Interactions among sources of cognitive load: an EEG perspective

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Abstract
The cognitive load theory (CLT) distinguished two types of human memory: working memory and long-term memory. It further assumes that the working memory system has pictorial and audio channels and each channel has a limited processing capacity. Based on such human cognitive architecture, CLT further differentiates three categories of cognitive load: extraneous, intrinsic and germane and argues that the cognitive load is the addition of these three sources of cognitive load (Sweller, 2010; Moreno & Park, 2010). In order not to exceed available working memory capacity, we should decrease the extraneous cognitive load, manage the intrinsic cognitive load and foster the germane cognitive load. However, many studies have reported interactions among different cognitive loads. That is, the additivity model might not be enough to explain the variation of the total cognitive load without considering possible interaction effects. Yet, very few studies have checked the interactions among three sources of cognitive load with rigid designs. Therefore, this study aims to test the additivity assumption of CLT through the electroencephalograph (EEG) technique. Such neural technique can track a real-time change of human cognitive load during processing tasks compared with traditional self-report cognitive load measurement. A three-way (three sources of cognitive load) repeated measures design will be adopted. Each type of cognitive load has two levels induced through eight different types of two-digit addition tasks. The intrinsic cognitive load is manipulated through levels of task difficulty. The lower level is two-digit addition with one carry. The higher level is two-digit addition with two carries. Colors will be adopted to disturb information chunk so as to construct extraneous cognitive load on learning based on the split-attention effect. The germane cognitive load will be generated through adding lines to connect different digits so as to scaffold individual mental addition. Thirty participants will be recruited from a university. They will be required to get the right answers as soon as possible and finish all types of task in a randomized order. Individual's EEG waveforms during the execution of experimental tasks will be recorded. As to the measurement of learning performance, the reaction time and accuracy of each task will be collected. Other data includes participants' demographics information and their alertness level. Data will be analyzed at both neural and behavioral levels through a three-way repeated measures ANOVA analysis. According to previous studies, the EEG power spectrum in the theta frequency band of the prefrontal cortex is a well-investigated sensitive event to the variations in task demands. The EEG waveforms will be systematically decomposed through different techniques to find an optimal cognitive load estimation index. As to the behavioral level analysis, individual's performance will be used to indicate their cognitive load level. The overall performance will be calculated through the ratio of total number of correct task and total amount of reaction time. Main effects of the three types of cognitive load will be analyzed first. It was expected that intrinsic and extraneous cognitive load will negatively relate with individual performance while the germane cognitive load will positively enhance the performance. As to the two-factor interaction, it is expected

that the effects of both germane and extraneous cognitive loads will be enhanced under the high level intrinsic cognitive load condition. A three-factor interaction will also be tested so as to analyze how these three sources of cognitive load affect each other. In the end, it is expected to give a revised formula on how to calculate the overall cognitive load based on the three separate cognitive load levels. It will also be discussed whether the neural and behavioral level analysis generate the consistent results.

1. Introduction of the problem

1.1 Three sources of cognitive load

Cognitive scientists seek to understand human mental process in perceiving and knowing. The cognitive load theory (CLT) (Sweller, 1988; Swezller & Sweller, 1994) is a famous one attempting to explain human psychological construct and behavioral phenomena in learning activities. It assumes that each human sub-working memory has a limited processing capacity. It differentiates three categories of cognitive load which represents three development stages of CLT: extraneous, intrinsic and germane. Extraneous cognitive load refers to those unnecessary cognitive demands caused by instructional design which could be eliminated through redesigning. Intrinsic cognitive load depends on the learning task and leaners' prior knowledge. CLT assumes the cognitive demand of the learning task was determined by the number of elements that need to be simultaneously processed. The germane cognitive load refers to those positive mental process which devotes cognitive resources to schema acquisition and automation.

1.2 The additivity assumption

The above three types of cognitive load add to the total cognitive load which is the additivity hypothesis in CLT (Figure 1). To promote learning, CLT suggests that the total load shouldn't exceed the available working memory capacity, and we should decrease the extraneous cognitive load and foster the germane load.

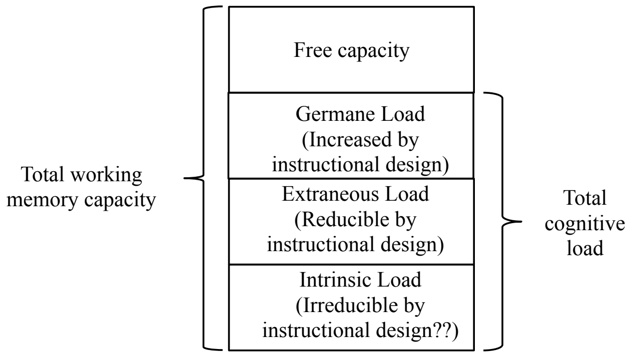

Figure 1 Three types of cognitive load and the additivity assumption

The intrinsic and extraneous cognitive load are task-oriented. The intrinsic cognitive load generally provides a base cognitive load. Inappropriate instructional design will cause extraneous processing. while the germane cognitive load is learning-oriented. It happens when individuals try to acquire schema and build automation based on the task (Schnotz and Kürschner, 2007). The additivity assumption indicates a linear consumption of human cognitive resources and doesn't consider interactions among these three different sources of cognitive load. Sweller (2010) further proposed an additivity interaction among these three types of cognitive load. That is, a decrease of extraneous cognitive load will automatically increase germane cognitive load when the intrinsic cognitive load is high, while such interaction will disappear under a low intrinsic cognitive load. Moreover, the germane cognitive load will transform to the extraneous cognitive load along with the increase of individual expertise in a task.

This additivity assumption is also challenged by some studies on seductive details and decorative pictures. Park et al (2011) found learners reported lower cognitive load with additional seductive details, and further argued that different extraneous cognitive load factors are not necessarily additive at least according to self-report. Schneider et al also found additional decorative pictures decreased learner's perceived task difficulty (Schneider, Nebel, & Rey, 2016). These positive effects induced by extraneous cognitive load might be explained by the interaction between extraneous cognitive load and germane cognitive load. The seductive details and decorative pictures could induce better affective experience as well as motivation which could foster germane processing when cognitive resources available (Park et al., 2011).

Taken together, the additivity model may be not enough to represent the relationships among the three types of cognitive load.

1.3 Problem and hypothesis

This study aims to test the additivity assumption of CLT through the electroencephalograph (EEG) technique. EEG captures neuroelectrical signals on the scalp through a net of regularly spaced electrodes. I hypothesize that there are interactions among the three sources of cognitive load. That is, the overall cognitive load will not linearly change along with different sources of cognitive load. Rather, it should be:

Overall cognitive load=Intrinsic cognitive load + Extraneous cognitive load +Germane cognitive load + Interactions

1.4 Advantages of approaching the problem through neuroimaging

1.4.1 Studies at behavioral level

Existing studies have tried to test the additivity assumption based on behavioral level experiments. Galy et al. (Galy, Cariou, & Mélan, 2012) adjusted levels of intrinsic, extraneous and germane cognitive load through manipulating three mental workload factors: task difficulty, time pressure, and alertness. They didn't find a three-way interaction among the proposed mental factors but only the interaction between task difficulty (intrinsic cognitive load) and time pressure (extraneous cognitive load). Therefore, they claimed that both task difficulty and time pressure had additive effects on cognitive load which was modulated by individual alertness. In this study, the authors failed to actively adjust the germane cognitive load level since the alertness was explained to affect the amount of cognitive resources available rather than the germane cognitive load as hypothesized. Moreover, it is not rigid to define change of time pressure as the manipulation of extraneous cognitive load since time pressure could also be viewed as the change of task difficulty rather than instructional design. It's also questionable to view the detected interactions between intrinsic and extraneous cognitive load as the confirmation of additive consumption. Rather, it reveals an interaction beyond the addition model. The author also didn't further explain how the intrinsic and extraneous cognitive load interacts. On the other hand, this study also revealed the inconsistency among different measurements of cognitive load (self-rated mental effort, heart rate and task performance) which referred to the current challenge facing the cognitive load theory (Ayres & Paas, 2012) and also weakened their findings. The commonly used self-report method was not sensitive to change on task-independent factors (Galy et al., 2012).

1.4.2 Neural level findings

The use of neuroimaging techniques (Ghaderyan & Abbasi, 2018; Smith, Hardman, Wall, & Mroz, 2004) is a promising direct and objective measurement. They can continuously capture tiny and real-time changes of human cognitive states and allow a fine-grained measurement of cognitive load. Therefore, neuroscientific techniques have been argued to give the most precise measurement of cognitive load (Brünken, Plass, & Leutner, 2003). The challenge of the neural level analysis is to select a specific neural index to measure individual's real-time cognitive load level. According to previous studies, the electroencephalograph (EEG) power spectrum in the theta frequency band of the prefrontal cortex is a well-investigated sensitive event to the variations in task demands (Borghini, Astolfi, Vecchiato, Mattia, & Babiloni, 2014). Such theta band is often located at the midline of scalp. Its power increase has been reported in multiple tasks like visual searching (Yamada, 1998), simulations (Borghini et al., 2011), and memorization (Berka et al., 2007). It can also be triggered through a more focused attention (Doppelmaryr et al., 2008). Some scholars also found a theta increase at parietal areas when task is more demanding (Fairclough, Venables, & Tattersall, 2005).

Besides EEG, Ghaderyan and Abbasi (Ghaderyan & Abbasi, 2018) developed an Electrocardiograph (ECG) based cognitive load estimation algorithm. ECG also use electrodes like EEG but attach these electrodes to the chest, legs, arms and neck so as to measure people's electric impulses of the heart and the brain. They adopted addition tasks at five levels of difficulty and collected ECG recordings of 22 subjects. The cepstral-based algorithm they proposed can achieve an accuracy over 90% for the estimation of workload imposed by variations in the digit numbers as well as the number of carry operations.

The present study will adopt number addition tasks. According to previous studies, mental arithmetic involves a distributed brain network including dorsal and ventral visual pathways, the frontal lobe, the medial temporal lobe and the hippocampus (Menon, 2015). The mental processing of mathematical knowledge is not only related with memory and control and detection systems of our brain, but also the visual processing regions. Mental calculation will also light up the somatosensory finger area which is related with finger perception and representation (Berteletti & Booth, 2015).

Taken together, traditional subjective and indirect measurements of cognitive load are not sensitive and sometimes inconsistent. While neuroimaging techniques can provide more precise measurement of cognitive load compared with the common self-report technique. There're also some neural studies that have found the distribution of neural network that mental calculation will trigger as well as some typical components to represent task demands (the theta frequency band of the prefrontal cortex). Therefore, it is necessary as well as feasible to involve neuroimaging techniques to test the interactions among cognitive load.

2. Experimental design

This study aims to manipulate the three types of cognitive load to test their interactions. A three-way repeated measures design will be adopted. All tasks will be based on familiar two-digit addition so as to avoid overload to the best. Participants are encouraged to give the right answers as best as they can.

2.1 Participants

There will be 30 participants recruited from a university with an age between 20-30. They should have no problem in recognizing red and blue. Demographic information including major, age, gender etc. will be collected. All participants will be suggested not to drink tea or coffee before the experiment.

2.2 Task design

I will design two levels of intrinsic, extraneous and germane cognitive load separately. As to the intrinsic cognitive load, it is determined by the interactive elements in the task and individual prior knowledge. Therefore, with similar expertise, task difficulty is always manipulated to create different intrinsic cognitive load. In this study, two-digit addition with 2 carries, that is both the additions of units digits and tens digits are separately over 10, will be used as the high intrinsic condition, while those with 1 carry, that is only the addition of units digits is over 10 will be used for the low intrinsic condition (see Table 1). These two types of task require individuals to hold different number units in their working memory when doing the addition. The addition task was also used by Ghaderyan and Abbasi (2018) in developing an ECG-based cognitive load estimation algorithm.

With respect to the extraneous cognitive load, I will adopt colors to disturb information chunk so as to construct counterproductive effects on learning based on the split-attention effect (Sweller, Ayres, & Kalyuga, 2011). The germane cognitive load is the productive consumption of cognitive resources which aims to promote learning process. I add lines to connect different digits so as to scaffold individual mental addition. Therefore, there will be eight different tasks in total (see Table 1).

Table 1 Tasks for different sources and levels of cognitive load.

	Low-Intrinsic (LI)	High-Intrinsic (HI)	
Low-Germane (LG)	**34** + **55** = ____ **68** + **21** = ____	**57** + **69** = ____ **74** + **38** = ____	Low-Extraneous (LE)
High-Germane (HG)	**34** + **55** = ____ **68** + **21** = ____	**57** + **69** = ____ **74** + **38** = ____	Low-Extraneous (LE)
Low-Germane (LG)	**34** + **55** = ____ **68** + **21** = ____	**57** + **69** = ____ **74** + **38** = ____	High-Extraneous (HE)
High-Germane (HG)	**34** + **55** = ____ **68** + **21** = ____	**57** + **69** = ____ **74** + **38** = ____	High-Extraneous (HE)

2.3 Procedure

Given the individual alertness may affect the overall cognitive resources available (Galy et al., 2012), all experiments will be conducted in the afternoon. Participants alertness level will also be tested through Thayer's Activation–Deactivation Adjective Checklist (Thayer, 1978) before the experiment. To avoid the order effect, participants will be randomly assigned the eight types of task. The carry over effect will be minimized through a one-minute break between each two types of task and 500ms disturbing stimulus between adjoining tasks. Participants will be allowed enough time to practice the addition tasks and get familiar with the task variations as well as overall experimental settings. Then, they will be required to get the right answers as soon as possible so as to make sure the reaction time an effective indicator of their performance. The eight types of task will be assigned in a randomized order with each type containing 15 specific addition questions (see Figure 2). The whole procedure will last around 40-60 mins.

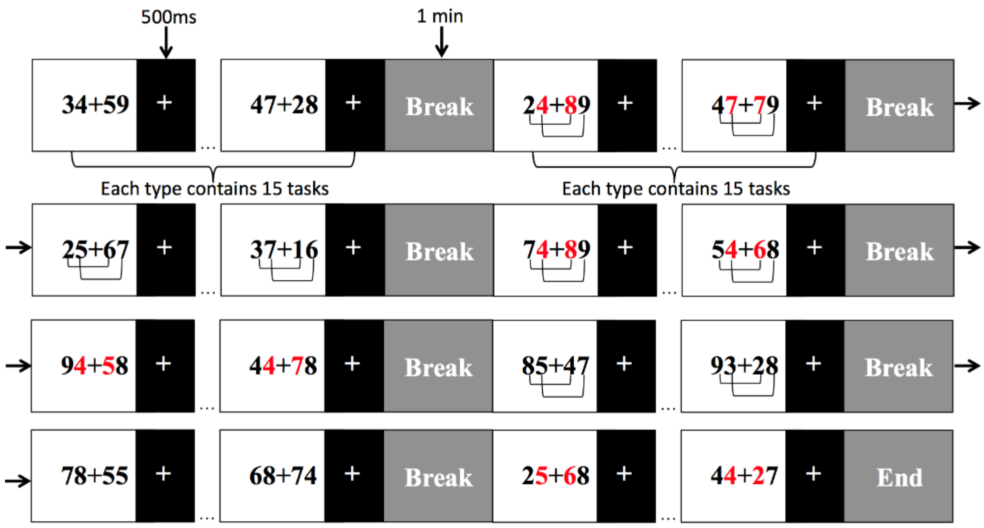

Figure 2 One example of the experiment procedure

2.4 Data collection

Individual's EEG waveforms during the execution of experimental tasks will be recorded. As to the measurement of learning performance, the reaction time and accuracy of each task will be collected. Other data includes participants' demographics information and their alertness level.

2.5 Data analysis

Data will be analyzed at both neural and behavioral levels to test my hypothesis through a three-way repeated measures ANOVA analysis.

In terms of neural activities, the cognitive load level will be measured through the theta frequency band of the prefrontal cortex. The spatial distribution and temporal change of the whole neural network triggered by mental calculation will also be systematically analyzed to check whether there're better component to represent the cognitive load of different tasks.

As to the behavioral level analysis, individual's performance will be used to indicate their cognitive load level. The overall performance will be calculated through the ratio of total number of correct task and total amount of reaction time. Given the expertise reversal effect (Kalyuga, Ayres, Chandler, & Sweller, 2003), I will adopt individual performance data in the low intrinsic, extraneous and germane cognitive load condition to represent their expertise level. The effectiveness of the germane cognitive load will firstly be checked to see whether it enhanced performance as designed. Otherwise it may become extraneous cognitive load due to high expertise.

3. Expected results and discussion

Main effects of the three types of cognitive load will be analyzed first. It was expected that intrinsic and extraneous cognitive load will negatively related with individual performance while the germane cognitive load will positively enhance the performance. However, the germane cognitive load condition may fail to generate positive effects on individual performance due to the expertise reversal effect. Therefore, it will be necessary to conduct a pilot study to check the task design whether they can generate different types and levels of cognitive load successfully.

As to the two-factor interaction, I expect that the effects of both germane and extraneous cognitive loads will be enhanced under the high level intrinsic cognitive load condition. If this was true, Sweller's (2010) additive interaction assumption will be confirmed. Besides, the power of germane cognitive load is expected to be enhanced during the high extraneous cognitive load condition. If this was also true, I could infer that the effect size of germane cognitive load depends on the overall level of both intrinsic and extraneous cognitive loads but not limited to the intrinsic cognitive load. Likewise, I could analyze the effect size of the extraneous cognitive load was also affected by the level of the germane cognitive load.

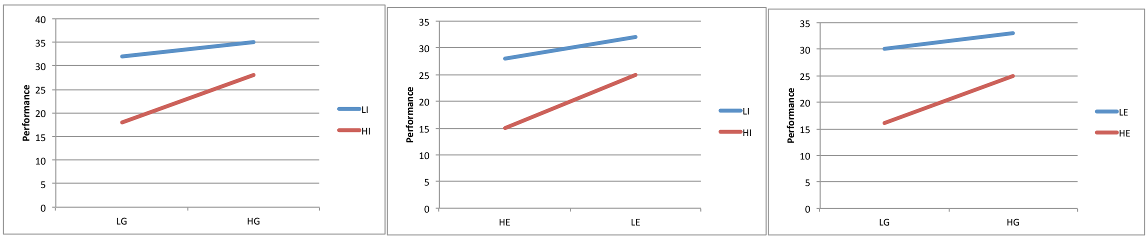

Figure 3 Expected two-factor interactions

I will further test whether there's a three-factor interaction so as to analyze how these three sources of cognitive load affect each other. In the end, I expect to give a revised formula on how to calculate the overall cognitive load based on the three separate cognitive load level.

All the above analysis will be conducted at both neural and behavioral level. It was expected that it will generate consistent results theoretically. If it was true, I could indicate the cognitive load measure through individual performance was sensitive this context, which was contradictory to the prior critic on the post-hoc performance measurement of cognitive load. This could be explained due to the simplicity of the tasks in this experiment which allow me to collect precise reaction time. Reaction time is a commonly used parameter in measuring secondary task cognitive load (Brünken et al., 2003). However, if there was any inconsistence, I would reflect further whether it was due to the neural amplitude data was not appropriate based on prior neuroscientific research on cognitive load, or it was due to the behavioral measurement was imprecise.

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