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Working memory resource depletion effect in academic learning. Steps to an integrated approach

André Tricot[1], Sébastien Puma[2], Rémi Capa[3], Michel Audiffren[4], Nathalie André[4], Florence Lespiau[5], Stéphanie Roussel[6], Camille Jeunet[7], Emilie Massa[7], Dominique Bellec[8], Elisabeth Fonteneau[1], Pom Charras[1]

[1] Epsylon, University Paul Valéry Montpellier, route de Mende, 34090 Montpellier, France
[2] Paragraphe, Cergy Paris University, 2 rue de la Liberté, 93526 Saint-Denis, France
[3] SCOTE, INU Champollion, Place de Verdun, 81012 Albi, France
[4] CeRCA, CNRS, Université Poitiers, 5, rue T. Lefebvre, 86073 Poitiers, France
[5] Chrome, Université Nîmes, rue du Docteur Georges Salan, 30021 Nîmes, France
[6] Laces, Université Bordeaux, 3 ter place de la Victoire, 33076 Bordeaux, France
[7] CLLE, CNRS University Toulouse 2, 5 allées Antonio Machado, 31058 Toulouse, France
[8] Lycée Nelson Mandela, 63 rue de la Bugellerie, 86022 Poitiers, France

andre.tricot@univ-montp3.fr, mr.aethis@gmail.com, remi.capa@univ-jfc.fr, michel.audiffren@univ-poitiers.fr, nathalie.andre@univ-poitiers.fr, florence.lespiau@gmail.com, stef.roussel@gmail.com, camille.jeunet@univ-tlse2.fr, emilie.massa@univ-tlse2.fr, dominique.bellec@ac-poitiers.fr, elisabeth.fonteneau@univ-montp3.fr, pomcharras@gmail.com

Abstract. Learning at school requires cognitive effort. Optimizing these efforts is one of the keys to academic learning achievement. Many controlled experiments, for example within the cognitive load theory framework, have identified the factors that impact this optimization. The temporal dimension of this optimization was evoked in 2018: certain academic learning tasks could exhaust students, resulting on learning impairing. The hypothesis of Sweller and other authors from cognitive load theory is that working memory resources would be depleted during a demanding learning task. The authors point out that this depletion of working memory resources could explain a famous effect in learning literature: the massed / spaced effect. But these authors do not say: What mechanisms govern this exhaustion? How can this depletion be measured? The working memory resource depletion effect project proposes to answer these questions. Our aim is to present this project, its objectives, method and the first results.

Keywords: cognitive load, cognitive load theory, working memory resources, resources depletion, instructional design, educational psychology.

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1 Introduction

In the last 30 years, many studies have shown that the optimization of working memory resources is a key factor in academic learning success. In educational psychology, cognitive load theory has shown (based on several thousand published experiments) that decreasing cognitive load in working memory could lead to a learning rise [1]. Recent works in this area have shown that working memory resources can be depleted during a learning task [2] [3]. Sweller and colleagues found that students performed better at a working memory test after a less demanding task than when the same test was completed immediately after a very demanding and time-consuming task. These authors thus introduce a new, dynamic variable in the field of working memory resource optimization for learning: The depletion of these resources. While they are insightful, these papers do not answer important questions: What is getting depleted? Due to what mechanisms? How is this depletion recovered? How long does it take?

The aim of the working memory resource depletion effect project (WM-RDE from now) is to investigate working memory resource depletion effect by considering Barrouillet's and Camos' Time-Based Resources Sharing model (TBRS [4]). The TBRS model allows simple and straightforward predictions about cognitive load in working memory, as well as about the solicited resource (controlled attention), and about the causes of this resource depletion (the temporal sharing of controlled attention between the processing devoted to refreshing memory traces and the processing devoted to new items). Therefore, the project's objectives are:

a) to design, test and validate a new experimental paradigm, more rigorous than the one used by Sweller et al.'s, to obtain working memory resource depletion when performing an academic knowledge learning task;

b) to propose an integrated approach based on multiple measures of working memory resource depletion, through four complementary standpoints: phenomenological (subjective measures), behavioral (task performance), physiological (cardiovascular reactivity) and neurophysiological (EEG measures);

c) to study resource sharing over time as a critical factor responsible for resource depletion in working memory.

Once these objectives are achieved, and if the depletion effect is linear, then a secondary benefit will be obtained: we will be able to run objective cognitive load measures in instruction research.

We make the following hypotheses:

1. The depleted resource is controlled attention (*i.e.* effortful control), as in the TBRS Model.

2. The TBRS model allows defining the consumption of attentional resources during the realization of a complex academic task.

3. When the task requirement is higher than the individuals' resources, the latter are gradually depleted and consequently task performance decreases, as in Sweller et al. results.

4. This depletion is measurable through a working memory test (behavioral performance) and physiological and neurophysiological techniques.

5. Increasing the time available to perform the task reduces or cancels the depletion effect, as predicted by the TBRS Model.

6. If resources are depleted, then the students will only be able to mobilize fewer resources and their performance at the task will decrease, as obtained by Puma et al. (2018).

7. The individuals can also disengage from the task (initially or throughout), thus preserving their resources at the expense of the learning task performance.

Our aim here is to present WM-RDE project, its theoretical background, its method and measures, and the results of a first pre-experiment.

2 State of the art

2.1 The depletion of cognitive resources: from ego depletion to WM resources depletion

Resource depletion has attracted considerable interest in psychology in recent years, since the first study on the ego depletion effect [5]. This effect is obtained when using the sequential-task protocol (see Figure 1).

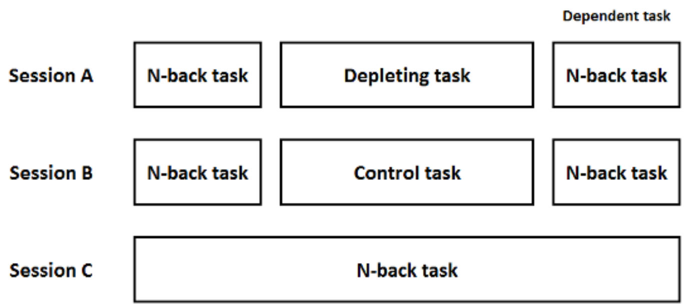

Fig. 1. The sequential-task protocol

This protocol encompasses two conditions: (A) a depleting condition, and (B) a control condition. In the depleting condition, the participants perform two consecutive tasks: a depleting task and a dependent task. These two tasks require a high level of self-control, i.e., the ability to inhibit embarrassing emotions, pressing urges, intrusive negative thoughts, behaviors repressed by social rules, habits and automated action patterns[1]. In the control condition, the participants also perform two consecutive tasks,

[1] The ego depletion effect has been much studied, often replicated [6], but the replication of the Sripada, Kessler and Jonides' experiment [7] by 23 labs (N = 2141) failed to obtain the ego depletion effect [8]. Another replication study by 12 labs (N = 1775) obtained a small but significant ego depletion effect [9]. A meta-analysis [10] shows that the ego-depletion is obtained under certain conditions (emotion videos) and not obtained under others conditions

the control task and the dependent task, with exactly the same time course than in the depleting condition. The control task, by definition, requires a low level of self-control by contrast to the depleting task. The ego depletion effect reflects a lower performance in the dependent task when it is carried out after the depleting task rather than after the control task. Within the framework of this resource approach, performance in the depleting condition drops and is assumed to be a direct consequence of a decrease in available resources induced by the depleting task. From that standpoint, cognitive fatigue is conceived as a state of depleted resources (and thus resource depletion can result in cognitive fatigue). This literature has led other researchers to question the depletion of resources of other cognitive processes. For instance, Sweller et al.'s studies have targeted working memory, considering its importance in academic learning.

Based on an ego depletion effect study, which used a working memory post-test as a measure of resource depletion due to a self-control task, Chen et al. [2] described a working memory resource depletion effect. These authors have compared the performance obtained by primary school students in massed vs. spaced learning conditions. In addition, the researchers asked the participants to perform a complex working memory test (involving processing and memorization) at the end of the learning sessions. The results confirmed the expected classic effect (spaced > massed). Chen et al. also observed that the participants who completed the massed condition obtained lower performances at the working memory test. The authors interpret this result as a working memory resource depletion effect. The following year, Leahy and Sweller [3] replicated the results in a series of experiments on the testing effect. They showed that the learning performance obtained in a delayed post-test (compared to an immediate post-test) was associated with better performance in the working memory test. They interpreted this dual performance as a recovery of working memory resources. Thus, for Sweller and colleagues, the working memory resource depletion effect is close to the ego depletion effect, but possibly more general: for any complex, resource-depleting and time-consuming task, the effect should be obtained, because it involves a central part of human cognitive architecture: working memory.

While the idea of cognitive resources depletion is empirically supported, the authors quoted above do not explain what is depleted or what mechanisms govern this depletion. Different researchers have proposed that brain glucose depletion could be a possible candidate of cognitive fatigue (e.g. [13]), but this hypothesis has been challenged and seriously criticized (e.g. [14]). Another plausible mechanism explaining cognitive fatigue has been recently proposed: a progressive deterioration of the connectivity within and between large-scale neuronal networks involved in effortful control. This phenomenon could be caused by an accumulation of adenosine in overloaded brain regions [15] [16]. In order to better understand the working memory resource depletion effect, our project uses the time-based resources sharing model of working memory [4]. These alternative theories will be taken into consideration in the present project by controlling different variables (e.g.,

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(attention videos). More recent meta-analyses also show a negative effect of ego depletion on subsequent physical endurance performance [11] [12].

motivation, cost/benefit of effortful control) and measuring other variables (e.g., prefrontal theta waves).

2.2 Contribution of the Time-Based Resources Sharing model

The TBRS model [4] assumes that the resource used by working memory is controlled attention. The activation of information maintained in working memory when a task is performed decreases over time. Maintaining information in working memory requires refreshing, using attentional focus. During a complex task, the system quickly alternates the attentional focus between the new elements to be processed and the maintained information to be refreshed. The model proposes to define the cognitive load in working memory as a ratio. In a classic complex memory span protocol, the time spent processing distracting elements (Td) cannot be spent refreshing the information in working memory (Tr). As a matter of fact, the attention focus is being shared between the two activities. Thus, cognitive load can be defined as the ratio Td / (Td + Tr) or Td / T total. The more time spent on distracting elements increases, the more the ratio Td / (Td + Tr) increases and therefore the more the cognitive load increases. Similarly, reducing the time spent refreshing working memory information by keeping the time spent on distracting elements constant increases cognitive load.

We have tested the robustness of this model in school learning situations and shown its compatibility with cognitive load theory [17] [18]. We have shown that the load predicted by the TBRS model was well observed at the physiological level [19] as well as neurophysiological level [20], particularly through the modulations of theta EEG activity [21].

One purpose of this project is to manipulate the different elements of the cognitive load during the depleting task and examine the residual depletion effect in the subsequent dependent task.

3 Method

The experiments conducted within the framework of this project will use the sequential-task protocol [5] described in Figure 1. But, contrary to the depletion tasks used in this protocol, we will use a complex "processing and refreshing" task. This new protocol has already been tested (see bellow, section 4).

3.1 Depleting task

The depleting task included in session A must be a long and effortful task tapping working memory and inducing cognitive fatigue (*i.e.* a depletion of working memory resources). Several depleting tasks will be used throughout the project. However, a second language transcription task[2] will be used as main depleting task in several of our planned experiments.

In this task, the participants (French) have to write down an oral speech provided in English, i.e. a classical learning task for students in foreign language departments. It is a dual task: (1) listening comprehension of an oral speech and (2) transcription writing task. But, during the second task, it demands the temporal sharing of controlled attention between refreshing memory traces (the sentences they just eared) and the processing devoted to new items (writing this sentence). It is therefore highly compatible with the TBRS model. This task is also demanding because it is in a second language. The task can be run over a long period of time (20 to 60 minutes): this is an experimental precaution to obtain a cognitive fatigue effect (e.g. [22]). The transcript of the speech is recorded in order to track accurately the words that have been correctly transcribed, the ones that have not. In this way, we are able to make a continuous measure of the performance during the task. The duration and frequency of pauses are empirically calibrated to make the task feasible, but demanding.

3.2 Control task

The control task included in session B must be as effortless and emotionally neutral as possible but with exactly the same duration than the depleting task. In addition, the control task must not be boring because boredom decreases arousal and requires compensatory effortful control. As for the depleting task, several control tasks will be used throughout the project. However, a simple listening task will be used as the main control task in several of our planned experiments.

In the simple listening task, the participants do not have to transcript. A comprehension test is administered at the end of the session. Comprehension is evaluated with the Kintsch et al. protocol [22]: surface, text base and inference questions. Participants' resources are evaluated with standardized tests of English proficiency (Cambridge English Language Assessment) and typing speed (computerized test, words per minute, with French words and with English words).

Other control tasks will be used in several of our planned experiments, such as watching an emotionally neutral movie that does not involve listening to a commentary. This type of control task is often used in studies examining the effects of cognitive fatigue on physical performance (*e.g.* [12]).

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[2] It is well known that simultaneous translation tasks are very demanding and exhausting [37], but we decided to begin our set of experiments with a second language transcription task because it is easier to objectively evaluate the performance. We previously developed methods and measure to evaluate performance and cognitive load in second language speech comprehension tasks [38].

3.3 Dependent task

The dependent task must be an effortful working memory task for the purpose of the project. One of the most popular measures of working memory is the n-back task (*e.g.* [23]). We chose a computerized visual version of the 2-back because it has been shown to be more sensitive to cognitive fatigue than the 3-back task [24]. In classical sequential-task protocols, the dependent task is performed immediately after the main task (*i.e.* depleting or control task). In order to have an additional reference performance in the beginning of each session, particularly for physiological measures, we add a 2-back task before the main task. To sum-up, participants will have to perform two blocks of 72 n-back trials before and after the main task. Finally, a session C will be added in several of our planned experiments to examine whether and how effortful control modulates physiological indexes over time spent on the n-back task.

3.4 Participants

Participants included in experiments throughout the project are French-speaking students studying English at university, typically year 3 and year 4. They are familiar with the task and enough fluent in English to perform it. English proficiency and typing speed are evaluated with standardized tests.

Other asymptomatic or symptomatic populations will be selected in several of our planned experiments, as well as middle, high school and, more broadly, university students.

3.5 Procedure

Participants will achieve sessions A and B (plus session C in several experiments) in different days spaced by a minimum of 2 days. The orders of the sessions are counterbalanced across participants. Participants complete an n-back working memory test before and after performing the main task so that, unlike Sweller and colleagues' experiences cited above, we have two working memory measures per participant and per session. We will test the interaction Session (A vs B) x Moment (before vs after the main task) with the hypothesis that the n-back performance will not vary in control condition while it will degrade in the depleting condition. Experiments included in several of our planned experiments will evaluate the effect of changing the frequency and duration of breaks during the depleting task to increase or decrease the cognitive load in working memory in a way that is described by the TBRS model and that should be observable on measures of performance, resource depletion and task commitment.

3.6 Measures of cognitive resources use and depletion

As above mentioned, we assumed that performing a long and effortful task depletes intrinsic resources, i.e. weakens effortful control. Achievement of the WM-RDE project then requires different measures of resource depletion through the assessment of the capacity to exert effortful control. We will use three complementary approaches to assess effortful control: subjective, behavioral and physiological (cardiovascular and EEG) measures. Complementarity between these indexes is required to interpret the results. For example, a decrease of performance coupled with a higher feeling of fatigue and greater physiological activity could be interpreted as a compensatory effort mobilization, whereas an improvement of performance linked with a lower feeling of effort and less physiological activity could be interpreted as a learning effect. The different patterns of results are clearly identified and regularly discussed in the literature (*e.g.* [25] [26] [27]).

Subjective measures. Subjective motivation, boredom, cognitive load and cognitive fatigue will be measured before and after each task with very simple visual-analogue scales. We will assess the costs and benefits of achieving the goal, task engagement and motivation, with a short version of the Motivated Strategies for Learning Questionnaire [28]. We will assess boredom and cognitive fatigue with a short version of the Fatigue Impact Scale [29], cognitive load and effort with Leppink et al. scale [30].

Behavioral measures. The principal behavioral outcomes include percentage of correct and incorrect responses, percentage of omissions and reaction times recorded during the n-back task. We also operationalize accuracy by calculating the d prime index. Secondary behavioral outcomes include performance related to the depleting and control tasks.

Physiological measures. Cardiovascular (electrocardiography -ECG-, impedance cardiography -ICG-) and EEG outcomes (spectral bands and ERPs) used in this project allow assessing effortful control but they differ in their temporality and capability to focus on specific cognitive processes. Cardiovascular indices will allow us to identify relatively slow effects (e.g. difference between blocks) and a general mobilization of resources, but without targeting specific brain areas. Spectral bands of brain activity allow identifying relatively slow effects (e.g. difference between blocks) and the approximate location of the brain regions involved in the generation of a specific rhythm (e.g. frontal-midline theta). ERPs provide a very fast temporal analysis during the time course of a trial and a way to determine the nature of cognitive processes impacted by a variation in effortful control according to the wave time-window.

Physiological signals (ECG, ICG, and EEG) will be recorded throughout the three two sessions A, B and C (see Figure 1), but only in several of our planned experiments. Cardiovascular reactivity indexes and density of theta rhythm will be analyzed during the n-back, the depleting task and the control task as a function of time on task. ERP will be exclusively analyzed during the n-back tasks.

- *Cardiovascular reactivity*. Physiological indicators measure the level of activation of the sympathetic nervous system (SNS), which is responsible for mobilizing the resources the individual needs. One measure, the pre-ejection period (PEP), has been extensively used in recent years. This period represents the time between the contraction of the left ventricle of the heart and the first blood release. Unlike other physiological measures in the literature, PEP is the sole measure exclusively under the influence of beta-adrenergic SNS. Several studies have shown its sensitivity to resource mobilization [19] [31]. A decrease in PEP when performing a task can be interpreted as increased resource mobilization. Even if no study was published using the n-back task, a decrease in PEP was regularly obtained in working memory task (e.g. [31]).

- *Event-related potentials*. Several ERPs studies have obtained robust effects on the P300 amplitude with the n-back task (*e.g.* [32]). A time window of 250-500 *ms* was used after the onset of stimuli at frontal (F3, FZ and F4) and parietal (P3, PZ and P4) electrodes. The hypothesis is that P300 reflects available resources and a decrease of the P300 amplitude is associated with reduced attentional resources. ERP analyses are conducted only for correct responses to the target stimuli. The task is relatively easy to perform and generally leads to a low proportion of rejected trials (around 10%), even in the most difficult condition (4-back).
- *Spectral bands*. Brain oscillation frequencies are divided into the following spectral bands with distinct functional associations: delta (1-4 Hz), theta (4-8 Hz), alpha (8-14 Hz), beta (14-30 Hz), and gamma (>30 Hz). These oscillations cause fluctuations in cortical local field potentials that can be measured using EEG scalp detectors. Lakatos et al. [33] proposed that these oscillations are hierarchically organized as follows: brain regions that generate low-frequency oscillations (theta and alpha bands) modulate the activity of brain regions that generate higher frequency oscillations (beta and gamma bands). In that perspective, frontal-midline theta oscillations have been associated with effortful control exerted by anterior cingulate cortex over brain areas involved in the ongoing task (*e.g.* [16]). A large number of studies showed an increase in the amount of frontal-midline theta with increasing working memory load, task difficulty, or mental effort during working memory tasks (see [34], for a review). More recently, Fairclough and Ewing [35] showed that frontal-midline theta was significantly higher during hard demand (4-back) compared to easy (1-back) and very hard demand (7-back) during a n-back task.

3 Preliminary experiment

3.1 Participants

Eighteen university students in English language and civilization (year 4; average 22 years old) participated to the experiment. The results of only 12 participants were taken into account because 6 participants were either not expert enough to perform the main task, did not perform well enough at the n-back tasks, or encountered technical issues during the experiment (which were due to E-prime software).

Their English proficiency was evaluated with the Cambridge test. The group average performance was 21.6 (max 25; *s.d.* = 1.8).

Their typing speed was evaluated by the number of words typed per minute. The group average performance was 47 (*s.d.* = 15).

3.2 Materials

Participants had to transcript a 12 minutes sound file based on a TED conference in English language (Robert Waldinger "What make a good life. Lessons from the longest study on happiness"). Half the participants listened to the speech with normal pauses (control group) while the other half (test group), additional pauses (2.5 longer than natural pauses) were inserted in the speech, in order to transcript the discourse. The total time in the group was 35' (enough time to type but no other pauses were possible).

The transcription task was performed on a laptop and Open Office Writer software.

3.3 Procedure

1. Participants were trained at N-back tasks: 0-back (42 trials), 1-back (42 trials), 2-back (62 trials).
2. They performed the Cambridge level test.
3. They ran the Typing Speed test.
4. They ran the N-back pre-tests: Block 1 (42 trials), 5 second pause, followed by Block 2 (42 trials).
5. They ran the main task: transcription for the test group vs. listening task for the control group.
6. They ran, after a 5 seconds rest, the N-back post-test: Block 1 (42 trials) 5 second pause Block 2.
7. The participants' comprehension was evaluated: 8 literal and 8 inferential questions.
8. The participants answered 6 motivation, difficulty and fatigue questions: Before starting this study, did you feel motivated to participate? Was the letter memory task difficult for you? Was the transcription/listening task difficult for you? Was answering the questions difficult for you? Did you feel tired? Would you be willing to complete a new transcription/listening task?

3.4 Results

Both groups made fewer errors in the Post test than in the Pretest. The number of errors per block (and by splitting the blocks into sub-blocks of 21 trials), suggested irregular performances at the pre-test. We need to fix that point by training the participants before the pretest until their performance is stable and the training effect disappears.

We report participants' individual measures to highlight the wide distribution of n-back performance, which is the main issue we need to address.

Comprehension. The control group responds better to inferential questions than the test group.

Transcription task. No participant gave up the task. We analyzed the productions by counting the number of errors (including typos, rewording, spelling mistakes and untranscribed words). The transcription was split into seven consecutive 5 minutes parts to explore the evolution of the number of errors during the task: there is no general increase nor decrease of the performance during the task. This is a crucial aspect: no participant disengaged during the task and there was no learning effect.

Table 1. Main performances of the 6 participants of the test group, mean performances of the test and control groups.

Participant	English proficiency	Typing speed	n-back pre	n-back post	Motivation new task	Literal Questions	Inferences Questions
1	21	43	6	5	60	5	5
2	22	45	11	10	65	6	7
3	20	32	6	6	73	7	8
4	23	43	32	23	98	6	7
5	23	43	11	13	89	7	6
6	25	77	11	8	21	7	7
Test (average)	22,3	47	12,8	10,8	68	6,3	6,7
Control (average)	21		9,8	7,2	87	6,3	7,5

In figure 2, each participant is represented by a colour line. It is remarkable to note that there is apparently no general increase nor decrease of the performance during the task, despite an important variation of the performances and important differences between participants. This is a crucial aspect because one possibility for the participants is to disengage from the task, increase the number of errors and save their cognitive resources. One variation during the task (see the 15-20’ slot) is probably due to an easy part of the discourse to transcript, which can be explained by the fact that we used natural material for this experiment.

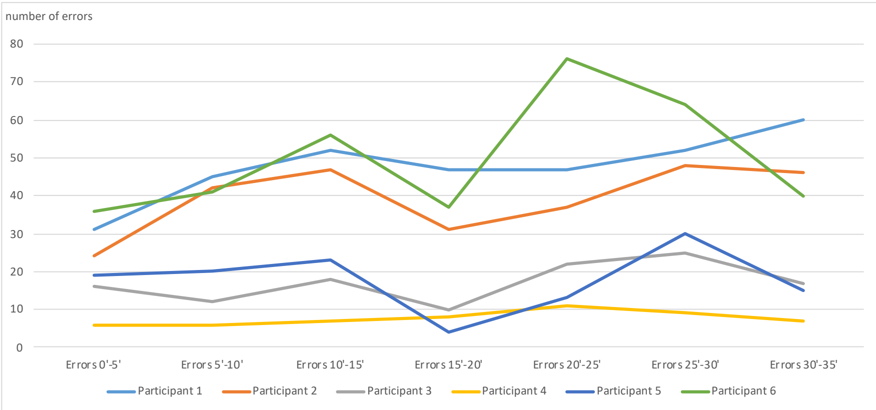

Fig. 2. Evolution of the number of errors according for each of the 6 participants of the test group

Perceived difficulty/fatigue. The test group found the n-back easier than the control group (perhaps they made a comparison with the transcription task). They also found the transcription task more difficult and were less motivated than the control group to do it again.

Performances of each participant. One of them is remarkable: he performed the best at the English test and, by far, at the typing speed; he is the one who makes the most mistakes at the transcription task, sometimes in huge proportion; his comprehension score is comparable to others; he makes few errors at n-back in pre-test and even less at n-back in post-test ; he indicates the lowest motivation score for starting the task once again. In short, the amount of effort invested in the task depends on motivation. And the depletion of resources depends on the amount of effort invested. This participant had the means to do better than the others, but he decided to do not and saved his resources.

Participant feedback. Participants reported that the task was stressful because they did not know how long it would last. They were relieved when the task ended and to move on to the n-back again.

4 Discussion

The WM-RDE project is summarized in figure 3. We aim at investigating the effect of the attentional demand of a task, according to time resources sharing, on resources depletion. We defined the variables involved, the relations between these variables, and how measuring these variables.

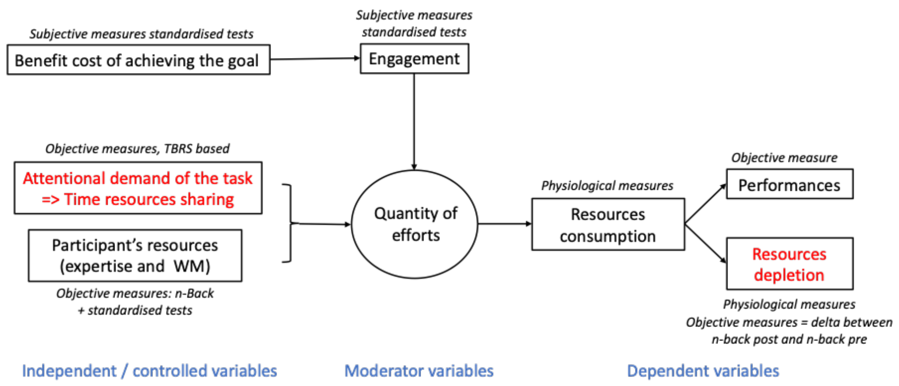

Fig. 3. Variables and measures involved in the WM-RDE project

We believe that the aim is new: understanding the mechanisms that govern the working memory resources depletion. The involvement of academic tasks and knowledge (i.e. ecological validity) is a very important aspect of the project.

We think that our protocol is a new experimental paradigm. We use physiological and neurophysiological measures that are not used in cognitive load theory experiments. Subjective motivation, cognitive load and fatigue are also assessed, making us able to perform a triangulation between resource depletion, task engagement and performance.

By submitting this paper to 4th International Symposium on Human Mental Workload, we hope to obtain feedback on this project, which is where it all started.

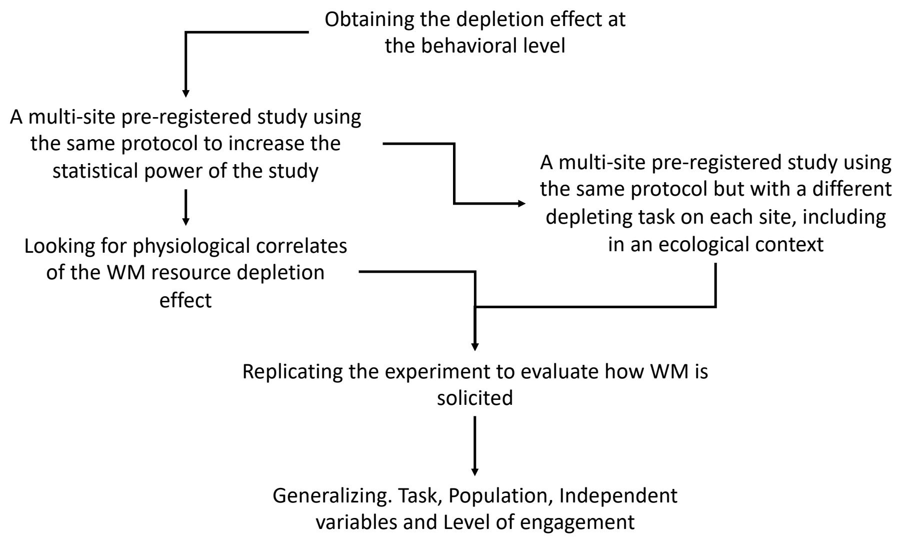

Fig. 4. General organization of the WM-RDE project

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