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Brief article

Sensory load incurs conceptual processing costs

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ABSTRACT

Theories of grounded cognition propose that modal simulations underlie cognitive representation of concepts [Barsalou, L. W. (1999). Perceptual symbol systems. *Behavioral and Brain Sciences*, *22*(4), 577–660; Barsalou, L. W. (2008). Grounded cognition. *Annual Review of Psychology*, *59*, 617–645]. Based on recent evidence of modality-specific resources in perception, we hypothesized that verifying properties of concepts encoded in different modalities are hindered more by perceptual short-term memory load to the same versus different sensory modality as that used to process the property. We manipulated load to visual and auditory modalities by having participants store one or three items in short-term memory during property verification. In the high (but not low) load condition, property verification took longer when the property (e.g., yellow) involved the same modality as that used by the memory load (e.g., pictures). Interestingly, similar interference effects were obtained on the conceptual verification and on the memory task. These findings provide direct support for the view that conceptual processing relies on simulation in modality-specific systems.

1. Introduction

In classic models of information processing, information is encoded in an abstract form that is functionally independent from the sensory systems that processed it (e.g., Fodor, 1975). In contrast, embodied simulation accounts (e.g., Barsalou, 1999; Barsalou, 2008) hold that modality-specific states that support perception, action, and introspection are used to represent these ideas when the original entity or situation is no longer present (Gallese, 2003). If using knowledge involves sensory-motor systems, then conceptual processing should follow the same principles as those of on-line perception. Here, we report direct evidence in support of this claim by showing reciprocal interference effects between explicit sensory load and conceptual processing in a same sensory modality.

The prediction that modality-specific systems support conceptual processing has received support from neuroimaging studies that demonstrate modality-specific processing of concepts. Kan, Barsalou, Solomon, Minor, and Thompson-Schill (2003) found selective activation of modality-specific brain areas when participants verified properties of concepts typically processed by those sensory modalities (e.g., gustatory for “LEMON – sour” or auditory for “BOMB – loud”). The property was apparently perceptually simulated when the conceptual task was performed (see also Simmons, Martin, & Barsalou, 2005).

Behavioral studies also support the grounded cognition account. Spence, Nicholls, and Driver (2001) showed that when participants judged the left-right location of stimuli presented in one of three sensory modalities, they responded more slowly if the stimulus on the preceding trial was perceived in a different (compared to same) modality. Extending switching costs to the case of conceptual processing, in Pecher, Zeelenberg, and Barsalou (2003) participants performed a property verification task in which the properties represented vision, audition, taste, touch,

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olfaction, and action. The critical manipulation was the type of property processed on the preceding trial, which represented either the same (e.g., *BUTTERMILK-sour*) or a different (e.g., *TELEVISION-noisy*) modality. Here again, switching costs were observed (see also Pecher, Zeelenberg, & Barsalou, 2004; Vermeulen, Niedenthal, & Luminet, 2007a).

Although the above findings were not predicted *a priori* from amodal models of representation, they may be explained *a posteriori* by such models: if concepts and properties are stored in a single system, then properties sharing a same modality could be more strongly associated. Priming a property in one modality might then facilitate the verification of other properties in the same modality through spread of activation. In light of this alternative interpretation, further empirical evidence is needed to support the grounded cognition view more directly. The present research was designed to provide such a demonstration. Specifically, we predicted more interference in conceptual processing when the same (relative to another) sensorial modality was taxed significantly by a secondary, short-term memory, task. Most associative accounts do not make this a priori prediction because they cannot naturally account for inference by load to a specific sensory modality with a modality-specific conceptual judgment. In contrast, grounded cognition models make such a prediction a priori because both sensory and conceptual systems are held to be inherently perceptual, sharing neural systems with perception (e.g., Barsalou, 1999).

Our hypothesis was partly derived from studies supporting the existence of modality-specific attentional resources. Alais, Morrone, and Burr (2006) showed that auditory and visual discriminations are affected by a concurrent task in the same modality. In their research, concurrent tasks in a different modality had no effect on visual or auditory thresholds, whereas thresholds were increased in the same modality condition. Using electrical recordings, Talsma, Doty, Strowd, and Woldorff (2006) showed that attentional capacity is more limited when relevant stimulus features have to be resolved among competing stimuli presented to the same modality as compared to a different one. Duncan, Martens, and Ward (1997) similarly showed that the "attentional blink" is modality dependent with little if no intermodal transfer.

A transcranial magnetic stimulation experiment that disrupted areas within parietal cortex during visual and somatosensory orienting (i.e., vertical upper/lower localization) revealed modality-specific attentional substrates (Chambers, Stokes, & Mattingley, 2004). In an fMRI study, Weissman, Warner, and Woldorff (2004) asked their participants to identify a letter presented either visually or auditorily while they varied the amount of cross-modal distraction from an irrelevant letter in the opposite modality. Results showed that activity in sensory cortices that processed the relevant letter (i.e., modality-specific) increased as the irrelevant letter became more distracting. Conversely, attention to the relevant letter did not significantly modulate the amount of activity observed in sensory cortices that processed the distracter. Conclusions from this review are clear-cut. Each sensory modality has access to its own independent pool of attentional resources (Rees, Frith, & Lavie, 2001) and attentional restrictions are therefore modality-specific (Duncan et al., 1997).

Our interference hypothesis was also partly derived from findings of a recent experiment on conceptual processing (Vermeulen, Corneille, Budke, & Niedenthal, submitted for publication). In that experiment, participants had to judge grey images and sounds on their intensity, and, interspersed with these judgments, had to verify properties of concepts that were either presented on a computer screen or via headphones. Results showed that participants took longer and were less accurate at verifying conceptual properties when the channel used to present the property and the type of property matched in sensory modality. The latter finding is consistent with the grounded cognition hypothesis. If resources are modality-specific, then sharing modality resources between channel and property verification yields a processing cost detrimental to verification performance. Unfortunately, Vermeulen et al. (submitted for publication) had no direct evidence to support that claim, as they did not manipulate sensory load during conceptual representation.

The interference hypothesis was tested more directly in the present research through manipulation of the modality of the sensory load (i.e., visual or auditory), the intensity of the sensory load (low or high) and the sensory modality of the conceptual verification task (i.e., visual or auditory). Load to visual and auditory modalities was varied by having participants store one or three visual or auditory items in short-term memory during property verification for later identification. This allowed us to test the hypothesis that high (but not low) load to short-term memory produces interference in conceptual property verification when the conceptual property is encoded in the same modality as that of the memorized (i.e., load-producing) items. Indeed, we hypothesized that the perceptual rehearsal induced by the three (but not one) items load manipulation would significantly tax the sensorial buffer. Whereas more interference was expected in the high than low load condition, no strong prediction could be made as to whether a switching cost would be observed or not in the low load condition. This was due to the enhanced difficulty of the task used in the present study, relative to tasks used in prior studies where switching costs were found (see also below).

Note that the goal was not to demonstrate that high load in the same modality as a judgment interferes with that judgment. Rather, the idea was that when keeping the judgment options (i.e., 'True' and 'False') identical over trials, access to conceptual properties is inhibited when the modality of a conceptual property matches that of the high sensory load. Furthermore, the verification and memory tasks involved different response options thus eliminating possible interference effects in response production.

Interestingly, the interference hypothesis could also be tested in the short-term memory task: Slower identification of the memorized items should also be observed under high but not low load following verification of properties that are processed in the same modality as that of the stored items. This secondary hypothesis was examined here as well.

2. Method

2.1. Subjects and design

Twenty volunteers (14 women; mean age = 20.55, SD = 1.5) from the Université Catholique de Louvain participated in fulfillment of a course requirement. The study conformed to a 2 (Conceptual Property: Auditory vs. Visual) × 2 (Load modality: Auditory vs. Visual) × 2 (Load size: 1 Item vs. 3 items) full within-subjects design.

2.2. Materials

For the short-term memory task, visual stimuli were selected from Delvenne and Bruyer (2004; Experiment 2A), which are grey-scaled non-language-based abstract shapes and textures (Fig. 1). Meaningless single auditory stimuli of different frequencies (e.g., Beep, Sinusoidal at 1500 Hz) were created by using Audacity 1.2.5 for windows. Each single sound was 500 ms in duration.

The property verification task was composed of 184 concept–property pairs, 48 of which constituted critical trials. The 48 "true" concept–property associations were selected from those used in previous experiments (Pecher et al., 2003; Vermeulen et al., 2007a; Vermeulen et al., submitted for publication). Half involved a visual property (e.g., *LEMON* can be *yellow*) and half an auditory property (e.g., *BLENDER* can be *loud*). Different pairs were created by coupling *CONCEPT-property* associations with short-term memory trials. Half of the pairs involved an auditory load and the other half involved a visual load. The 24 visual and 24 auditory critical *CONCEPT-property* associations were randomly assigned to four lists of concept verification trials, which were respectively associated with the four conditions defined by the crossing of the Load size and Load modality factors. We then generated four different versions of the program that counterbalanced the assignment of these four lists to the Load size and Load modality conditions.

A set of 136 fillers was also used. Of these, 92 were "false" (i.e., half involved visual or auditory properties) and 44 were "true" (i.e., 24 involved auditory and visual properties used with the zero load condition). On some of the filler trials, participants verified properties for modalities that were different from those used in the memory task. On other filler trials, participants verified properties in the absence of memory load. This zero load condition was used with 61 *CONCEPT-property* associations that were all fillers. Whereas all critical associations were true, participants also responded to a large number of false filler associations (67% of the fillers and 50% of the whole experiment). Those fillers were used to ensure a varied task. All the verbal material was presented in French.

2.3. Procedure

Participants were tested in a computer room. Stimuli were presented using E-Prime 1.1.4.1 on PCs with Processor IntelPentium 2.3 GHz/256 Mb SDRAM computers. They donned headphones and read computer-presented instructions. After completing a training session for the two tasks separately (i.e., short-term memory task followed by property verification), participants were informed that the tasks would be interspersed. Specific trial parameters were clarified (see Fig. 2 for a visual description of a trial).

Trials started with a 1500 ms text screen that informed the participant about the modality and size of the to-be-memorized item (e.g., "you will see 1 picture" or "you will hear 3 Sounds). Then, the visual or the auditory items were presented for 500 ms. In the low load condition, one sound or one picture was followed by a 750 ms blank screen; in the high load condition, three sounds or three pictures (i.e., each separated by a blank of 500 ms) were followed by a 1500 ms blank screen. A *CONCEPT-property* association then appeared on the screen. As in Pecher et al. (2003) and Vermeulen et al. (2007a), three lines of text were presented. The first line contained the concept word in uppercase letters, the second line contained the words "can be" (i.e., "peut être" in French) and the third line contained the property in lower case letters. The three lines of text appeared simultaneously and remained on the screen until the participant made a "true" ("1" key on the keypad) or a "false" ("3" key on the keypad) judgment on an AZERTY keyboard. In the present experiment, the property verification task was always displayed visually.

Upon the verification response, a blank screen appeared for 500 ms. The blank screen was followed by the presentation of a visual or auditory sequence (i.e., from the same modality and size as on the first part of the trial), which the participant evaluated as quickly and accurately as possible as "identical" (by pressing "C") or "different" (by pressing "B"). The next trial started 1000 ms after the identification response. The experiment was divided into three blocks of 60, 62 and 62 trials each separated by a fixed rest period of 20 s followed by a "get ready period" that the participants could terminate when ready.

Fig. 1. Examples of visual stimulations used for the short-term memory task.

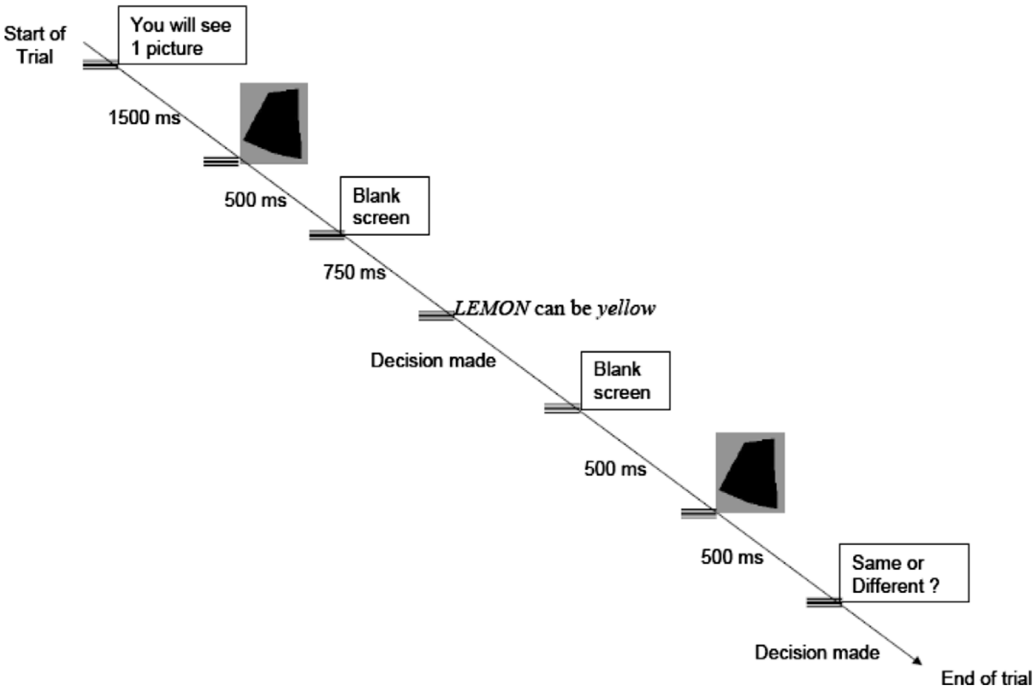

Fig. 2. Example of a typical one visual item load sequence used in the present experiment.

3. Results

Response times (RTs) for *CONCEPT-property* trials on which participants responded accurately to both the short-term memory and the conceptual judgments were retained for analysis. RTs shorter than 300 ms and longer than 3000 ms were deleted. RTs were then cleaned for outliers (2.2%) following a 2 SD cutoff. Analyses were also conducted on accuracy rates.

For concept-property associations, the 2 (Conceptual Property: Auditory vs. Visual) × 2 (Load modality: Auditory vs. Visual) × 2 (Load size: 1 item vs. 3 items) MANOVA revealed that RTs to verifying auditory properties of concepts were slower than RTs to verifying visual properties, $F\ (1,\ 19) = 11.51$, $p < .01$ (see Table 1 for mean RTs and accuracy rates). Auditory loads increased RTs, $F\ (1,\ 19) = 5.84$, $p < .05$ and decreased accuracy, $F\ (1,\ 19) = 6.41$, $p < .05$, as compared to visual loads. Load size increased RTs, $F\ (1,\ 19) = 8.89$, $p < .01$ and decreased accuracy, $F\ (1,\ 19) = 9.99$, $p < .01$ with slower RTs and lower accuracy for the three than for the one item load trials. In the accuracy analysis, the Property X Load Size was significant, $F\ (1,\ 19) = 6.01$, $p < .05$, with high load affecting more negatively responses on auditory than on visual properties.

Importantly, the three-way interaction was significant for RTs, $F\ (1,\ 19) = 4.60$, $p < .05$. As Fig. 3 shows, under the

Table 1
Mean response times (RT) in milliseconds and accuracy rates (ACC) for verifying properties of concepts as a function of conceptual property (Visual vs. Auditory), load modality (Visual vs. Auditory) and load size (Low: 1 item vs. High: 3 items)

Property modality	Visual load		Auditory load		*M*	
	RT	ACC	RT	ACC	RT	ACC
Overall						
Visual properties	1339 (56)	.95 (.01)	1377 (65)	.92 (.02)	1358 (58)	.93 (.01)
Auditory properties	1416 (55)	.95 (.02)	1525 (64)	.87 (.03)	1470 (55)	.91 (.02)
M	1378 (53)	.95 (.01)	1451 (59)	.89 (.02)	1414 (54)	.92 (.01)
Low load (1 item)						
Visual properties	1279 (50)	.95 (.02)	1406 (76)	.94 (.03)	1343 (59)	.94 (.02)
Auditory properties	1397 (51)	.99 (.01)	1457 (67)	.92 (.03)	1427 (54)	.95 (.02)
M	1338 (47)	.97 (.01)	1432 (59)	.93 (.02)	1385 (51)	.95 (.01)
High load (3 items)						
Visual properties	1399 (68)	.94 (.02)	1348 (64)	.90 (.03)	1374 (62)	.92 (.02)
Auditory properties	1435 (69)	.90 (.03)	1592 (77)	.82 (.04)	1513 (63)	.86 (.03)
M	1417 (62)	.92 (.02)	1470 (62)	.86 (.03)	1444 (59)	.89 (.02)

Note: Standard errors are presented in parentheses.

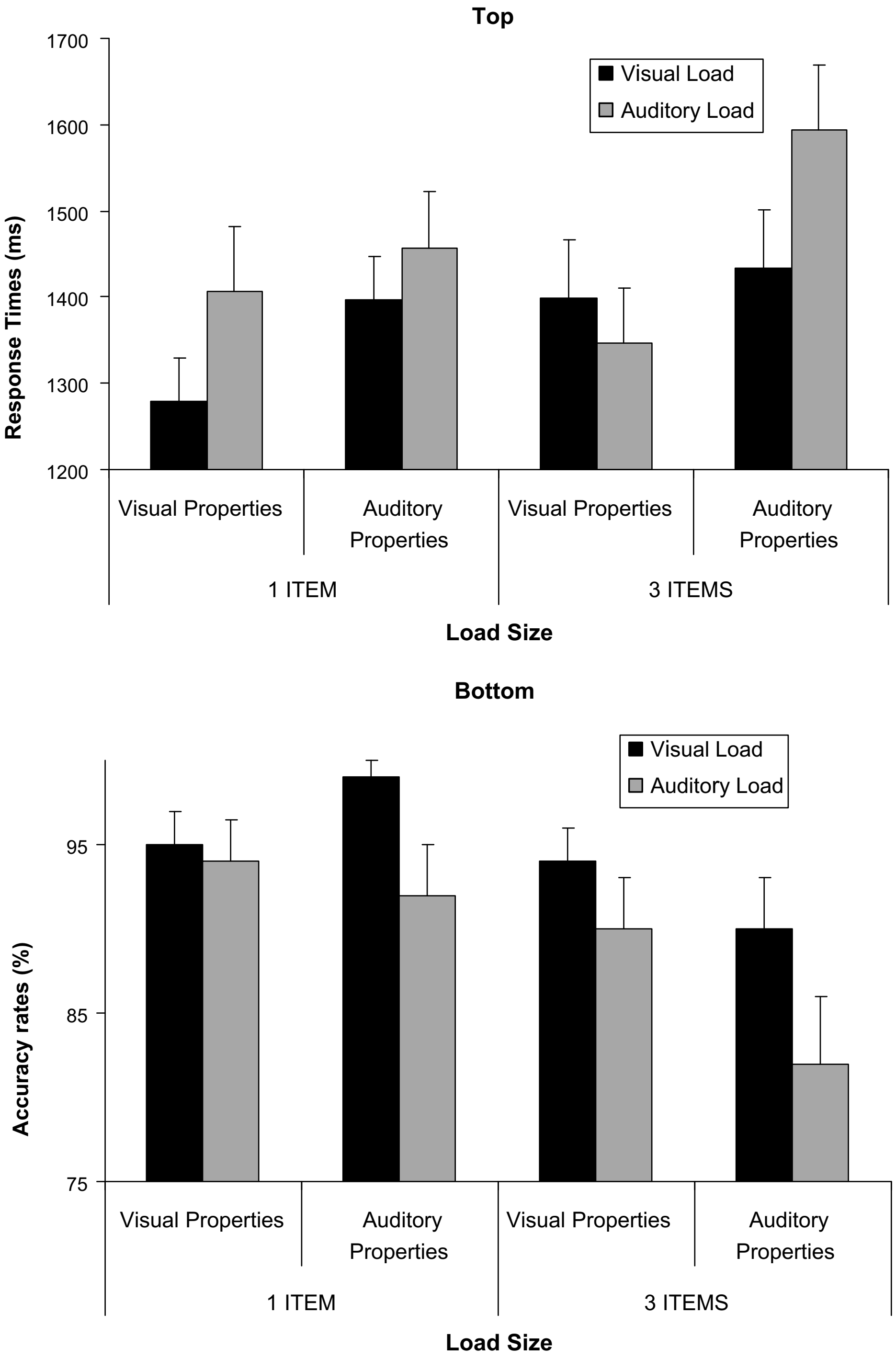

Fig. 3. Response times in milliseconds (Top panel) and Accuracy rates in percent (Bottom panel) to verify auditory and visual properties of concept as a function of load modality and load size.

high load condition, Modality interacted with conceptual Property, *F* (1, 19) = 5.41, $p < .05$, with slower property verifications made when load and property relied on a same sensory modality. In contrast, no such interaction emerged in the low load condition, *F* (1, 19) < 1, *ns*. There were no other significant effects.

For the memory task, analyses showed that identifications took longer, *F* (1, 19) = 43.04, $p < .001$ and were less accurate, *F* (1, 19) = 19.54, $p < .001$ in the high load than in the low load condition (see Table 2 for mean RTs and accuracy rates). The RT analysis also showed that Load size interacted with load modality, *F* (1, 19) = 17.88, $p < .001$,

Table 2
Mean response times (RT) in milliseconds and accuracy rates (ACC) for the short-term memory identification task as a function of load modality (Visual vs. Auditory), conceptual property (Visual vs. Auditory) and load size (Low: 1 item vs. High: 3 items)

Load modality	Visual properties		Auditory properties		*M*	
	RT	ACC	RT	ACC	RT	ACC
Overall						
Visual load	681 (50)	.90 (.02)	647 (41)	.90 (.02)	664 (39)	.90 (.02)
Auditory load	608 (40)	.94 (.01)	650 (41)	.94 (.02)	629 (39)	.94 (.01)
M	644 (36)	.92 (.01)	648 (38)	.92 (.01)	646 (35)	.92 (.01)
Low load (1 item)						
Visual load	644 (45)	.93 (.02)	676 (53)	.96 (.02)	660 (42)	.95 (.01)
Auditory load	424 (38)	.98 (.01)	425 (46)	.98 (.01)	425 (40)	.98 (.01)
M	534 (34)	.95 (.01)	550 (36)	.97 (.01)	542 (32)	.96 (.01)
High load (3 items)						
Visual load	717 (71)	.88 (.02)	619 (43)	.83 (.04)	768 (48)	.85 (.03)
Auditory load	792 (63)	.90 (.03)	875 (64)	.91 (.03)	833 (62)	.90 (.02)
M	755 (49)	.89 (.02)	747 (46)	.87 (.02)	751 (44)	.88 (.02)

Note: Standard errors are presented in parentheses.

with a larger load size effect obtained for the auditory modality than for the visual modality. Accuracy rates showed a main effect of load modality, with more accurate identifications obtained under auditory than visual load conditions, $F(1, 19) = 10.16$, $p < .01$. Of importance, a triple interaction between load size, load modality, and conceptual property was also obtained, $F(1, 19) = 4.77$, $p < .05$. As Fig. 4 shows, the interference effect was found in the high load condition $F(1, 19) = 5.59$, $p = .03$, with *slower* correct identifications obtained when the perceptual modality of the to-be-memorized item matched the perceptual modality of the to-be-verified property. No such interaction was obtained in the low load condition, $F(1, 19) < 1$, *ns*.

4. Discussion

In this experiment, participants stored visual or auditory items in short-term memory for later identification while performing a property verification task. In the high (but not low) load condition, property verification took longer when the modality of the to-be-verified property was the same as that used by the memory load. Correct identification in the short-term memory task showed the same pattern. In the high (but not low) load condition, slower correct identifications were observed when the modality of the to-be-memorized items matched the modality of the to-be-verified-property. Since conceptual stimuli were all presented via the visual channel in this research, our interaction effect could only be related to the overload of a "shared" sensory space used both off-line (during the conceptual representation of sensory properties) and on-line (during the buffering of perceptual information). No matter where this shared sensory space is located, the conclusion would remain unchanged: the conceptual representation of sensory properties requires to at least partially reactivating some of their sensorial components. This finding is consistent with the idea that conceptual representation involves the sensory-motor systems originally implicated in the experience of stimuli (Niedenthal, 2007).

It may be noted that no switching cost was observed in the low load condition for the conceptual verification task. As alluded to in the introduction, this null finding may be due to the higher complexity of the dual-task paradigm used for the purpose of the present study. Specifically, participants had to constantly navigate here across tasks, instructions and responses sets. It would then be interesting to examine more directly in future research whether switching costs effects in conceptual verification tasks are moderated by the general attentional load imposed upon participants.

The interference findings obtained here are fully consistent with those of Vermeulen et al. (submitted for publication) who found increased response times and decreased accuracy rates in property verification when the channel used to present the property (e.g., auditory) and the to-be-verified property (e.g., noisy) matched in sensory modality. The novelty of the present research lies in the fact that it directly examined the role of visual and auditory attentional resources during conceptual representation of visual and auditory properties. As just mentioned, this research additionally revealed mirror effects for the memory and conceptual verification tasks, providing further support to a grounded cognition account.

The findings are also consistent with extant research on sentence verification. Glass, Eddy and Schwanenflugel (1980; Experiments 3 and 4) showed that the verification of high imagery sentences (e.g., "The stars on the American flags are white") interfered more with short-term memory of visual patterns than did the verification of low imagery sentences. However, the reverse was not true: memorizing visual patterns had no effect on high imagery sentences verification. In addition, Glass et al. (1980) did not manipulate auditory load in their research. Therefore, to our knowledge, the present findings are the first to show that perceptual memory load directly and reciprocally interferes with conceptual representation.

Finally, the findings are also consistent with multimedia learning research (Mayer & Moreno, 2003). In relevant research, participants who viewed animation depicting the

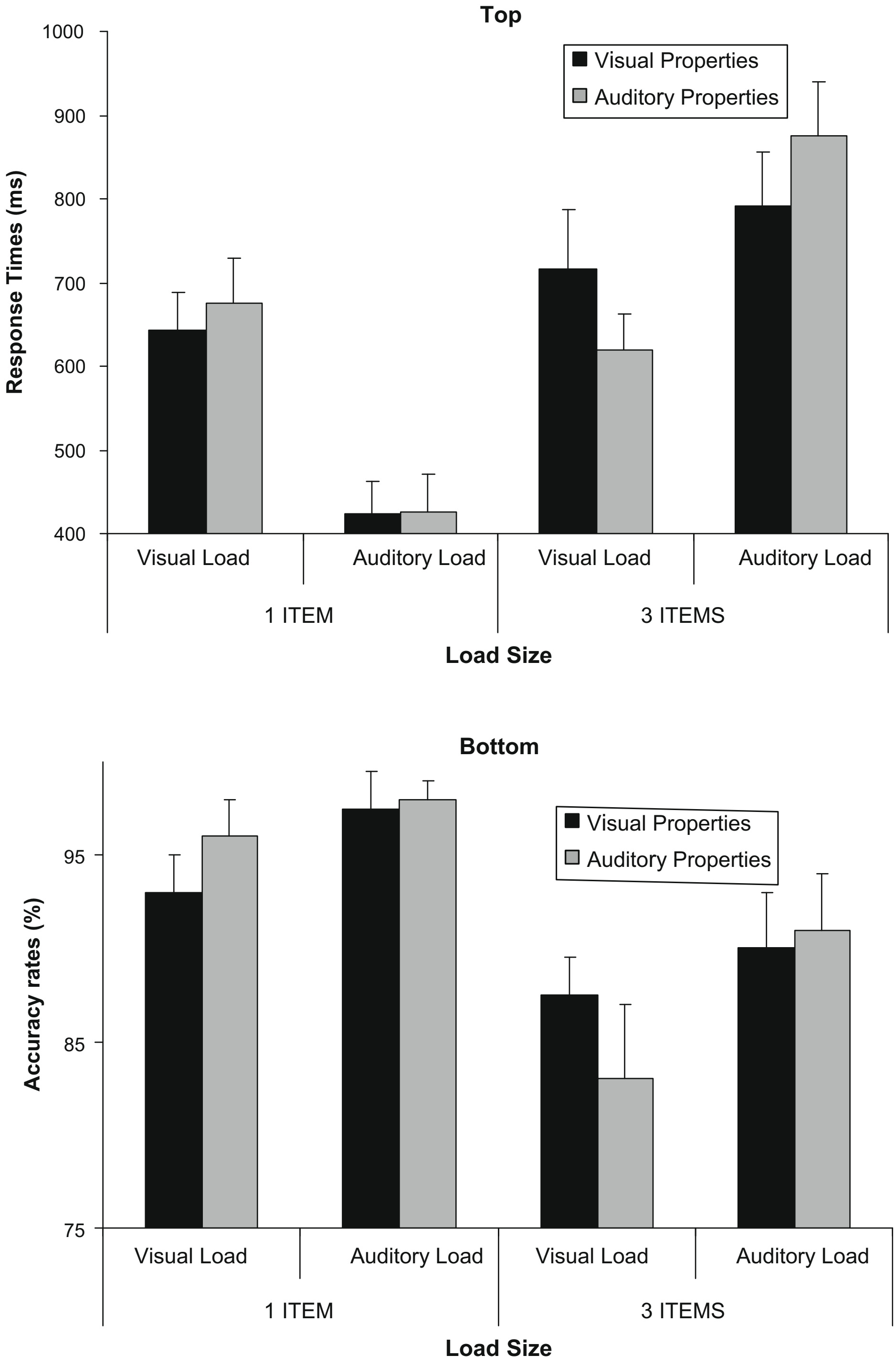

Fig. 4. Response times in milliseconds (Top panel) and Accuracy rates in percent (Bottom panel) for the identification of stored auditory and visual stimuli as a function of conceptual property and load size.

generation of lightning while also listening to a corresponding narration perform better than participants who view the same animation with corresponding on-screen text consisting of the same words as the narration (Mayer & Moreno, 1998). Mousavi, Low, and Sweller (1995) also found better performance when participants were presented with geometry statements in an auditory rather than a visual form.

In conclusion, the present experiments support the idea that knowledge is grounded in modality-specific systems (Barsalou, 1999): when resources of one sensory modality are taxed, processing costs are incurred in a conceptual representation. This novel finding is not predicted *a priori* by amodal conceptual representation systems, nor can it be accounted for *a posteriori* by such models. It may also have important implications for learning.

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