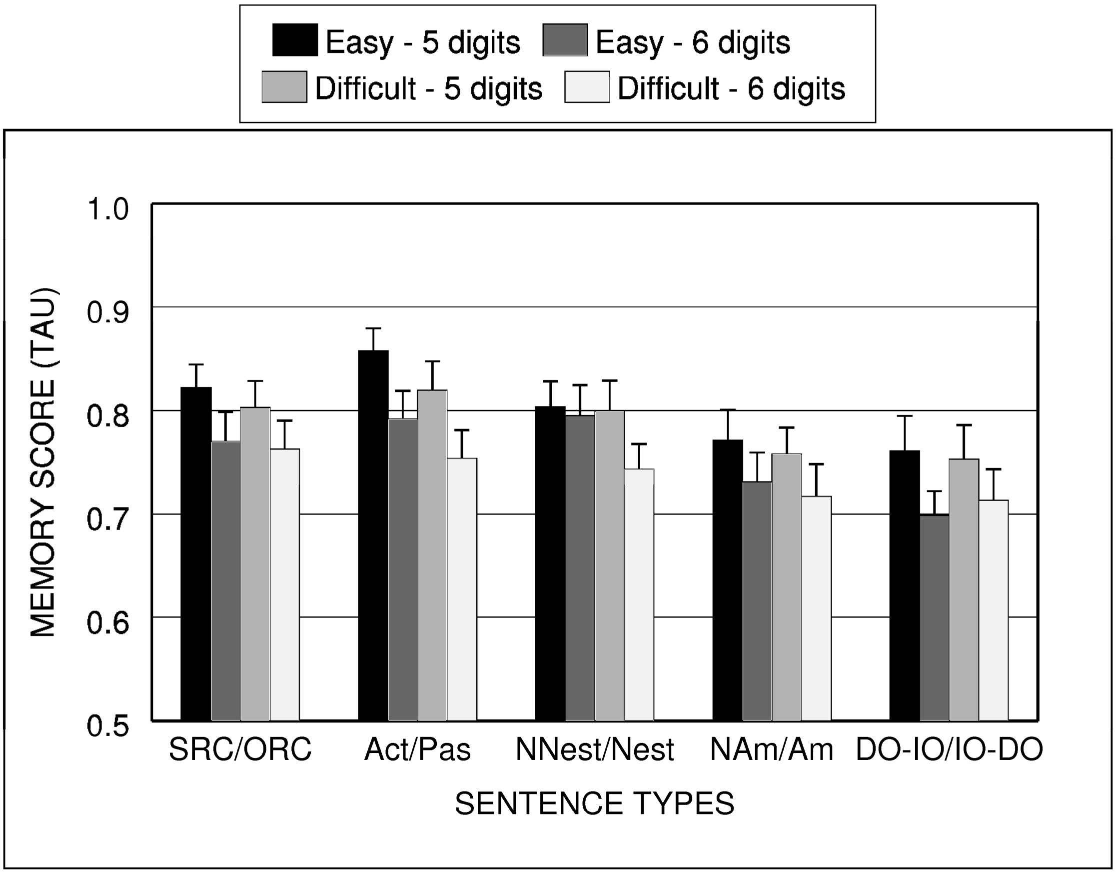

Figure 3. Digit recall scores based on a transformation of Kendall's rank correlation coefficient tau (τ') in Experiment 2, as a function of sentence-processing difficulty (Easy vs. Difficult), digit-load size (5 digits vs. 6 digits), and sentence type (SRC/ORC = Subject-extracted vs. Object-extracted relative clauses, Act/Pas = Active vs. Passive sentences, NNest/Nest = Non-nested vs. Nested relative clauses, NAm/Am = Unambiguous vs. Ambiguous pronoun sentences, DO-IO/IO-DO = sentences with the DO before the heavy IO vs. sentences with the DO after the heavy IO). Means and related standard errors (represented by the error bars) are taken from the participant analyses.

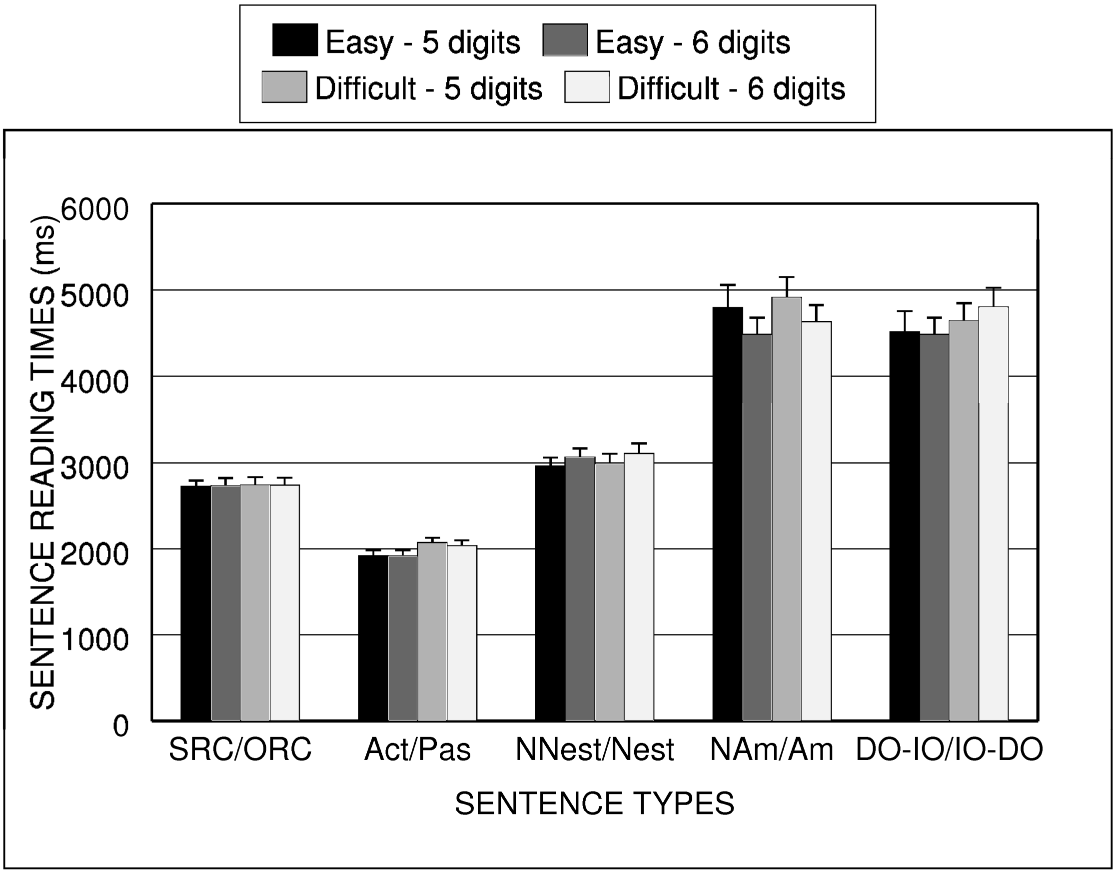

Figure 4. Mean sentence reading times in Experiment 2 in milliseconds, as a function of sentence-processing difficulty (Easy vs. Difficult), digit-load size (5 digits vs. 6 digits), and sentence type (SRC/ORC = Subject-extracted vs. Object-extracted relative clause, Act/Pas = Active vs. Passive sentences, NNest/Nest = Non-nested vs. Nested relative clauses, NAm/Am = Unambiguous vs. Ambiguous pronoun sentences, DO-IO/IO-DO = sentences with the DO before the heavy IO vs. sentences with the DO after the heavy IO). Means and related standard errors (represented by the error bars) are taken from the participant analyses.

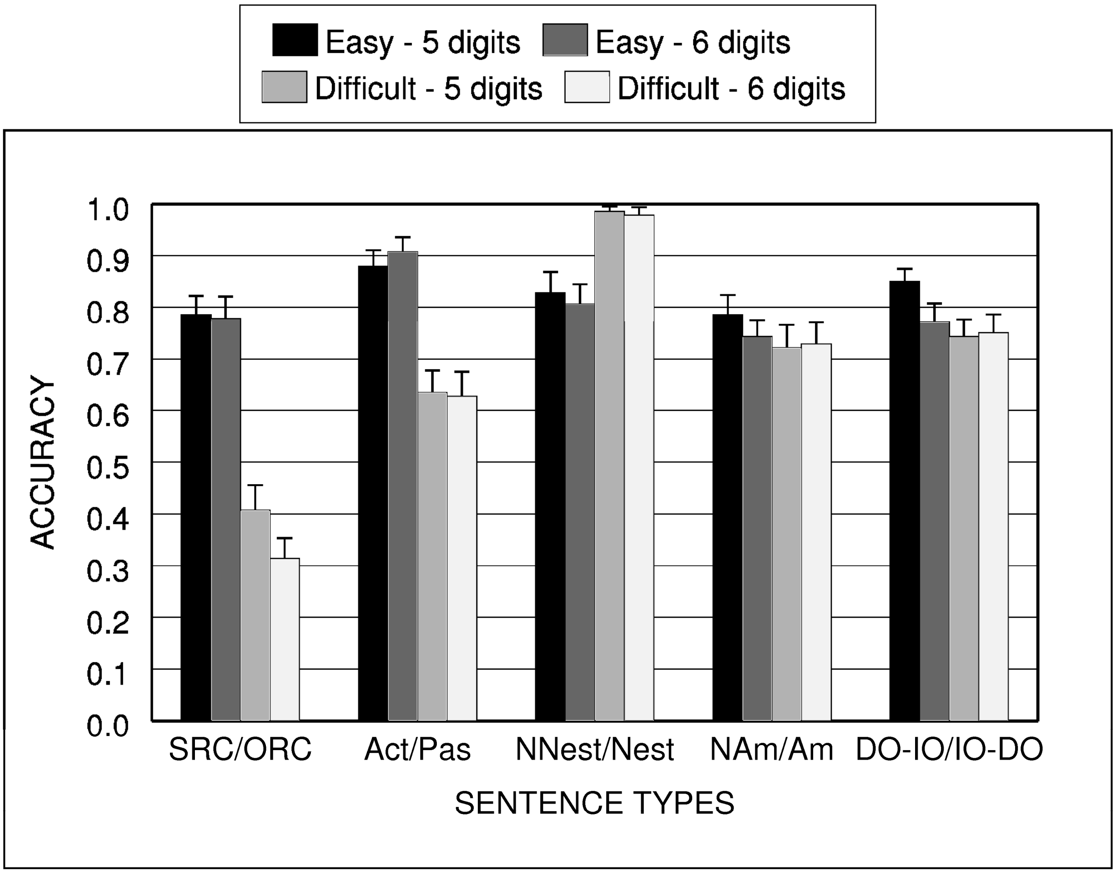

Figure 5. Mean accuracy rates of the answers to the comprehension questions in Experiment 2 in percentages, as a function of sentence-processing difficulty (Easy vs. Difficult), digit load size (5 digits vs. 6 digits), and sentence type (SRC/ORC = Subject-extracted vs. Object-extracted relative clause, Act/Pas = Active vs. Passive sentences, NNest/Nest = Non-nested vs. Nested relative clauses, NAm/Am = Unambiguous vs. Ambiguous pronoun sentences, DO-heavyIO/heavyIO-DO = sentences with the DO before the heavy IO vs. sentences with the DO after the heavy IO). Means and related standard errors (represented by the error bars) are taken from the participant analyses.

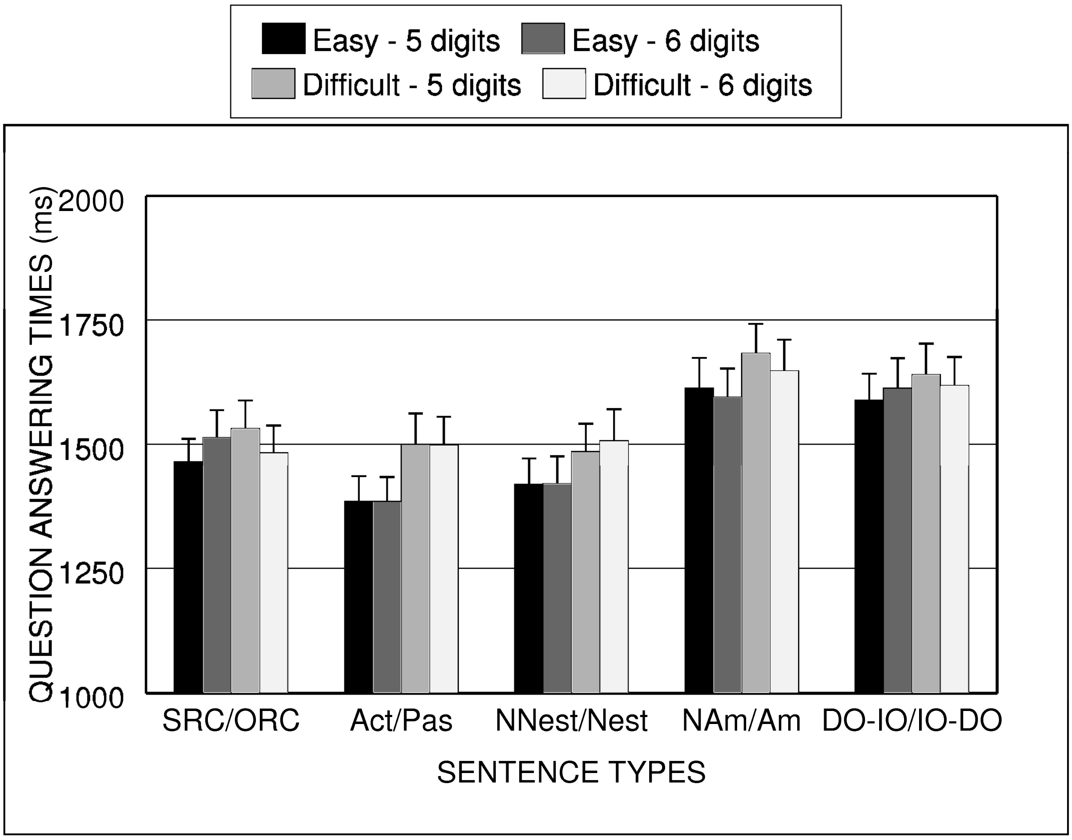

Figure 6. Mean response times to the comprehension questions in Experiment 2 in milliseconds, as a function of sentence-processing difficulty (Easy vs. Difficult), digit-load size (5 digits vs. 6 digits), and sentence type (SRC/ORC = Subject-extracted vs. Object-extracted relative clause, Act/Pas = Active vs. Passive sentences, NNest/Nest = Non-nested vs. Nested relative clauses, NAm/Am = Unambiguous vs. Ambiguous pronoun sentences, DO-IO/IO-DO = sentences with the DO before the heavy IO vs. sentences with the DO after the heavy IO). Means and related standard errors (represented by the error bars) are taken from the participant analyses.