Towards Better Theories in Psychology: A Formalization Attempt of the New Theory of Disuse by Bjork and Bjork (1992)

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Introduction

Psychological theories are usually described in verbal form and lack precision. In this seminar, we sought to address this gap by devising a framework to translate verbal theories into mathematical models that enable us to derive precise empirical predictions and generate novel hypotheses for empirical research.

As learning is a fundamental component of human existence, the scientific investigation of learning processes has been a central focus within psychology for more than a century, resulting in the development of numerous learning theories. One notable theory is the New Theory of Disuse by Bjork and Bjork (1992), which explains learning and forgetting through a complex interplay between two constructs named retrieval strength and storage strength.

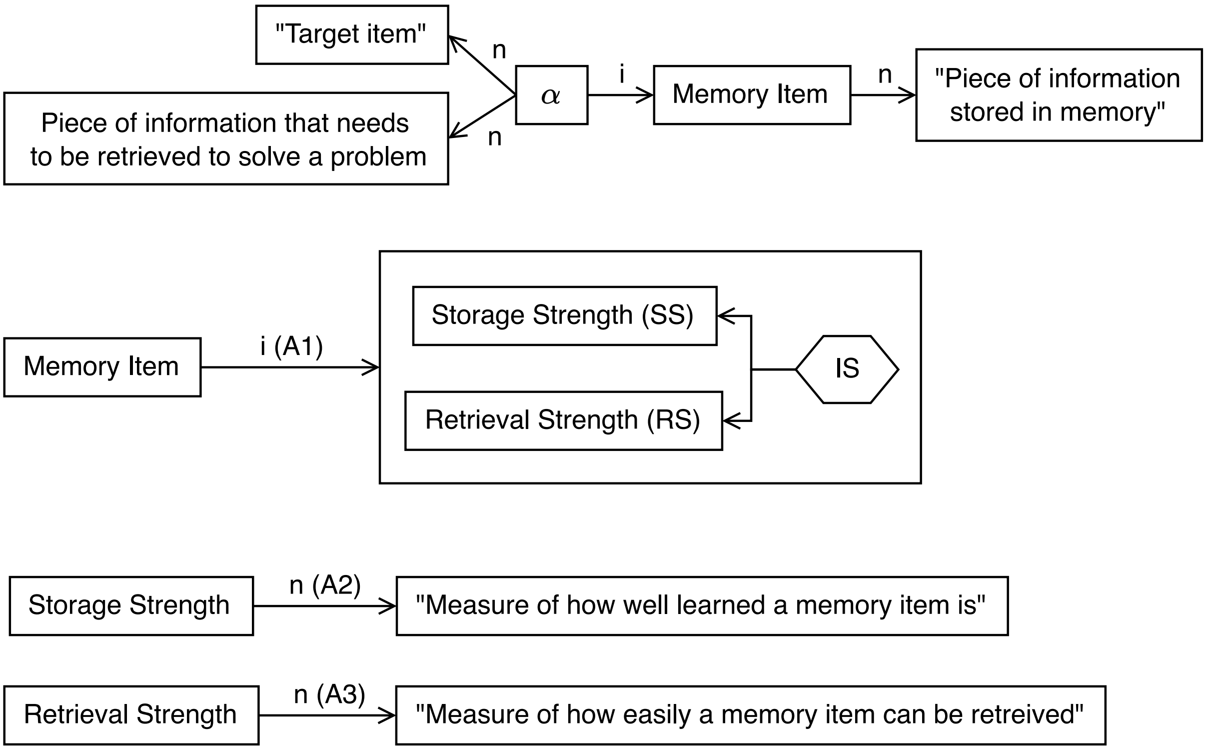
In this paper I present these key constructs and their theoretical relationships and then attempt to formalize this theory into a mathematical model. As connecting piece between verbal and mathematical model, displays of the Visual Argument Strucutre Tool (VAST; Leising et al., 2023) will be used throughout the paper. Finally, to evaluate the model, I examine the theory's capacity to explain two well-documented learning phenomena known as the spacing effect and the retrieval practice effect. The associated GitHub project with this paper is accessible at: https://github.com/deminok/disuse-theory-formalization.

New Theory of Disuse by Bjork and Bjork (1992)

The theory revolves around memory items, i.e. pieces of information stored in memory. What memory items are retrievable at a certain point in time is dictated by the cues (i.e. environmental, interpersonal, emotional, or physical) available at that point in time (Bjork & Bjork, 1992, p. 42). For a lack of definition in the literature, I define a target item α as a piece of information that needs to be retrieved to solve a problem.

Each memory item has two properties: Storage strength (SS) and retrieval strength (RS). Storage strength is a measure of how well the item is learned. Retrieval strength is a measure of how easily the item can be accessed, i.e. retrieved from memory (Bjork & Bjork, 1992, p. 42). Retrieval strength can be thought of as how activated a memory item is in response to a set of cues and expresses the probability that a memory item can be retrieved successfully (Lang et al., 1999, p. 82). See Figure (1) for a VAST display of these central constructs.

Figure 1
VAST display of central constructs of the New Theory of Disuse (Bjork & Bjork, 1992)



Note: See Table (A1) for the quotes referenced in parentheses on the arrows.

Learning events, either study (e.g. reading) or retrieval (e.g. testing), increase an items storage strength and retrieval strength while retrieval strength declines over time with disuse of that item (Lang et al., 1999, p. 82). The core of the theory is a set of assumptions how storage strength and retrieval strength interact with each other to influence growth and loss of the two strengths. I will expand on these interactions later.

Obviously, the human memory system is limited in its capacity. According to the theory, storage strength is never lost, hence the human memory is assumed to have an unlimited storage capacity. Instead, the human memory is assumed to have a limited retrieval capacity, that is, a finite number of memory items that can be retrieved from memory at a point in time (Bjork & Bjork, 1992, p. 42). Memory items compete for retrieval capacity, where retrieval strength of one memory item decreases as a result of studying and retrieving other memory items. When one memory item gains retrieval strength, other memory items that share the same retrieval cues lose retrieval strength, making it less retrievable in the future (Lang et al., 1999, p. 82).

The Spacing and Retrieval Practice Effect

According to the definition by Latimier et al. (2021), "Distributed learning or spacing refers to the deliberate insertion of lags between learning episodes on the same content" (p. 960). The spacing effect states that inserting time intervals between two study sessions lead to better retention of the studied material compared to massed practice, where the material is studied in only one session.

Recent meta-analyses report effect sizes for the spacing effect of $d = 0.85$ in verbal tasks (Wiseheart et al., 2019) and $d = 0.71$ in motor and performance tasks (Hattie, 2009).

Latimier et al. (2021) define retrieval practice as "any activity that requires the learner to retrieve previously learnt information from memory" (p. 960). Typical retrieval practice exercises include free or cued recall and multiple choice questions.

Recent meta-analyses confirm that retrieval practice is superior to learning styles that do not include retrieval such as re-study or reading. Rowland (2014) report a Hedges $g = 0.50$ based on 159 independent effect sizes. Adesope et al. (2017) report a mean effect size of $g = 0.61$ based on 272 independent effect sizes.

Regarding the generalizability of these effects, the findings from the meta review by Carpenter et al. (2022) suggest that the effects have been observed across different units, treatments, outcomes, and settings, in line with the UTOS framework (Cronbach & Shapiro, 1982).

First off, the effects have been demonstrated across different age groups ranging from preschool children through all levels of formal education to adults older than 50 years old. There seems to be a lack of data for people with no tertiary education. Second, the included studies eployed a large variety of learning techniques (e.g. reading, summarizing, practice testing), hence the effects are not limited to a specific learning method. Third, the studies employed different measures to assess the learning effect. These measures included performance in cued and free recall, multiple-choice, and free answer tests, recognition tests, and motor skill tests indicating that the effects are not dependent on a specific measure of the outcome. Lastly, the effects have been observed in various settings, including learning of factural knowledge from different subjects and work environment (e.g. medical and engineering) and general learning of word pairs or image pairs. Also, studies with different ethnicities, nationalities and cultural contexts are included in the review. This suggests that the spacing effect and retrieval practice can be applied in different contexts and has the potential for broad applicability.

Formal Model of the New Theory of Disuse

In this section I will begin to formalize the interactions between storage strength and retrieval strength and outline how the theory explains the spacing effect and the retrieval practice effect. Figure (2) shows a VAST display of these interactions.

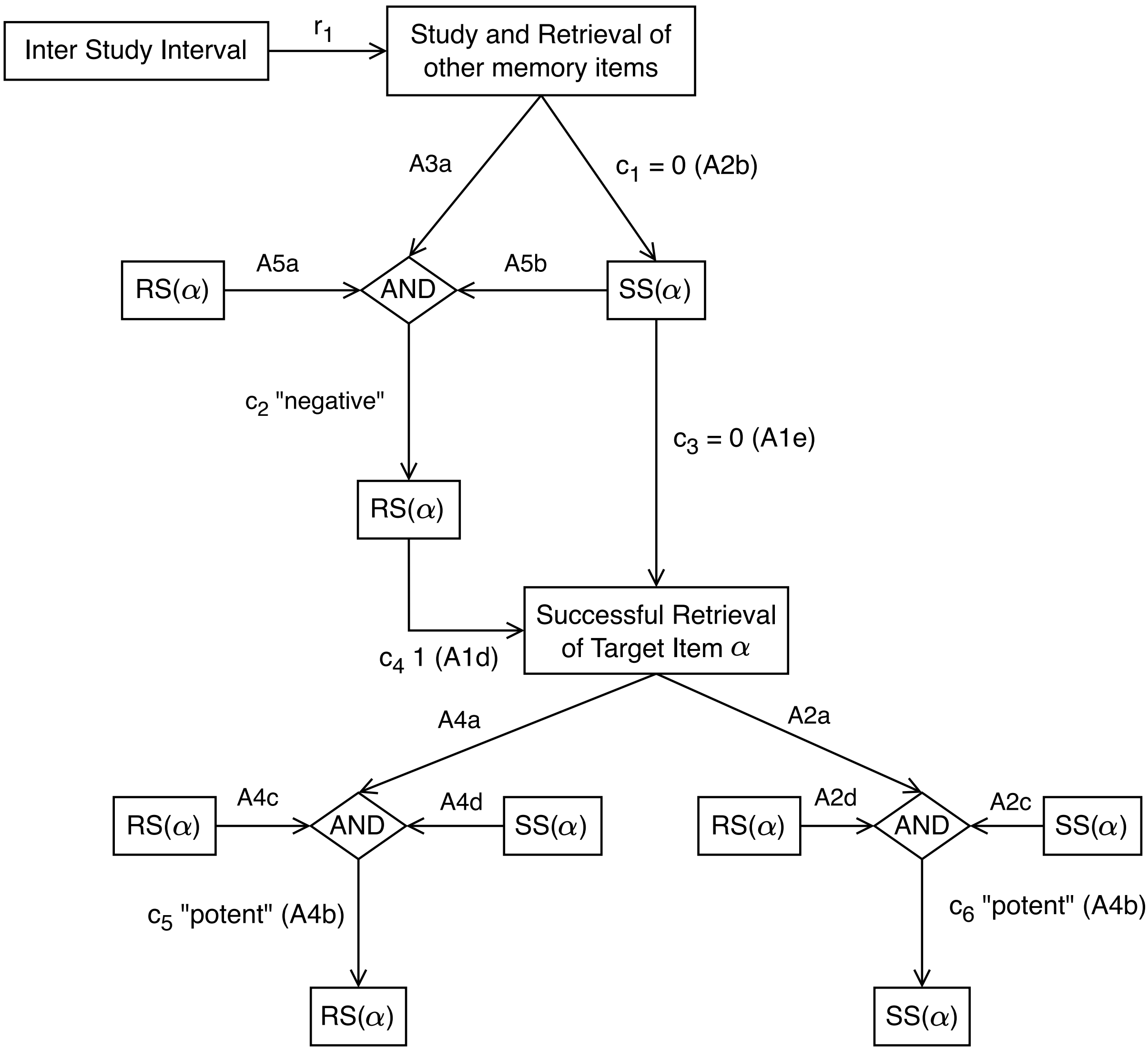
According to Bjork and Bjork (1992) retrieval strength decreases (c_2) as a result of study and retrieval of other items in memory (cf. A3a). It is reasonable (r_1) to assume, that during an inter study interval of arbitrary length study and retrieval of non-target items in memory takes place. The decrement in retrieval strength depends on the current levels of storage strength and retrieval strength. Retrieval strength declines faster when the item currently has high retrieval strength and it declines slower when the item currently has high storage strength.

Storage strength is assumed to never decline once accumulated (cf. A2b), hence any study and retrieval of other items has no effect (c_1) on storage strength of the target item.

According to the theory, successful retrieval of the target item from memory depends only on its current retrieval strength (c_4, cf. A1d) and is assumed to be independent of the item's storage strength (c_3, cf. A1e).

Figure 2

VAST display of New Theory of Disuse (Bjork & Bjork, 1992)



Note: SS = storage strength, RS = retrieval strength, α = target item. See Table (A1) for the quotes referenced in parentheses on the arrows.

Successful retrieval is described as a potent learning event ($c_{5,\,6}$, cf. A4b), resulting in greater increments in storage and retrieval strength compared to studying the item, although both learning events follow the same mechanism.

The increment in retrieval strength depends on the current levels of the two properties. When the item has high storage strength, i.e. it is well learned, the increase in retrieval strength is larger. When the item has low retrieval strength, the act of retrieving the item is more effortful which results in larger increments in retrieval strength.

The increment in storage strength also depends on the current levels of both strenghts. When the item currently has high retrieval strength (cf. A2d) the increase in storage strength following successful retrieval will be lower. When the item currently has high storage strength (cf. A2c), i.e. it is well learned, the accumulation of further storage strength is slower.

Taken together, the theory explains the two phenomena as follows. During the inter study interval retrieval strength of the target item decreases due to study and retrieval of other items stored in memory. The lower retrieval strength at the next learning event leads to a greater increase in storage strength which results in a slower decline in retrieval strength in the subsequent inter study interval. This leads to longer retention of the studied material, hence the spacing effect.

Retrieving an item from memory results in a greater increase in storage and retrieval strength compared to studying an item because during retrieval more effort is required to access the item in memory.

Both of these phenomena underlies the idea that more effort leads to more learning. When retrieval is effortful, it requires deeper cognitive engagement forcing the brain to more elaborate encoding which strengthens the memory trace making it more resistant to forgetting (Bjork, 1994, p.192).

Mathematical Model of the New Theory of Disuse

In the following section I develop a mathematical model of the interactions between storage strength, retrieval strength and learning events. See Table (1) for the variables used in the model and Table (A1) for the referenced statements from the original paper by Bjork and Bjork (1992). Going forward, index t refers to the current (input) value of a variable and $t+1$ refers to the updated (output) value.

The first functional relationship describes the decrease in retrieval strength during an inter study interval. As a simplification, this will be a function of time alone, assuming that during this time uniform study and retrieval of other items takes place. Together with statement A3a, retrieval strength decreases as a function of time, denoted in days (d). Statement D1 adds that retrieval strength declines

Table 1
List of Variables in Formal Model

Construct	Scale Level	Range	Anchors
storage strength (SS)	continuous	$[0, \infty[$	0 = item not stored in memory
retrieval strength (RS)	continuous	$[0, 1]$	0 = item cannot be retrieved from memory 1 = item can 100% be retrieved from memory

asymptotically to zero, therefore an exponential decay function seems plausible. According to A5a, retrieval strengh declines faster, when the item currently has high retrieval strength. Inversely, storage strength is said to slow the decrease in retrieval strength, according to statement A5b. The function

$$RS_{t+1}(d) = RS_t \cdot \exp\left(-d \cdot RS_t \cdot \frac{1}{SS_t}\right) \tag{1}$$

will be used to model these relationships. In Figure (3) curves for three memory items with different values of RS and SS are displayed following this equation.

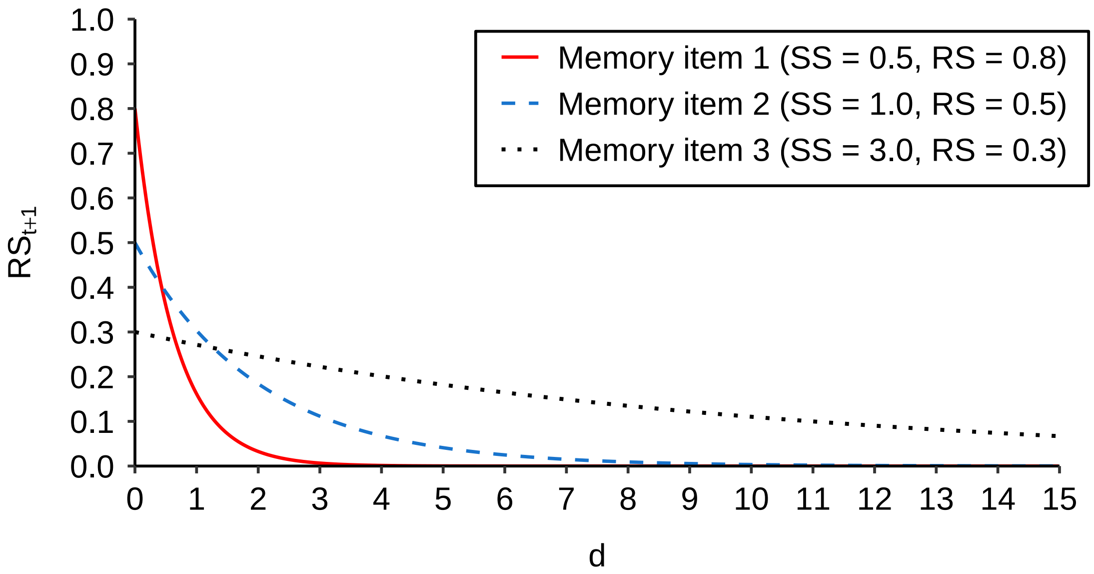
The second functional relationship describes the increase in storage strength after a successful learning event, i.e. study or retrieval. According to statement A2a, storage strength grows monotonically in response to a learning event. Following A2d, this growth in storage strength is inversly proportional to the item's current retrieval strength. High retrieval strength means it is easy to retrieve the item from memory, resulting in lower gains to storage strength. Higher levels in storage strength also retard the growth of additional storage strength. A function that has these characteristics is the following:

$$SS_{t+1} = SS_t + \frac{b}{SS_t \cdot RS_t} , \tag{2}$$

where b is a compression factor that could model individual differences and

Figure 3

Change in retrieval strength over time of three memory items



differentiate the potency of study and retrieval events (cf. A4b). See Figure (4) for the curves of two memory items.

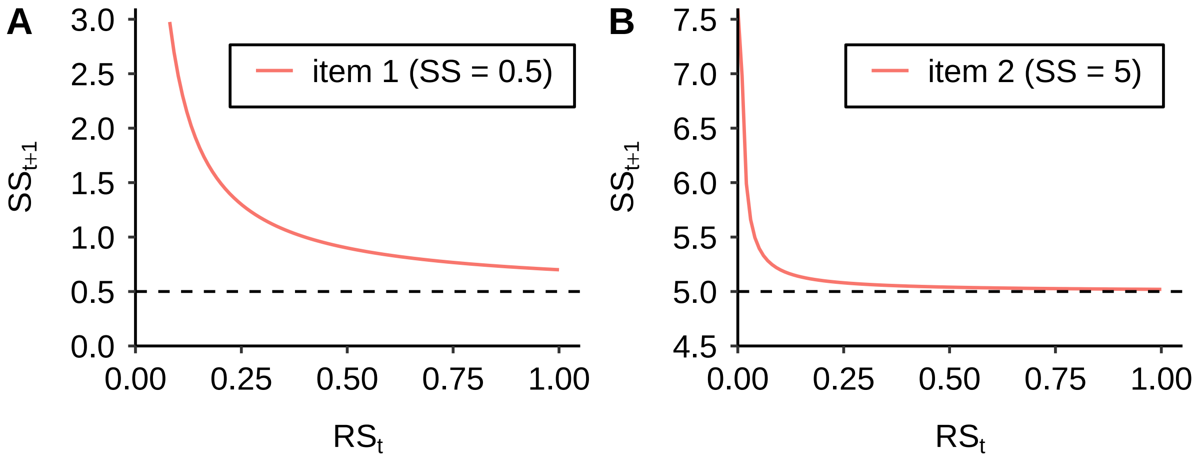
The third functional relationship desribes the increase in retrieval strength after a learning event. Following statement A4c, increments in retrieval strength are higher when the item currently has low retrieval strength and according to A4d are higher the higher the current storage strength of the item. I assume the following linear function to model the increment in retrieval strength:

$$RS_{t+1} = \frac{1}{c \cdot SS_t} \cdot (RS_t - 1) + 1 \,, \tag{3}$$

where c is a compression factor that could model individual differences and differentiate the potency of study and retrieval events. Figure (5) demonstrates the uplift in retrieval strength for two memory items.

Figure 4

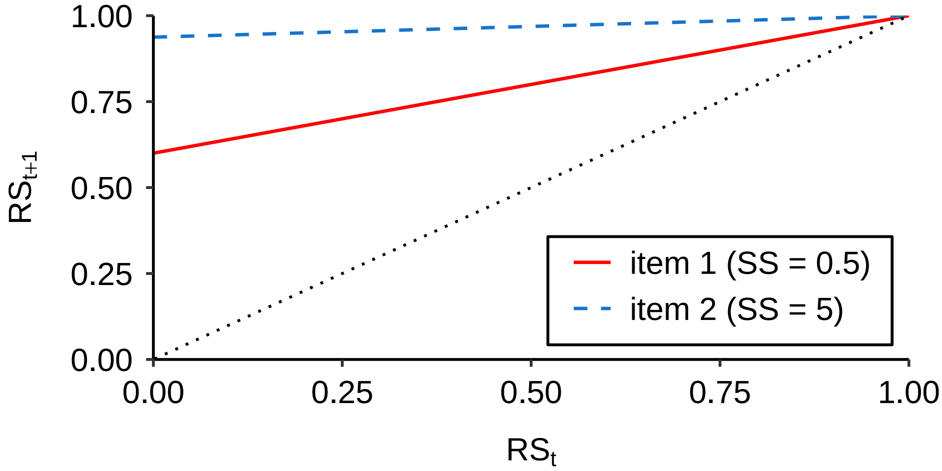
Change in storage strength following a learning event



Note: Dashed lines represent storage strength of the two items before learning, $b = 0.1$.

Figure 5

Change in retrieval strength following a learning event

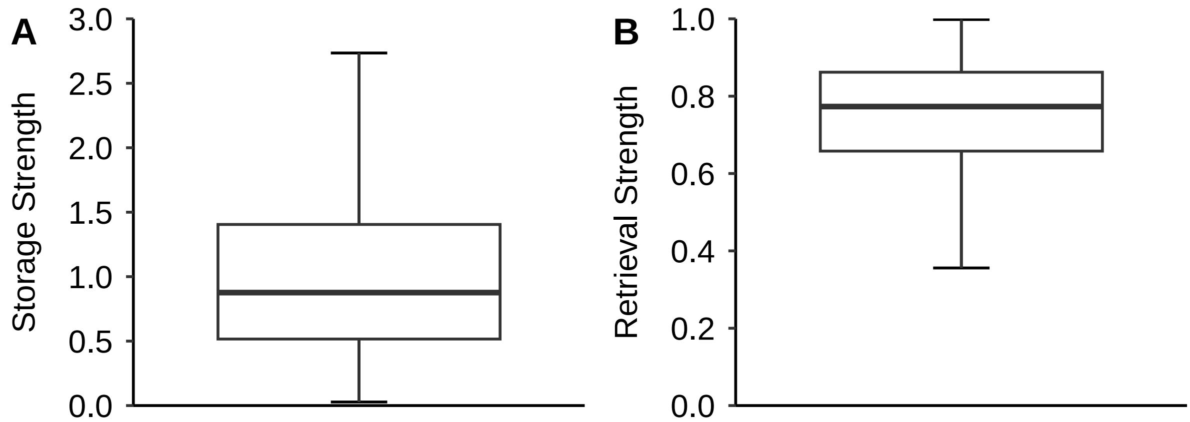


Note: The net increase in retrieval strength is the distance between the dashed line and the line for either memory item, $c = 3$.

Evaluation of the Formal Model

To evaluate the formal model, I ran two experiments with simualted data to see whether the model could reproduce the spacing effect and the retrieval practice effect. I simulated 4,000 memory items and initialized them with random levels of storage and retrieval strength within a range I deemed plausible after initial learning to account for interindividual differences in learning speeds. See Fig. (6) for a distribution of these two properties.

Figure 6
Initial values in SS and RS of simulated memory items



Note: **A** simulated data for storage strength is based on a beta distribution with p = 12 and q = 3. **B** simulated data for retrieval strength is based on an F distribution with params df1 = 5 and df2 = 15.

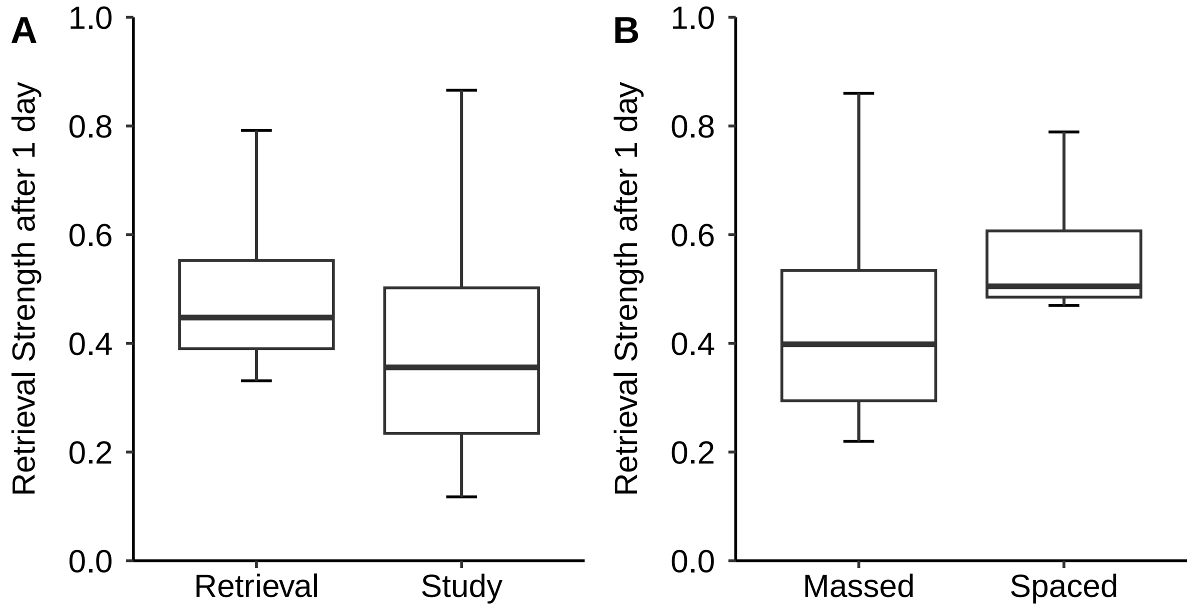
To differentiate the effects of study and retrieval events, the compression parameters for the functions were set as $b_{\text{study}} = 0.05$ and $b_{\text{retrieval}} = 0.2$ for the increase in storage strength and $c_{\text{study}} = 3$ and $c_{\text{retrieval}} = 5$ for the increase in retrieval strength making the retrieval event more potent. All 4,000 memory items were distributed equally to one of four experimental groups. Mean retrieval strength 1 day after the final learning event was used as a proxy for final test performance.

In experiment 1, I sought to reproduce the retrieval effect. Group 1 ("Study") was simulated to perform a study event immediately after initial exposure and Group 2 ("Retrieval") was simulated to do a retrieval event immediately after initial exposure. Comparing group mean differences in retrieval strength after 1 day, there was a significant difference between the study group (M = 0.38, SD = 0.18) and the retrieval group (M = 0.48, SD = 0.11); t(1693.6) = 14.725, p < .001. Hedge's g was estimated as 0.66 which is very close compared to the published effect sizes of g = 0.5–0.61. See Fig. (7 A) for a graphical comparison of these results.

One simplification in experiment 1 is that I ignored the probability whether a memory item was retrieved successfully (i.e. a probabilistic function of its retrieval strength). Instead, I assumed that the retrieval of the target item was always successful.

In experiment 2, Group 1 ("Massed") was simulated to do 4 study events with no break in between immediately after initial exposure to the items. Group 2 ("Spaced") did spaced study events after 1, 3, 5 and 7 days. Again, comparing group mean differences in retrieval strength 1 day after the last study event showed a significant difference between massed study (M = 0.43, SD = 0.15) and spaced study (M = 0.58, SD = 0.14); t(1813.2) = -26.011, p < .001. Hedge's g was estimated as -1.01 which is also close to the published effect sizes of g = 0.71–0.85. See Fig. (7 B) for a graphical comparison of these results.

Figure 7
Group differences of experiments 1 and 2



Note: Results of experiment 1 left, results of experiment 2 right

Discussion

Initially, I found the New Theory of Disuse relatively easy to formalize, as **1992** already described the relationships between storage and retrieval strength in a formal, almost mathematical way. Also, the entire theory is based on just two constructs which seemed simple at first. Understanding the interactions between storage strength and retrieval strength and their combined effect during learning events turned out to be complex. Transforming these interactions into mathematical functions was feasible as the authors were sufficiently specific in how the formulas should look.

The only gap I stumbled upon in the formalization is that the theory did not include an assumption or prediction of what would happen in the case of an unsuccessful retrieval of the memory item. It remains unclear, whether this would lead to a decrease or marginal increase in storage and retrieval strength or no change in either strength. Therefore, in my formalization I included the unrealistic assumption that retrieval would always be successful, even if a memory item had a very low retrieval strength.

I struggled most in fitting the parameters of the functionans to plausible values of and changes in storage and retrieval strength. The concept of storage strength is especially difficult to grasp. Assigning values to questions such as "What storage strength does a memory item have after I studied it once?" seemed arbitrary. Retrieval strength was easier to think about in that regard, as the questions such as "After 1 day, what's the probability I could still remember a piece of information?" were easier to answer based on my own experience.

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Appendix

Table A1

Key Quotes from Literature for VAST Displays

ID	Quote from original paper	Reference
A1a	item in memory can be characterized by two "strengths," a storage strength and a retrieval strength.	Bjork and Bjork (1992, p. 42)
A1b	Storage strength measures, in a general way, how well learned an item is	Bjork and Bjork (1992, p. 42)
A1c	Retrieval strength measures the current ease of access to the item in memory	Bjork and Bjork (1992, p. 42)
A1d	The probability that an item can be recalled in response to a given cue is completely determined by its retrieval strength	Bjork and Bjork (1992, p. 42)
A1e	The probability that an item can be recalled in response to a given cue is independent of its storage strength	Bjork and Bjork (1992, p. 42)
A2a	The storage strength of a given item grows as a pure accumulation process, that is, as a monotonic function of opportunities to study or recall that item	Bjork and Bjork (1992, p. 42)
A2b	[...] it is assumed that storage strength once accumulated is never lost.	Bjork and Bjork (1992, p. 42)
A2c	The increment in storage strength for a given item owing to a study or test event is assumed to be a decreasing function of its current storage strength	Bjork and Bjork (1992, p. 42)
A2d	[...] the increment in storage strength is a decreasing function of its current retrieval strength; that is, high retrieval strength is assumed to retard the accumulation of additional storage strength.	Bjork and Bjork (1992, p. 43)
A3a	[...] retrieval strength [...] is lost as a function of subsequent study and test events on other items.	Bjork and Bjork (1992, p. 43)
A4a	The act of retrieving an item from memory, and the act of studying an item, both result in increments to that item's retrieval strength as well as to its storage strength [...].	Bjork and Bjork (1992, p. 43)
A4b	Retrieval is the more potent event, [...] the act of retrieving an item (successfully) results in larger increments to storage strength and retrieval strength than does studying an item.	Bjork and Bjork (1992, p. 43)
A4c	Increments in retrieval strength [...] are assumed to be a decreasing function of an item's current retrieval strength. The increments [...] are larger the more dillicult or involved the act of retrieval (low retrieval strength)	Bjork and Bjork (1992, p. 43)
A4d	Increments in retrieval strength [...] are assumed to be an increasing function of its current storage strength. The increments [...] are larger the better registered the item is in memory (high storage strength).	Bjork and Bjork (1992, p. 43)

A5a	The decrement in an item's retrieval strength owing to the learning or retrieval of other items is [...] assumed to be greater the higher the item 's current retrieval strength	Bjork and Bjork (1992, p. 43)
A5b	The decrement in an item's retrieval strength owing to the learning or retrieval of other items is [...] assumed to be lower the item's current storage strength.	Bjork and Bjork (1992, p. 43)
D1	Retrieval strength declines over time to an eventual asymptote of zero	Bjork and Bjork (1992, p. 60)