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Repetition priming for multisensory stimuli: Task-irrelevant and task-relevant stimuli are associated if semantically related but with no advantage over uni-sensory stimuli

David Hecht[a,b,*], Miriam Reiner[a], Avi Karni[b]

[a]The Touch Laboratory, Department of Education in Technology and Science, Technion - Israel Institute of Technology, Haifa, Israel
[b]The Brain-Behavior Research Center, Department of Neurobiology and Ethology, Faculty of Science and Science Education, University of Haifa, Haifa, Israel

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ABSTRACT

Signals presented simultaneously in two sensory modalities are detected faster and more accurately than their uni-modal presentations. We investigated the effect of repeated experience in successive test blocks (Repetition Priming, RP) for simultaneously presented multi-sensory stimuli, as compared to uni-sensory, visual, stimuli. Participants had to decide whether the order of letters in two letter-strings (the visual stimulus) was reversed or not. The visual stimuli were presented alone or accompanied by a task-irrelevant auditory or a haptic signal. The letter-strings denoted words that were either semantically related or unrelated to the auditory or haptic signals. RT measurements showed significant RP across all conditions, with accuracy at ceiling. The RP gains were not significantly different for the uni- and the bi-sensory stimulus combinations in the initial three blocks. However, in the 4th block, where instead of the paired bi-sensory stimuli the previously paired visual stimulus was presented alone, the RP gains were significantly smaller in the semantically-related stimuli (disassociation cost). Congruent bi-sensory stimuli had been shown to improve perceptual learning compared to uni-sensory stimuli when both signals were task-relevant. Our results suggest that when an additional signal, in a different sensory modality, is irrelevant for the task's performance, there may be no advantage – in terms of greater RP gains – for multisensory stimuli. Nevertheless, semantically related stimuli experienced simultaneously in different sensory modalities may be represented in an associative manner in implicit memory even when only one stimulus is task-relevant.

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1. Introduction

Multi-sensory signals presented simultaneously can be detected at lower thresholds, faster and more accurately compared to the same signals presented separately in each sensory modality (Hershenson, 1962; Miller, 1982; Stein et al., 1996; Odgaard et al., 2004; Hecht et al., 2008a,b). Multi-sensory experiences can also be better remembered compared to single-sensory events. Animal studies had shown that a signal presented in one sensory modality is learned faster and may have a greater chance to be retained in long-term memory if accompanied by other signals in a different

* *Corresponding author*. The Touch Laboratory, Gutwirth Building, Technion - Israel Institute of Technology, Haifa, 32000 Israel. Fax: +972 4 8226783.
E-mail address: davidh@tx.technion.ac.il (D. Hecht).

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modality. For instance, the quality of nightingales' singing was improved and their song repertoire was greater if during the tutoring sessions the auditory exposure to the songs was accompanied by light pulses (Hultsch et al., 1999). Similarly, quail embryos exposed to maternal assembly call did not show, after hatching, a preference for the familiar call. However, if during the learning stage the call was accompanied by a flashing light the chicks preferred it over an unfamiliar call (Lickliter et al., 2004). The same effect in the opposite direction – improved memory and learning of a *visual* signal if accompanied by a *sound* – was also demonstrated in chicks trained to find food under specific-colored cones. An accessory tone improved the speed of color-discrimination learning (Rowe, 2002). Similarly, in *Drosophila* flies learning to associate a visual or an olfactory signal with a punishment, it was found that conditioning with bi-sensory visual and olfactory cues reduced the threshold for uni-sensory memory retrieval. Furthermore, bi-sensory pre-conditioning followed by uni-sensory conditioning with either a visual or olfactory cue led to cross-sensory memory transfer (Guo and Guo, 2005).

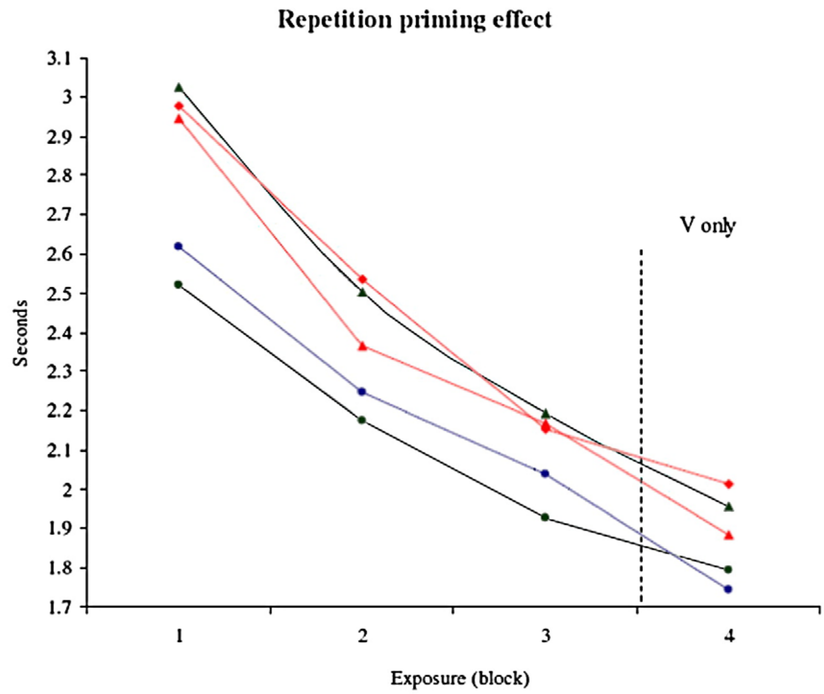
Studies in humans reported that news stories presented audio-visually (e.g. text or images as in a TV format) were remembered better, with more details, than in conditions in which only uni-sensory, audio or visual, stimuli were presented, however this multisensory enhancement in memory may characterize young adults but not older individuals (e.g., Stine et al., 1990; Frieske and Park, 1999). A similar enhancement of memory by multi-sensory stimuli was reported in laboratory studies. Laboratory-created 'events', in which participants were presented with a list of words, were found to be better recalled when they were initially presented bi-modally (visual and auditory) than words presented uni-modally (Kobus et al., 1994; Lewandowski and Kobus, 1993; Martin, 1980). Likewise, images presented with semantically corresponding words or sounds (e.g. a bell image paired with a "dong" sound) were remembered in higher proportions than visual images presented alone (Murray et al., 2004; 2005; Lehmann and Murray, 2005; Goolkasian and Foos, 2005). Recent studies on perceptual learning (long-term implicit memory) reported that visual motion coherence detection learning improved significantly when a congruent auditory cue was added compared to training in a visual-only condition (Seitz et al., 2006; Kim et al., 2008). The auditory signal comprised an additional salient indication for the direction of motion and, despite being in a sense redundant, provided a relevant cue for optimally performing the task (Seitz et al., 2006; Kim et al., 2008).

The current study was designed to test whether multi-sensory stimuli would show an advantage, over uni-sensory stimuli, in repetition priming. Specifically, we studied multi-sensory stimulus pairs in which one stimulus was task-irrelevant, but nevertheless could be either semantically related or unrelated to the task-relevant stimulus. Repetition priming refers to the effects of a prior presentation of a stimulus (the prime) on the processing of a subsequent stimulus (the target). The priming effect is expressed as faster and often more accurate performance on the target. For example, recent observations of objects or words can speed up their subsequent identification and classification (Tulving and Schacter, 1990). Participants in the current study were exposed to visual stimuli (letter-string pairs) several times, once in each block in a sequence of test blocks. The task was to make a decision about the visual stimuli. However, some of the visual stimuli were accompanied by an auditory or a haptic signal, which could be either semantically related to the visual word or not, but always task-irrelevant. We investigated whether the magnitude of the repetition priming effect for trials with bi-sensory audio-visual and haptic–visual stimuli may be greater than for trials with uni-sensory visual stimuli. Second, we tested whether stimuli initially experienced bi-modally are implicitly associated so that when the association is subsequently broken and the task-relevant stimulus is presented alone, a 'dis-association cost' in terms of smaller repetition gains, will occur. The difference between uni-sensory and bi-sensory stimuli was expected to be larger when a semantic relationship existed between the bi-sensory stimuli.

2. Results

Two participants failed to show repetition priming in the initial blocks in the bi-sensory conditions and were excluded from the analysis ($n=38$). Participants' responses were accurate at 97% of trials. The errors were distributed without significant differences between the five modality-combination conditions. Mean RT (in seconds) for correct responses in the four exposures (test blocks) in the uni-sensory and the different bi-sensory conditions are summarized in Fig. 1. The data were analyzed by a two-way repeated measures ANOVA with stimulus combinations (V, AV+, AV−, HV+, HV−) and the number of exposures (blocks 1–4) as within-participant factors (Greenhouse-Geisser correction was used for violation of sphericity). There were significant main effects for both blocks [$F_{(3,111)}=107.63$, $p<.0001$] and the stimulus combinations [$F_{(4,148)}=28.45$, $p<.0001$]. The interaction between blocks and stimulus combinations was also significant [$F_{(12,444)}=2.19$, $p<.05$]. However, because the fourth block was different (only visual uni-sensory stimuli were presented in all stimulus combinations), a second repeated-measures ANOVA was run on the initial 3 blocks. Again, there were significant main effects for both blocks [$F_{(2,74)}=96.91$, $p<.0001$] and stimulus combinations [$F_{(4,148)}=24.4$, $p<.0001$]. The interaction between blocks and stimulus combinations was not significant. To study the effects of switching from the repeated bi-sensory conditions to a uni-sensory (visual-only) condition an additional repeated measures ANOVA was run comparing the performance in the 3rd and 4th blocks. There were significant main effects for both blocks [$F_{(1,37)}=37.51$, $p<.0001$] and the stimulus combinations [$F_{(4,148)}=13.92$, $p<.0001$]. The interaction between blocks and stimulus combinations was also significant [$F_{(4,148)}=2.52$, $p<.05$]. Altogether, the analysis indicated a significant difference in the response times to different stimulus conditions as well as a significant priming effect across all conditions. There was also an indication that the rate of improvement in the 4th block may have been dependent on stimulus condition.

As can be seen in Fig. 1 there were differences in the initial RT (1st exposure) between the stimulus combinations.



V	2.617 ± 0.741	2.246 ± 0.806	2.038 ± 0.650	1.743 ± 0.449
AV+	2.522 ± 0.659	2.176 ± 0.624	1.925 ± 0.585	1.792 ± 0.503
HV+	2.976 ± 0.865	2.535 ± 0.762	2.155 ± 0.644	2.013 ± 0.585
AV-	3.023 ± 0.823	2.501 ± 0.698	2.193 ± 0.630	1.956 ± 0.480
HV-	2.946 ± 0.891	2.367 ± 0.662	2.169 ± 0.709	1.885 ± 0.543

Fig. 1 – Mean response times on the 1st–4th exposures for uni- and bi-sensory stimuli.

Because different words were used in each stimulus combination (see Appendix 1), it may be the case that factors such as differences in the words' length or their frequency in the Hebrew language, or the position of the unmatched letters (i.e., 2nd letter vs. 5th letter), may account for the significant stimulus combination effect. In order to control for possible word/list effects on the absolute RT in the different conditions, the proportion of time gained in each successive repetition relative to the mean RT in the initial block (1st exposure to the stimuli) was calculated for each participant, for each stimulus combination condition. Table 1 presents the group average of these proportional gains.

2.1. *Repetition priming effect*

A repeated-measures ANOVA for the time gained in the 1st and 2nd repetitions relative to initial performance (comparing the 1st, 2nd and 3rd blocks), in the five stimulus conditions revealed a clear repetition priming effect: participants responded significantly faster on subsequent than on their previous exposures [$F_{(1,37)}=73.71$, $p<.0001$]. Post-hoc paired t-tests (with Bonferroni adjustments) revealed that the repetition priming effects in the 2nd and 3rd blocks were significant ($p<.005$) for all stimulus combinations.

Participants' responses at the 4th exposure were also significantly faster than at the 3rd exposure [$F_{(1,37)}=37.51$, $p<.0001$]. Thus, overall, there were significant repetition priming effects for the 4th block, despite the fact that in the 4th block only the visual stimuli were presented in all of the stimulus conditions (i.e., without the auditory and haptic stimuli to which they were paired in blocks 1–3). Post-hoc paired *t*-tests (with Bonferroni adjustments) comparing RT in the 3rd and 4th exposures revealed that the repetition effect was significant ($p<.005$) for all stimulus combinations (Table 1).

2.2. *Stimulus combination effect*

A repeated measures ANOVA on the proportional gains in the 2nd and 3rd blocks relative to the initial exposure, showed that both the stimulus combination conditions and the interaction between blocks and stimulus combinations were not significant. Thus, in the repetition priming gains of the 2nd and 3rd blocks, there were no significant differences between the

Table 1 – Repetition priming gains for uni- and bi-sensory stimuli

Stimuli	Repetition priming gains (in percentage)				
	Relative to initial performance (1st block)				Relative to 3rd block
	1→2	1→3	1→4	3→4	3→4
V	13.5±4	21.4±3.7	31.5±4.6	10±3.4	11.9±4.2
AV+	13±4.9	23.2±4.1	28±3.9	4.9±2.8	5.2±2.7
HV+	12.2±4.7	24.5±4.6	29.3±5.2	4.8±3	5.4±3.1
AV−	16.4±4.8	26.5±4.7	33.8±5.3	7.3±3.2	9.2±4
HV−	18.2±5	25.6±5.2	34±4.9	8.5±3.1	10.8±3.9

Columns 1→2,3,4 show the percentage of time gained in subsequent exposures as compared to the 1st exposure (mean±s.d.). Columns 3→4 show the time gained in the 4th exposure compared to the 3rd exposure as percentage of RT in the 1st and in the 3rd blocks. All repetition gains were significant.

visual (uni-sensory) and bi-sensory stimulus combinations. However, in the 4th exposure gains (compared to the 3rd block) there was a marginal effect for stimulus combination [$F_{(4,148)}=2.42$, $p=.05$].

2.3. *Semantic-relationship effect*

The repetition priming gains, expressed by the 4th block, were smaller when there was a semantic-relationship between the previously presented pair of bi-sensory stimuli as compared with conditions in which they were semantically unrelated. As can be seen in Table 1 when the bi-sensory stimuli, in the initial three presentations, were semantically related the cumulative repetition priming gains were 28 and 29.3% for the auditory–visual and haptic–visual combinations respectively. However, when the bi-sensory stimuli were not semantically related the cumulative repetition gains were 33.8 and 34% for the auditory–visual and haptic–visual combinations respectively. The semantic-relationship effect was even more robust for the gains expressed by the 4th block relative to performance in the 3rd block (Table 1, right-most column). The gains expressed in the AV+ and HV+ conditions were 5.2 and 5.4% but 9.2 and 10.8% in the AV− and HV− conditions, respectively, much near the values for the V condition (11.9%).

To test whether the semantic-relationship effect was statistically significant, a two-way repeated-measures ANOVA was run with semantic-relationship (uni-sensory visual (V), bi-sensory semantically related (average of AV+ and HV+), bi-sensory semantically unrelated (average of AV− and HV−)) and blocks (1st, 2nd, 3rd, 4th) as within-participants factors. There were significant effects for repetition [$F_{(3,111)}=105.04$, $p=.0001$] and for semantic-relationship [$F_{(2,74)}=24.92$, $p<.0001$]. The interaction between repetitions and semantic-relationship showed a trend towards statistical significance [$F_{(6,222)}=2.32$, $p=.07$]. Post-hoc paired *t*-tests (with Bonferroni adjustments) showed no significant differences in the gains across the first three blocks, between the uni-sensory visual and the bi-sensory semantically related and the bi-sensory semantically unrelated conditions. However, in the transition from the bi-sensory stimuli to the visual only trials (blocks 3→4) the repetition-gains (normalized to the 1st block) of the semantically related conditions were smaller than the gains in both the semantically unrelated condition [$t_{(37)}=-2.48$, $p<.05$] and the uni-sensory (V) condition [$t_{(37)}=2.31$, $p<.05$]. The difference between the semantically unrelated condition and the V condition was not significant. When the 4th block repetition-gains (blocks 3→4) were normalized to the 3rd block the semantic-relationship effect was clearer and even more significant. The gains in the semantically related conditions were smaller than the gains in both the semantically unrelated condition [$t_{(37)}=-2.9$, $p<.01$] and the V condition [$t_{(37)}=2.77$, $p<.01$], but the difference between the V condition and the semantically unrelated condition was again not significant.

2.4. *Summary of the results*

Altogether, these results indicated that across the initial 3 blocks: a) significant repetition priming effects occurred across all conditions. b) There was no significant difference, in the magnitude of the repetition priming gains, between the bi-sensory stimulus combinations (auditory–visual, haptic–visual) and the uni-sensory, visual, stimulus condition. However, in the transition from the 3rd to the 4th block (i.e. from bi-sensory stimuli to visual only presentation) c) there was an effect for the semantic relationships between the bi-sensory stimuli. Although, priming gains continued also when the visual stimulus was presented alone rather than with the previously paired (auditory or haptic) stimulus, smaller priming gains occurred for the previous semantically-related pairs of auditory–visual or haptic–visual stimuli compared to the previous semantically-unrelated pairs.

3. Discussion

The results of the current study show a robust repetition priming effect in both uni- and bi-sensory stimulus conditions. When exposed to the same stimulus combinations while performing the same task, repeatedly, participants responded to each subsequent exposure faster than in the corresponding previous exposures. Note that in all five sensory combinations, the four words used were all synonyms (in the Hebrew language), and therefore may have contributed to a 'synonym priming' effect (Holland, 1992; Lukatela et al., 1993). It cannot be ruled out that the words may have been primed by their synonyms *within* each block of trials. Thus, although the words were presented in a random order in each block, the robust priming effect that was observed in the current study may be attributed to a 'double' priming effect (*repeated exposures* to the same word across different blocks of trials, as well as priming by *synonym* words *within* the block).

If multi-sensory stimuli are better represented in implicit memory from the very first experiences of paired stimuli, one may expect a greater magnitude of the repetition priming gains (larger relative performance gains upon subsequent experiences of the stimuli) for bi-sensory stimuli than for uni-sensory stimuli. If however, after a certain (small) number of iterations multi-sensory stimuli come to be co-represented in memory in an associative manner, there may be only a cost — smaller or no repetition priming gains, when the association between the stimuli established in the prior three blocks is broken and only one uni-sensory stimulus is presented. Our results show that, in all four blocks, the magnitude of the repetition priming gains in the bi-sensory auditory–visual and haptic–visual conditions were not significantly different than those attained in the uni-sensory visual condition. Given a rather limited amount of experience with multi-sensory stimuli the combined stimuli may not generate larger repetition gains when the auxiliary stimulus is task-irrelevant. On the other hand, significant differences were found between semantically related and semantically unrelated bi-sensory signal pairs in terms of disassociation costs.

3.1. *Semantically related multi-sensory stimuli are represented in an associative manner*

The results of the current study showed that additional gains occurred also in the 4th (visual only) exposure, despite the absence of the previously paired auditory and haptic stimuli. These 4th block gains were significantly smaller (almost half) in the semantically related bi-sensory conditions compared to the semantically unrelated conditions. In fact, the gains in the latter conditions were not different from those attained for the uni-sensory (V) condition. Thus our results indicate that the semantic relationship between stimuli in the bi-sensory conditions may have resulted in an association which when subsequently broken was reflected in a 'disassociation cost' — the expression of lower repetition priming gains.

Semantic compatibility is well known to facilitate perceptual processes. For instance, in the Stroop interference and facilitation effects (Stroop, 1935; MacLeod, 1991; MacLeod and MacDonald, 2000) a semantically congruent stimulus, one with all its elements in correspondence and conveying the same concept (e.g. the word RED written in red ink) is processed more rapidly and with fewer errors, compared to stimuli with neutral or incongruent (conflicting) elements (e.g. the word RED written in green ink). The Stroop effect is not limited to a correspondence/conflict within the same modality (as in the original color–word version). Many studies had demonstrated Stroop-like effects also when the semantic congruence/incongruence was between elements simultaneously presented to different sensory modalities (e.g. Shimada, 1990; Stuart and Carrasco, 1993; Langton et al., 1996; Elliott et al., 1998; Pauli et al., 1999; Damian and Martin, 1999; Langton, 2000; Elliott and Cowan, 2001; Hanauer and Brooks, 2003; Gottfried and Dolan, 2003; Roelofs, 2005; Beeli et al., 2005; Reiner et al., 2006).

Not only perceptual processes may benefit from semantic congruency. It has been shown that in a 'semantic priming' paradigm (Meyer and Schvaneveldt, 1971) the RT to a target word (e.g. BUTTER) was faster when the word was preceded by a semantically related 'prime' word (e.g. BREAD) than when it followed an unrelated prime word (e.g. DOG). Semantic priming effects were reported also across sensory modalities. Words presented visually facilitated semantically related words presented acoustically and vice versa (Swinney et al., 1979; Holcomb and Anderson, 1993). Similarly, tactile exploration of an object facilitated its subsequent visual recognition and vice-versa (Easton et al., 1997, 1999; Reales and Ballesteros, 1999).

In the current study, the semantic relations were not between a 'prime' word and a 'target' word in different trial-blocks, but between the bi-sensory stimuli presented simultaneously in each trial (e.g. participants heard a sound while being presented visually with the word SOUND or their stylus-holding hand was lightly pushed while being presented visually with the word MOVEMENT). Our results suggest that semantically related multi-sensory stimuli co-presented a small number of times may come to be represented in implicit memory in an associative manner. Thus, in the transition from the 3rd to the 4th block, there was a 'cost' of breaking the bi-sensory association – lower repetition priming gains – selectively for the semantically-related stimuli but not for the semantically-unrelated stimuli.

A semantic effect for bi-sensory stimuli was reported also in an explicit memory test where repeated audio-visual presentations had a positive effect on subsequent recognition performance selectively for semantically congruent audio-visual stimuli, but not for incongruent stimuli (Lehmann and Murray, 2005). Likewise, a perceptual learning study reported that training with congruent audiovisual stimuli produced significantly better learning than training with incongruent audio-visual stimuli or with only visual stimuli (Kim et al., 2008). Based on a review of neuroimaging studies, Doehrmann and Naumer (2008) proposed a possible functional differentiation of the temporal and frontal cortical regions, with the former being more responsive to semantically congruent and the latter to semantically incongruent audio-visual stimulation.

3.2. *Multi-sensory enhancement in learning and memory*

A leading notion in current memory research is that long-term memory is subserved by two largely independent and anatomically non-overlapping memory systems (Mishkin et al., 1984; Squire, 1994, 2004; Karni, 1996). The knowledge retained in declarative memory is in general accessible to overt, explicit reporting and is usually measured by recall and recognition tests, while the knowledge retained in procedural memory is often implicit and manifested in actual enhanced performance following repeated task experience. It has been suggested that *implicit* memory can be related to perceptual or motor *modality-specific* representations, and *explicit* memory conceptualized as an a-modal cognitive representation often independent of perceptual or motor aspects of the learning experience (Tulving and Schacter, 1990; Roediger and McDermott, 1993; Easton et al., 1997, 1999; Schacter and Buckner, 1998).

The current results show that the pairing of auditory or haptic stimuli to the visual stimuli did not result in significant enhancement of the repetition priming gains compared to the gains attained in the uni-sensory (V) condition. As intact declarative memory has been shown to be unnecessary for repetition priming gains (Tulving and Schacter, 1990), repetition priming effects are considered to reflect an initial, critical but not sufficient, stage in the generation of long-term implicit memory, such as in perceptual and motor learning (Karni and Sagi, 1993; Hauptmann and Karni, 2002; Korman et al., 2003).

In the majority of studies in which significant enhancements of memory were reported for multi-sensory stimuli compared to the corresponding uni-sensory stimuli (e.g. Martin, 1980; Stine et al., 1990; Lewandowski and Kobus, 1993; Kobus et al., 1994; Frieske and Park, 1999; Murray et al., 2004, 2005; Lehmann and Murray, 2005; Goolkasian and Foos, 2005), the measures used were recall and recognition tests — tests of explicit memory. Recently, however, a study of visual motion discrimination task has provided direct evidence for multi-sensory (the addition of an auditory directional cue) enhancement in perceptual learning, an instance of long-term implicit memory (Seitz et al., 2006; Kim et al., 2008). The auditory stimuli were task relevant, and the learning-related enhancements in subsequent performance tests were larger when the two stimuli, paired in the multi-sensory conditions, were congruent.

There are several differences between the current study and the study of Seitz et al. (2006) and Kim et al. (2008) which may point towards critical factors that may determine whether multi-sensory experience will result in implicit learning gains compared to repeated experience with the corresponding uni-sensory stimuli. Firstly, in the current study the additional, auditory or haptic cue was completely task-irrelevant. It may be the case that multi-sensory enhancement of learning and subsequent memory occurs only when the additional signal is relevant and can contribute to the particular task's performance. There is evidence suggesting that implicit learning and memory processes may be gated by task relevancy, i.e., stimuli are learned and retained in implicit, procedural, memory only when task-relevant (e.g., Karni, 1996). Thus, our results suggest that there may be no advantage for bi-sensory signals over uni-sensory signals, in terms of greater magnitude of repetition priming gains, if the bi-sensory association is not relevant for performing the given task.

Second, in the current study, there were only three training iterations on each stimulus list, with a single session, while in Seitz et al. (2006) and Kim et al. (2008) study participants were trained over five days with hundreds of repetitions afforded in each condition. Two notions may be relevant in this context: the notion, discussed above, that repetition priming effects are not synonymous with implicit (procedural) memory, and the notion of a critical number of repetitions that are required for long-term implicit memory. Repetition priming effects are considered to reflect an initial stage in the triggering of long-term implicit memory, such as in perceptual and motor learning. However, the generation of long-term implicit memory may necessitate memory consolidation processes which take place after the termination of training and are triggered only when repetition priming effects have been saturated (e.g., Karni 1996; Hauptmann and Karni, 2002; Korman et al., 2003). There is evidence from several perceptual as well as motor implicit learning paradigms that memory consolidation processes may be triggered only after a critical number of task repetitions (in most cases tens or hundreds of repetitions) and moreover, that the nature of the knowledge retained in long-term memory may change as a function of the amount of training afforded (Karni and Sagi, 1993, Hauptmann and Karni, 2002; Korman et al., 2003).

4. Conclusion

Our results show that there was no advantage for bi-sensory stimuli (paired task-relevant and task-irrelevant inputs) over uni-sensory task-relevant stimuli in terms of repetition priming gains. Nevertheless, there was a 'cost' of breaking the bi-sensory association – lower repetition priming gains – selectively for semantically-related bi-sensory stimuli. Thus, our results support the notion that when a semantic relationship exists between stimuli repeatedly experienced, simultaneously, in two sensory modalities, an association, in implicit memory, may evolve even when the association of the pair is task-irrelevant. We propose that whether multi-sensory stimuli are better retained in memory may reflect in part factors such as the amount of experience with the stimuli, the semantic relationship between the stimuli and the gating of the learning by the task-relevancy of both stimuli.

5. Experimental procedures

5.1. *Participants*

Forty students participated in the experiment, twenty one males and nineteen females (mean age 23.9±3 years). Thirty eight participants were right-handed and two were left-handed according to the Edinburgh handedness inventory (Oldfield, 1971). All participants had normal hearing and normal or corrected to normal vision and were without any known tactile dysfunction. Participants were paid for participation, and were unaware of the purpose of the experiment, except that it tested eye-hand coordination in different conditions. The experiment was carried out under the guidelines of the Technion's ethical committee.

5.2. *Apparatus and stimuli*

A haptic device – pen-like robotic arm (stylus) gripped and moved as in handwriting or drawing (PHANTOM® Omni™) – was connected to a standard computer interface, so the system was capable of providing users with visual, auditory and haptic stimuli. The haptic stimulation was a resisting force delivered through the stylus that pushed lightly the stylus-holding palm rightward. Participants responded by pressing designated buttons on a SpaceMouse®.

The visual stimuli consisted of pairs of Hebrew letter-strings with their vowel punctuations (font: Times New Roman, letter size: 36). Viewing distance from the screen was 40 cm. Each pair of strings was simultaneously presented with a distance of 2.5 cm between the strings (Fig. 2). The strings presented on the right side were standard and recognized words in the Hebrew language. On the left side however, the same letters were arranged as a non-sense, but pronounceable, sequence. These visual stimuli were presented either alone or simultaneously with an auditory or haptic stimulus. The auditory stimulus consisted of a compound sound pattern of a horn — (11 kHz, 50 dB SPL) emitted from a loudspeaker located right of the workspace, 65 cm from the participants' ear. The haptic stimulus was a resisting force (1.2 N) delivered through the stylus that pushed lightly the stylus-holding palm rightward from its fixed position. The visual and haptic stimuli persisted until participants pressed the response buttons. However, due to technical limitations, the duration of the auditory stimulus was fixed — 800 ms.

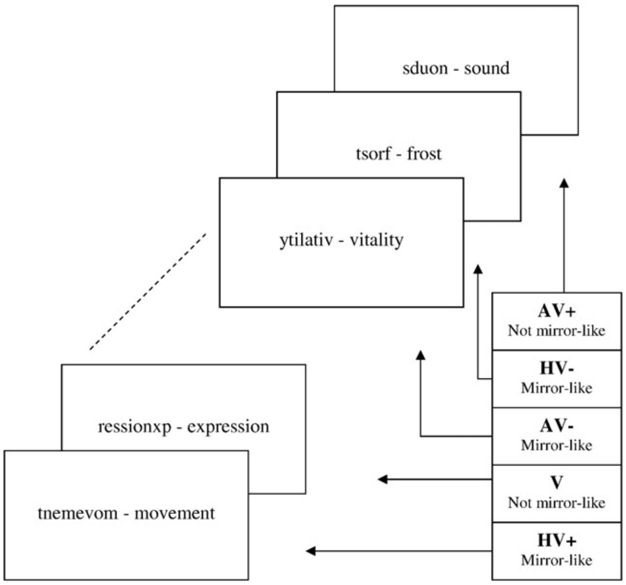


Fig. 2 – The visual stimulus consisted of letter-string pairs. Participants' task was to determine if the left string was the exact reverse of the right string – mirroring it – or not. The visual stimuli were presented either alone or simultaneously with an auditory (sound) or a haptic (a force applied through the stylus) stimulus. The bi-sensory stimuli were either semantically related (e.g. the word MOVEMENT presented while the stylus-holding hand is lightly pushed; the word NOISE presented together with a sound) or unrelated. Note that the words were presented in Hebrew.

The pairs of letter-strings were presented in five experimental conditions. Only visually (V), accompanied with a semantically related auditory signal (AV+; e.g. the word "noise" presented with a sound), accompanied with a semantically unrelated auditory signal (AV–; e.g. the word "vitality" presented with a sound), accompanied with a semantically related haptic signal (HV+; e.g. the word "movement" presented together with a force slightly pushing the stylus-holding hand), accompanied with a semantically unrelated haptic signal (HV–; e.g. the word "coolness" presented with a force slightly pushing the stylus-holding hand). The words presented on the right side of the letter-string pairs are listed in Appendix 1.

5.3. *Procedure*

Participants sat comfortably in front of the workspace, directing their gaze to the center of the display. They were instructed to hold the stylus in their dominant hand, in a manner similar to holding a pen, then to rest the stylus-holding hand on the table without initiating any movements through the entire experiment. In each trial, a pair of letter-strings was presented at the center of the screen. Participants' task was to read the letter-string on the right and then decide whether the letters in the left string are ordered exactly mirroring the word on the right (e.g. "tnemevom — movement") or not (e.g. "emnvetom — movement"). Participants were informed that their best strategy for performing these judgments would be to try to read the left letter-string from left to right (i.e. backwards, as Hebrew is read from right to left) and if they got the same word as in the right letter-string then the pairs are ordered in a mirror-like manner. Participants responded by pressing a designated button on the mouse, with the left hand, when the order of the letters in the left and right letter-strings mirrored each other, and another button when the letter-strings did not mirror each other.

Trials were delivered in blocks of twenty trials constituting four letter-strings pairs from each condition (V, AV+, AV–, HV+, HV–) randomly intermixed. Each participant was presented with four test blocks. The order of the stimuli was randomized across blocks with different blocks for each participant. The first three blocks contained uni- and bi sensory signals as described above, however, in the fourth block of trials, all the letter-string pairs were presented visually without an accompanying haptic or auditory signal. The inter-trial interval was between 2.5 to 4 s in intervals of 100 ms (i.e. 2.5, 2.6. 2.7 … 4 s), randomly determined. The between-blocks interval was 15 s long during which participants were presented with a white screen.

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Appendix 1

List of the Hebrew words (and their English translation)

Condition	Mirror-like		Not mirror-like	
V	הבעה	מילה	אות	ביטוי
	Expression	Word	Letter	Expression
AV+	קול	צופר	צליל	רעש
	Voice	Honk	Sound	Noise
AV-	אנרגיה	רעננות	חיוניות	מרץ
	Energy	Vitality	Liveliness	Vigor
HV+	תנועה	דחיפה	תנודה	תזוזה
	Movement	Push	Fluctuation	Motion
HV-	כפור	קרירות	קרח	צינה
	Frost	Coolness	Ice	Chill

The table reads from left to right (i.e. in an English form, as opposed to Hebrew which is read from right to left).

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