Exploring Heterogeneity of Individual Cognitive Workload and Capacity Limitations in a Consecutive Ascending Task

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Abstract. Cognitive work is a key factor in modern business. More knowledge about the diverse heterogeneity of distinctive learning characteristics, limited by respective cognitive resources, might improve learning outcome and will give valuable measures for human-computer interaction. The study explores individual differences by examining the differential reaction of the doubling of workload compared to the standard language processing demands. Both well-established findings for capacity limitations are observed conjointly here supporting the slot-like finite *and* the continuous resource model. A putative memory competition or capacity-sharing of working memory is suggested. Additionally, the differential approach shows and quantifies that individuals with lower cognitive abilities are more sensitive to an ascent of workload.

Keywords: cognitive capacity limits, individual variability, working memory (WM), cognitive workload.

1. Introduction and Aim

1.1 Intrinsic workload is not individual workload

Information processing of human brains involves learning and forgetting. As a highly complex task for our mental resources, it is profoundly restricted and determined by individual memory capacity (Barrett & Tugade 2004; Williams et al. 2008). However, current research discusses if item storage number is fixed or continuous giving rise to the slot-like or resource-like memory limitation theories (Endress & Szabó 2017; Wei et al. 2012).

Cognitive workload is defined as the mental resource that is necessary to perform a specific task. As the task intrinsic difficulty is unequal to the specific individual workload, mental workload varies among humans (Barrett & Tugade 2004; Williams et al. 2008). This individual effort defines if a person suffers from excessive cognitive workload “generated when the satisfactory performance of a task demands from the operator more resources than are available at any given time” (Gonzalez 2005).

1.2 Aim of study

The study focuses on the exploration of a two-step consecutive visual associated word-pairs task combining a first simple task with standard workload requirements, followed by a less simple memory task (complex) with doubled intrinsic complexity. The memorized word pairs of both tasks were not retrieved in-between resulting in a combined simple and a complex span task.

The study at hand aims to examine detailed baselines of the heterogeneity of individual cognitive workload limits. More knowledge about mental under- or overload prevents of situations where learning would become ineffective thus reducing errors and optimizing learning results.

2. Method development

2.1 Designing and measuring task complexity as Intrinsic Cognitive Workload

Language demands under normal or habitual standard conditions, in a sense of everyday use, are studied first. Two lists of word pairs (nouns) dealing with the topic "university", e.g. "student" or "admission requirement", are designed. Both lists are restricted to 7 word pairs following Miller (1956).

According to quantitative linguistics, the German language comprises 2.78 syllables/ word on average based on a German dictionary (Menzerath 1954) and 1.83 syllables/ word on average consulting the word frequency (Zipf 1968). In order to establish a memory baseline of standard language processing, word pairs of list L_0 are selected with approximately 2.5 syllables per word (simple).

However, research exists that the word length effect is also depending on lexical, linguistic and orthographic properties of word neighbors (Derraugh et al. 2017; Jalbert et al. 2011). It is therefore ensured here that the difficulty increase is distinctive enough from the daily spoken language so that the intrinsic workload is doubled in list L_1 to approximately 5 syllables per word (complex) to reduce these effects (see table 1). This doubling is a profound increase of intrinsic workload compared to *normal* or *typical* requirements of language processing with ~2.5 syllables as words with two syllables are utilized to 28.84%, words with three syllables to 12.93% and words with five syllables are only used to 1.82% regarding the word frequency in German language (Zipf 1968).

Table 1: *Number of syllables and letters of cue and target words of simple and complex list with intrinsic standard workload L_0 and doubled workload L_1.*

	syllables				letters			
	L_0 cue	L_0 target	L_1 cue	L_1 target	L_0 cue	L_0 target	L_1 cue	L_1 target
	3	2	5	4	8	7	16	14
	2	3	6	5	7	9	16	16
	2	3	4	6	9	9	15	15
	5	2	5	5	11	7	25	19
	1	2	7	7	6	5	23	20
	2	2	6	5	8	7	15	14
	3	3	5	4	8	9	14	16
sum	18	17	39	36	57	53	124	114
mean	2.57	2.43	5.57	5.14	8.14	7.57	17.71	16.29
median	2	2	5	5	8	7	16	16

In summary (table 1), list L_0 comprises a mean number of 2.5 syllables (cue 2.57 (8.14 letters); target 2.43 (7.57 letters)), list L_1 is designed with a mean number of 5.36 syllables (cue 5.57 (17.71 letters); target 5.14 (16.29 letters)).

2.2 Proactive/ retroactive interference and positional effects

Chosen cue and target words are unique, phonologically dissimilar and lists were immediately recalled to preclude effects of proactive and retroactive interference (Baddeley 1966; Campoy 2011). Because word span of the second list is doubled, word *length* similarity is eliminated as well to further reduce a neuronal competition of items. Positional primacy and recency effects are considered by mixing the sequence order in the retrieval section (Jahnke 1965; Oberauer 2003).

3. Results

In total, n=170 participants were tested in a self-paced trial; the two smallest samples were eliminated as outliers resulting in n=150. Mean age was 26.48 (standard deviation (sd) = 3.81; median = 26; 46% female (n=69)).

3.1 Word length effect and cognitive capacity limitations

Both well-established capacity limitations concerning simple and complex span for short-term memory and working memory are observed in this experimental setting. On average, 3-4 items are remembered in the respective *single* tasks in accordance with Cowan et al. (2001). However, 7 items (mean = 7.61; median = 7) are correctly associated on average when regarding the *sum* of both tasks denoting a profound tendency for an additive effect, reminiscent to *Miller's magical 7* (Miller 1956). Although intrinsic cognitive workload is doubled, the average decrease is 20.6% and the total reduction is only 0.87 items on average (table 2).

Table 2: *Average number of items (standard deviation is shown) recalled in L_0 and L_1 (n=150).*

	L_0	L_1	L_0+L_1	L_0-L_1
mean	4.24±1,8	3.37±2,16	7.61±3,39	0.87±2,09
median	4	3	7	1

3.2 Differential reaction and heterogeneity of individual workload

About 19.3% of participants achieved less than 30% (2±2 words) of the total sum of 14 correct words, 52% between 30% and 70% (7±2 words) and approximately 28.7% of participants accomplished more than 70% (12±2 items). About 19.3% (n=29) of individuals recalled 7 items correct in sum (modus), whereby the most frequent combination is {4;3} with n=13. Only ~5% (n=7) retained the maximum number of items (14) restricting further discrimination in this subgroup but denoting that an alignment to *Millers 7* is a suitable choice (see figure 1).

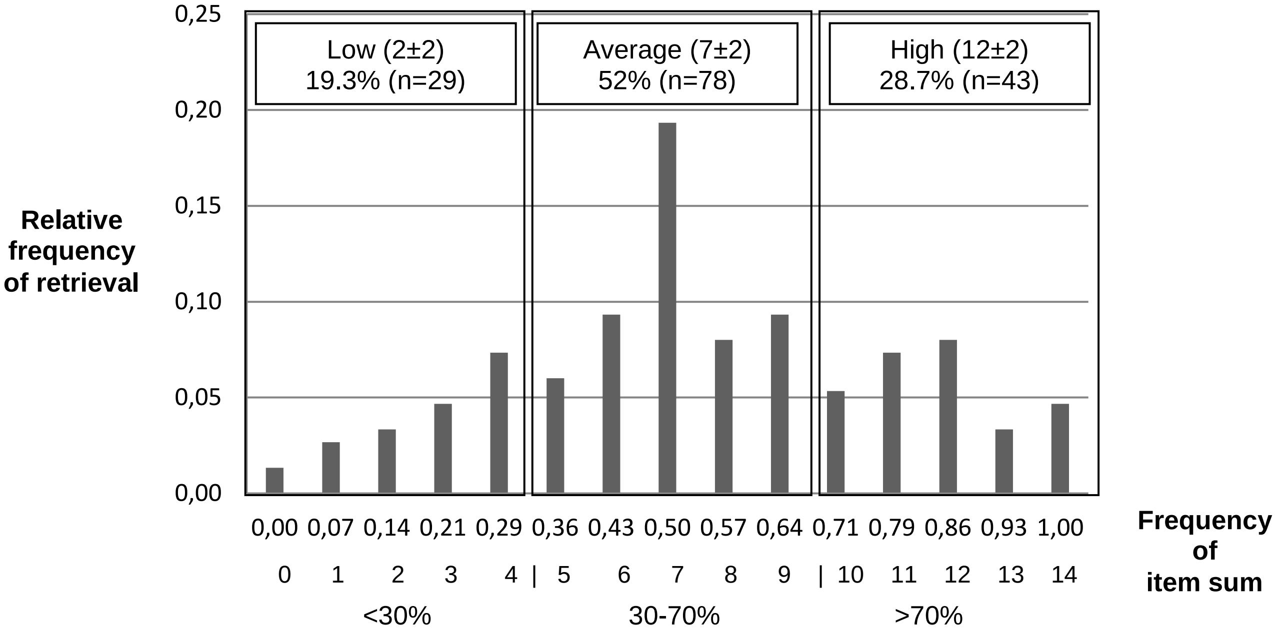

***Figure 1**. Sum of correct words of both tasks. Relative (upper line) and absolute (lower line) frequency of item sums; non-normal (Shapiro-Wilk) distribution right skewed with -0.023.*

3.3 Individuals with higher cognitive abilities are less sensitive to workload ascent

Even though the correct recall of the lowest sum of items from 1 to 3 denotes an increase of the proportion of L_1 (and a higher variability, data not shown), the sum of correct words of both lists from 4 to 14 items shows a clear convergence to a proportion from 0.318 to 0.5 for $L_1/(L_0+L_1)$ stating that with increasing memory ability the involvement of complex words from the second list increases (figure 2). The upper 25% (one quarter is n=38) recall on average 12 items, the bottom 25% only 3 items demonstrating the upper quartile to remember 4 times more words than the bottom quartile.

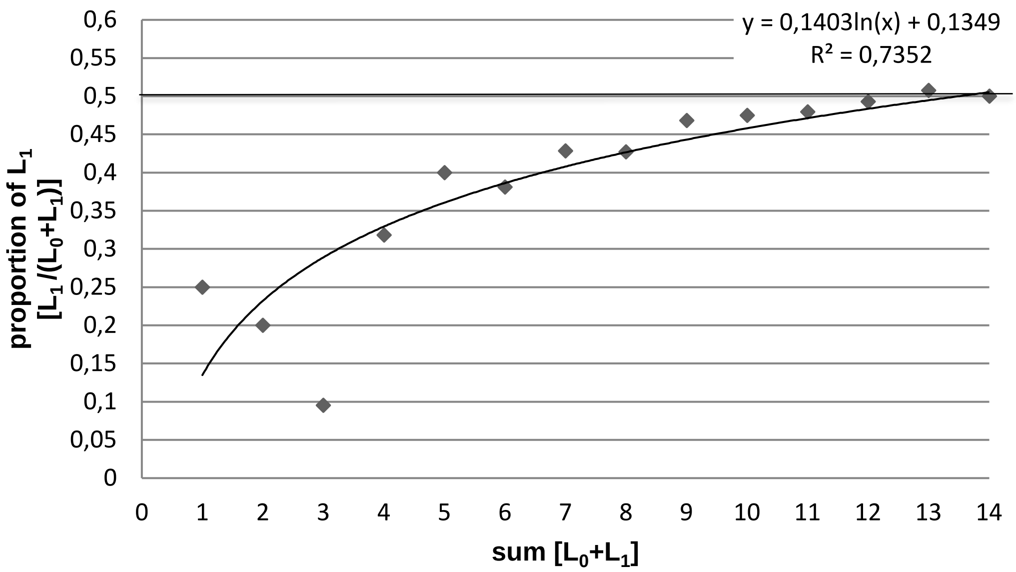

***Figure 2**. Logarithmic increase of L_1 proportion as a function of sum of correct items.*

4. Discussion

The goal of this study was to examine the heterogeneity of individual cognitive capacity by studying the differential reaction to a doubling of word complexity. The study demonstrates a higher sensitivity to workload ascent for individuals with lower cognitive ability and confirms the observations by Gonzalez et al. (2005).

The results show slot-like and resource-like memory limitations in one experiment. Both capacity limitations are discussed especially for the visual working memory (Barton et al. 2009; Donkin et al. 2016; Luck & Vogel 1997). Future analyses of the presented data might potentially contribute to this current debate (Endress & Szabó 2017; Wei et al. 2012).

It was anticipated here that memory ability determines the composition of recalled words from the respective lists profoundly. In contrast to the expectation, the proportion of complex words exhibited at least one third (~32%) for individuals achieving only 4 items in sum. Only n=20 participants (13.3%) accomplished all 7 simple words of list L_0, confirming that additional factors than word length alone are responsible for the partitioning in this consecutive setup. Overall, the doubling leads to a significant decrease of approximately 20% on average retrieval denoting that doubling word complexity of standard requirements modifies retrieval characteristics.

Regarding the experimental setup, there might be interference between the learned content (Endress & Szabó 2017). Although positional effects are minimized by excluding phonological similarity and mixing retrieval sequence, subsequent analyses will examine if specific items comprise advantageous storage properties, e.g. due to list position and/ or item complexity. Additionally, item and order error (transpositions), as well as the analyses of proactive and retroactive influences might give valuable insights.

5. Conclusion

It is confirmed and shown here that cognitive workload is highly heterogeneous and individually sensitive. The upper one fourth of participants remembers four times more items than the bottom quartile regarding a combination of simple words with the doubled complexity of standard language processing.

The complex interaction between the intrinsic task complexity, individual cognitive ability and personal characteristics determine the *quantity* and *content* of individual memory storage, thus more insight into the nature of the personal demands will result in more customized working environments (e.g. in human-computer interaction, user experience (UX) design) for the avoidance of excessive workload.

An open question is to clarify the role and extent of the co-occurring effects for a better understanding of individual differences of human cognitive work.

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