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Research Article

Multisensory Integration in Complete Unawareness: Evidence From Audiovisual Congruency Priming

Nathan Faivre[1,2], Liad Mudrik[1], Naama Schwartz[1], and Christof Koch[1,3]

[1]Computation and Neural Systems, California Institute of Technology; [2]Laboratory of Cognitive Neuroscience, Brain Mind Institute, School of Life Sciences, École Polytechnique Fédérale de Lausanne; and [3]Allen Institute for Brain Science, Seattle, Washington

Abstract

Multisensory integration is thought to require conscious perception. Although previous studies have shown that an invisible stimulus could be integrated with an audible one, none have demonstrated integration of two subliminal stimuli of different modalities. Here, pairs of identical or different audiovisual target letters (the sound /b/ with the written letter "b" or "m," respectively) were preceded by pairs of masked identical or different audiovisual prime digits (the sound /6/ with the written digit "6" or "8," respectively). In three experiments, awareness of the audiovisual digit primes was manipulated, such that participants were either unaware of the visual digit, the auditory digit, or both. Priming of the semantic relations between the auditory and visual digits was found in all experiments. Moreover, a further experiment showed that unconscious multisensory integration was not obtained when participants did not undergo prior conscious training of the task. This suggests that following conscious learning, unconscious processing suffices for multisensory integration.

The environment carries sensory signals of high variability, both with respect to their physical nature (e.g., photons for vision, air vibrations for audition, chemical substances for taste) and to the way they are processed (e.g., transduced by different sensory receptors, processed by different brain areas). Despite such variability, subjective percepts are not experienced as sums of independent features but as integrated multimodal experiences. For example, people experience perceiving a black crow squawking rather than seeing a crow and hearing a squawk. This phenomenological observation is central to most theories of consciousness that postulate strong interdependencies between integration and consciousness (e.g., Baars, 2002; Dehaene & Changeux, 2011; Tononi, 2008, 2011). Arguably, whereas unconscious processing is thought to be encapsulated without any exchange of information between different brain areas, conscious perception involves long-range and feedback projections that enable the integration of different types of information across the brain (Dehaene & Changeux, 2011).

When information is spread across sensory modalities, its combination into a new, unified representation is called *multisensory integration*. This term refers both to combination of information into a perceptual experience (e.g., combining the visual properties of a crow with the squawking sound it makes) and to combination of information into semantic judgments (e.g., detecting the incongruity of a meowing crow). Is consciousness necessary for multisensory integration? To claim that it is not, one would need to demonstrate that two subliminal (i.e.,

Corresponding Author:
Nathan Faivre, California Institute of Technology, Biology Division, Mail Code 216-76, 1200 E. California Blvd., Pasadena, CA 91125
E-mail: nathan.faivre@epfl.ch

not consciously perceived) stimuli can nevertheless be integrated.

Previous studies of unconscious multisensory integration have shown that the processing of an invisible stimulus (e.g., under visual masking, binocular rivalry, or continuous flash suppression) is influenced by the simultaneous presence of an auditory (Alsius & Munhall, 2013; Chen & Spence, 2010, 2011; Ngo & Spence, 2010; Palmer & Ramsey, 2012), tactile (Lunghi, Binda, & Morrone, 2010), or proprioceptive (Salomon, Lim, Herbelin, Hesselmann, & Blanke, 2013) stimulus that is consciously perceived. Yet because participants in these studies were always conscious of one of the two stimuli, it could still be argued that it is the conscious perception of that stimulus that allowed for its integration with the subliminal one. Thus, none of the previous studies provides evidence for multisensory integration in the complete absence of awareness. An exception is a recent study by Arzi and colleagues (2012), in which novel associations between tones and odors were learned during sleep. However, as acknowledged by the authors, controlling stimulus awareness during sleep is difficult, and the possibility remains that the stimuli were consciously accessed when presented, but forgotten by the time of awaking.

Here, we measured multisensory integration of two subliminal stimuli at the behavioral level. To do so, we presented participants with a pair of digits—one auditory, the other visual—and asked them to judge whether the two were identical to or different from one another (e.g., the sound "eight" and the written digit "8" or "6," respectively). Critically, we tested whether such judgment can be formed even when both the written digit and the speech sound representing that digit are unconsciously presented. For this purpose, we used response priming (Kiesel, Kunde, & Hoffmann, 2007), so that after the subliminal pair of audiovisual digits, a supraliminal audiovisual pair appeared, this time of spoken and written letters, which could again be either identical to or different from one another—for example, the sound "b" (/b/) and the visual letter "b" or "m," respectively. First, participants were asked to indicate whether the auditory letter was identical to or different from the visual letter (the target task). Then they were asked to determine whether the auditory digit was identical to or different from the visual digit (the prime task). We reasoned that if the audiovisual primes were integrated despite lack of awareness, judgments of the relations between the auditory and visual target letters would be influenced by the relations between the auditory and visual prime digits (i.e., congruency priming; see van Opstal, Gevers, Osman, & Verguts, 2010, for similar experimental logic).

Accordingly, we expected shorter reaction times when judging target letters conveying the same relation as the prime (i.e., an identical target pair preceded by an identical prime pair, or a different target pair preceded by a different prime pair) than when judging target letters conveying a different relation than the prime digits (i.e., an identical target pair preceded by a different prime pair, or a different target pair preceded by an identical prime pair).

Note that this task does not probe cross-modal processing (e.g., whether participants processed the written digit "8" more quickly after hearing the sound "eight" than after hearing the sound of a different number). Rather, it directly measures the ability to integrate two stimuli by judging the relations between them, which cannot be subserved by independent unimodal processing of each stimulus separately. Such independent processes would not allow for the comparison of the prime digits, because such a comparison requires the visual and auditory pathways to be functionally connected either directly or indirectly through bimodal neurons receiving inputs from each sensory modality. Accordingly, we consider congruency priming as evidence for multisensory integration.

In the following set of experiments, we sought to (a) replicate previous findings showing that a subliminal visual stimulus can be integrated with a supraliminal auditory stimulus (Experiment 1), (b) explore whether such integration can also take place when the auditory stimulus is subliminal and the visual stimulus is supraliminal (Experiment 2), and—most important—(c) determine whether integration can occur when both auditory and visual stimuli are subliminal (Experiment 3). We further tested the role of conscious training in enabling unconscious integration (Experiment 4). Taken together, these experiments allowed us to directly estimate the role of perceptual awareness in multisensory integration.

Method

Participants

In total, 172 healthy volunteers with normal or corrected-to-normal visual acuity were recruited from the student population of the California Institute of Technology (age range: 18–34 years). Twenty-six students participated in Experiment 1 (13 females, 13 males), 28 in Experiment 2 (17 females, 11 males), 21 in Experiment 3 (10 females, 11 males), and 22 in Experiment 4 (12 females, 10 males). For Experiments 1 and 2, sample sizes were set to include 25 to 30 participants. After analyzing the results of these experiments, we estimated the effect sizes and accordingly redefined the sample sizes for Experiments 3 and 4 to include 20 to 25 participants. Seventy-five subjects participated in the control experiments (see Supplemental Experiments in the Supplemental Material available online).

Participants who could discriminate the relations of the prime pairs with an accuracy above 65% in the unconscious block were excluded from further analyses (9 in Experiment 1, 6 in Experiment 2). This cutoff was based on the accuracy distributions obtained in pilot experiments and in Experiments 1 and 2, in which most accuracy scores were distributed around chance level with a certain amount of noise that we estimated to be approximately 15% (standard deviation of accuracy was 13.0% in Experiment 1 and 14.0% in Experiment 2). All participants were naive to the purpose of these experiments and gave informed written consent. All experiments conformed to institutional guidelines and to the Declaration of Helsinki.

Stimuli and apparatus

Stimuli were presented using MATLAB (The MathWorks, Natick, MA) and the Psychophysics Toolbox (Brainard, 1997; Kleiner et al., 2007; Pelli, 1997). Participants' heads were stabilized using a chin rest located 57 cm away from a 19-in. CRT screen (resolution: 1,024 × 768; refresh rate: 100 Hz).

All primes and all targets were pairs of auditory and visual stimuli. Prime pairs were combinations of the written and spoken digits "2," "4," "6," and "8." Target pairs were combinations of the written and spoken letters "b," "j," "k," and "m" (speech sounds: /b/, /dʒeɪ/, /keɪ/, and /m/, respectively). All visual stimuli were presented in Courier font. Prime digits subtended 0.8° × 1.0° of the visual field (0.16 Michelson contrast), and target letters subtended 0.9° × 1.0° of the visual field (0.33 Michelson contrast). The visual mask was the symbol "#" (0.8° × 1.2°; 0.33 Michelson contrast). All auditory stimuli were mono sounds from Internet resources and were played binaurally using headphones. They were first resampled at 48,000 Hz, normalized, and then compressed using Audacity software (Version 2.0.5; http://audacity.sourceforge.net/) to have a 300-ms duration. Prime digits were played at 10% of the maximal intensity allowed by the sound card in the conscious condition, and 0.1% of this intensity in the unconscious condition (i.e., with a relative decrease of 20 dB compared with the conscious condition). The target letters were played at 20% of the maximal intensity. The auditory mask was a 300-ms noise pattern generated by time-domain scrambling (Ellis, 2010) the spoken sounds "3," "5," "7," and "9," played at 20% of the maximal intensity allowed by the sound card. An overlap of 80 ms was introduced between the masks and the prime and between the prime and the target, as pilot experiments showed that it substantially improved masking. Our auditory-masking method was validated by the observation of an unconscious numerical-distance effect (see Experiment 5 in the Supplemental Material).

Procedure

Experiments 1, 2, and 3 included a conscious condition that served as a training phase, followed by an unconscious condition that differed only in the presentation of the prime pair: In the conscious condition, the digits were presented supraliminally, whereas in the unconscious condition, either one or two of the stimuli in the prime pair were presented subliminally. Our task followed the logic of the congruency-priming paradigm by van Opstal and colleagues (2010; Fig. 1). In a nutshell, it consisted of manipulating the relations between an auditory and a visual digit (primes) and between an auditory and a visual letter (targets): The relations between the items in the prime pair could either be similar to those in the target pair (items in both pairs are identical or both are different) or not similar to those in the target pair (items in the prime pair are identical and in the target pair are different, or vice versa).

In each trial, the first event was the prime pair. In the visual domain, a digit was presented for 30 ms, preceded and followed by one mask and one blank screen, each lasting 50 ms. In the auditory domain, a 300-ms spoken digit was preceded by a 300-ms mask, with an overlap of 80 ms between them (so that the prime started 220 ms after mask onset). Awareness of the visual digit was manipulated by changing the location of the blank screens (Dehaene et al., 2001). In the conscious condition, the prime pair was preceded and followed by blank screens (so the participants could consciously see the digit). In the unconscious condition, on the other hand, the prime pair was preceded and followed by masks, which suppressed it from awareness. Awareness of the auditory digit was manipulated by changing its intensity (see Stimuli and Apparatus). The onset of the auditory prime corresponded with the onset of the visual sequence (i.e., onset of the mask in the conscious condition and onset of the blank in the unconscious condition), so that the visual prime was presented 50 ms after the onset of the auditory prime.

The second event in each trial was the target pair. In the visual domain, a target was presented for 200 ms (this relatively short duration maximizes aftereffects; Wolfe, 1984). In the auditory domain, a spoken letter was played simultaneously with a second mask for 300 ms (again having an 80-ms overlap with the prime). The auditory target letter was presented 10 ms before the onset of the visual target letter. Participants were asked to indicate first whether the two letters (target pair) were identical to each other (right arrow key) or different from one another (left arrow key) and then to do the same for the two digits (prime pair). They were instructed to respond as quickly and as accurately as possible about the targets. No time pressure was put on the primes task, which served as an objective measure of awareness.
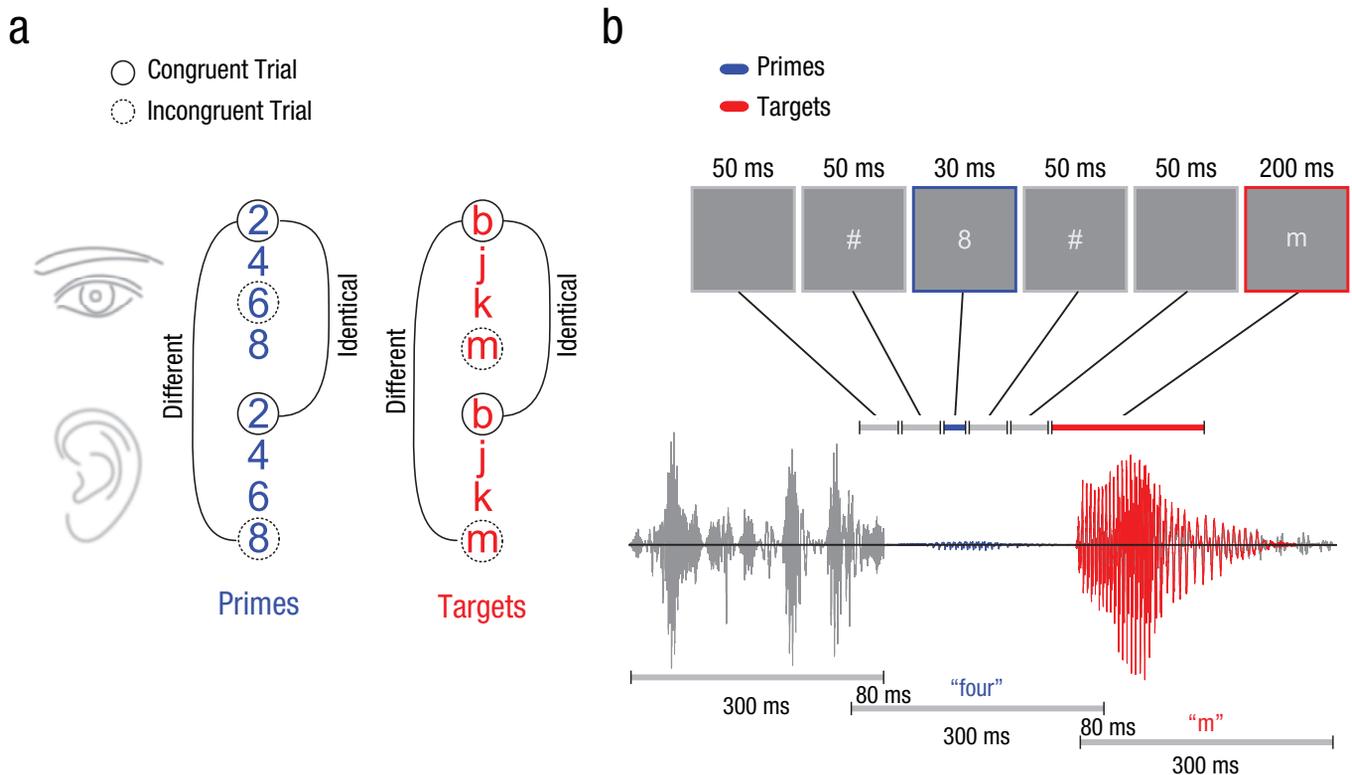
Fig. 1. Experimental design and procedure. As shown in (a), stimuli were presented in pairs consisting of a visual item matched with a spoken item. In each trial, an audiovisual prime pair was followed by an audiovisual target pair. Items within each prime pair and target pair were either semantically different (i.e., the written item did not correspond with the spoken item) or identical (i.e., the written and spoken items corresponded). In congruent trials, the items in the prime pair and the items in the target pair shared the same relation; that is, if the primes were identical, then the targets were identical, and if the primes were different, then the targets were different. In incongruent trials, the relation between items in the prime pair was different from the relation between items in the target pair; that is, if the primes were different, then the targets were the same, as in (b), and vice versa. In the example trial sequence shown in (b), streams of visual (top) and auditory (bottom) stimuli were presented simultaneously but for differing lengths of time. The middle line represents the visual stream with the same time scale as the auditory stream. Primes were preceded and followed either by blank screens (conscious condition) or by masks to suppress the stimulus from awareness (unconscious condition, shown here).

On each trial, one of four visual primes was combined with one of four auditory primes representing the same or a different digit. One of four visual targets was combined with one of four auditory targets representing the same or a different letter. The semantic relations between primes was congruent with those between targets in half the trials, and incongruent in the other half. Although congruency was mostly defined at a semantic level (i.e., on the basis of the comparison of the audiovisual primes' numerosity), it may also involve the phonetic level (i.e., phonemic awareness of "two" after seeing the digit "2" and comparison with the actual phoneme conveyed by the auditory prime). Trial order was fully randomized, both with respect to prime congruency and to its relations with the target. The first five trials of each experiment were considered training and were not analyzed. In Experiments 1, 2, and 3, participants first performed a block of 96 conscious trials in which both the auditory and the visual primes were consciously perceived. This conscious block served as training and was followed by a block of 96 partial or fully unconscious trials, in which masking was applied to the visual prime only (Experiment 1), the

auditory prime only (Experiment 2), or both the auditory and the visual primes (Experiment 3). In Experiment 4, participants performed two blocks of 96 fully unconscious trials, in which both the auditory and the visual primes were masked, with no prior conscious training.

Results

Reaction-time analysis

The average reaction time to the target pairs in the conscious and unconscious conditions were 1,412 ms (95% confidence interval, or CI = [1,230, 1,594]) and 984 ms (95% CI = [782, 1,186]) in Experiment 1, 1,165 ms (95% CI = [1,034, 1,296]) and 879 ms (95% CI = [750, 1,008]) in Experiment 2, 1,136 ms (95% CI = [983, 1,289]) and 820 ms (95% CI = [673, 967]) in Experiment 3, and 833 ms (95% CI = [653, 1,013]) in the unconscious condition of Experiment 4. Trials with a reaction time below 300 ms or above 4,000 ms were excluded (3.4% and 1.9% of trials in the conscious and unconscious conditions in Experiment 1, 0.8% and 1.5% in Experiment 2, and 1.0%

Table 1. Average Percentage of Correct Judgments Identifying the Semantic Relations Between Primes and Targets in the Conscious Conditions of Experiments 1, 2, and 3

Experiment	Primes	Targets
Experiment 1	84.4 [80.7, 88.1]	88.1 [84.8, 91.4]
Experiment 2	85.3 [82.2, 88.4]	90.4 [87.5, 93.3]
Experiment 3	80.3 [76.2, 84.4]	88.2 [84.5, 91.9]

Note: Values in brackets are 95% confidence intervals.

and 3.0% in Experiment 3, as well as 5.8% for the unconscious condition in Experiment 4).

Only trials in which the semantic relations of the target pairs were judged correctly were kept for further analyses (see Table 1 for accuracies in the conscious conditions and Table 2 for accuracies in the unconscious conditions). A logarithmic transformation was applied on the remaining reaction times in order to reduce deviations from normality that are commonly observed on raw reaction times (Whelan, 2010), so that the data met the normality assumption underlying analyses of variance (ANOVAs) and *t* tests. For a better estimation of effect sizes, we report the exponential of the effect values after logarithmic transformation (i.e., we report effects in milliseconds rather than the logarithmic unit). Reaction times in the target task were estimated using a two-way repeated measures ANOVA with targets' semantic relations (identical vs. different) and prime-target congruency (congruent vs. incongruent) as within-subjects factors and participants as the random variable. Congruency priming was calculated by subtracting participants' mean reaction time in congruent trials from their reaction time in incongruent trials, during the first task (i.e., to determine whether the target pair was made of identical or different letters). Thus, positive values indicate that reaction times were shorter in congruent trials than in incongruent trials. All tests were two-tailed. Statistical analyses were performed using R (R Development Core Team, 2013).

Experiments 1, 2, and 3

Conscious conditions. The conscious conditions of Experiments 1, 2, and 3 were identical and served as a training phase before the unconscious conditions. In all three experiments, participants could discriminate both the semantic relations of the audiovisual targets (accuracy > 88%) and the audiovisual primes (accuracy > 84%; Table 1). The ANOVA on reaction times for trials on which only correct responses were made in these first three experiments revealed a main effect of targets' semantic relations (all ps < .001; Table 3): Responses were faster for pairs of identical targets than for pairs of different targets (mean difference > 143 ms). In addition, main effects of prime-target congruency (all ps < .001; Table 3) demonstrated congruency priming: Responses were faster in congruent trials (identical prime pair and identical target pair, or different prime pair and different target pair) than in incongruent trials (identical prime pair and different target pair, or vice versa; mean difference > 269 ms). An interaction between prime-target congruency and targets' semantic relations was found in Experiment 2, $F(1, 27) = 5.29$, $p = .03$, $\eta^2 = .16$, and Experiment 3, $F(1, 20) = 5.70$, $p = .03$, $\eta^2 = .22$, which suggests that congruency priming was bigger for pairs of identical targets (e.g., the sound and the written letter "b") than for pairs of different targets (e.g., the sound "b" and the written letter "j") (respective mean differences: 78 ms and 80 ms). This interaction did not reach significance in Experiment 1, $F(1, 25) = 2.20$, $p = .15$, $\eta^2 = .08$.

Unconscious conditions

Prime visibility. In the unconscious conditions, masking was applied to the visual prime only (Experiment 1), the auditory prime only (Experiment 2), or both the visual and auditory primes (Experiment 3). We found that participants could accurately discriminate the similarity of audiovisual target pairs but not of audiovisual prime pairs, although the discriminability of prime pairs was close to being higher than chance in Experiment 1

Table 2. Average Percentage of Correct Judgments Identifying the Semantic Relations Between Primes and Targets in the Unconscious Conditions of Experiments 1, 2, 3, and 4.

Experiment	Primes		Targets
	Accuracy	*t* test	Accuracy
Experiment 1	53.3 [50.2, 56.4]	$t(16) = 2.06$, $p = .06$	92.3 [89.8, 94.8]
Experiment 2	51.6 [49.4, 53.8]	$t(21) = 1.47$, $p = .16$	95.5 [93.3, 97.7]
Experiment 3	47.2 [44.8, 49.6]	$t(20) = -2.27$, $p = .035$	94.5 [92.1, 96.9]
Experiment 4	50.0 [48.8, 51.2]	$t(21) = 0.04$, $p = .97$	93.3 [91.3, 95.3]

Note: Values in brackets are 95% confidence intervals. For primes, one-sample *t* tests were conducted to determine whether accuracy was better than chance (50%).

Table 3. Main Effects of Targets' Semantic Relations and Congruency Priming in the Conscious Conditions of Experiments 1, 2, and 3

Experiment	Effect of targets' semantic relations		Congruency priming for identical targets		Congruency priming for different targets	
	M	*F* test	*M*	*t* test	*M*	*t* test
Experiment 1	224 [134, 314]	$F(1, 25) = 26.16$, $p < .001$, $\eta^2 = .51$	390 [247, 533]	$t(25) = 5.21$, $p < .001$	337 [204, 470]	$t(25) = 5.25$, $p < .001$
Experiment 2	146 [87, 205]	$F(1, 27) = 36.10$, $p < .001$, $\eta^2 = .51$	304 [198, 410]	$t(27) = 6.11$, $p < .001$	225 [156, 294]	$t(27) = 7.09$, $p < .001$
Experiment 3	143 [67, 219]	$F(1, 20) = 15.49$, $p < .001$, $\eta^2 = .44$	312 [202, 422]	$t(20) = 6.68$, $p < .001$	232 [156, 308]	$t(20) = 6.30$, $p < .001$

Note: Main effects of targets' semantic relations were calculated by taking the mean reaction-time difference (in ms) between different and identical targets. Congruency-priming scores were calculated by subtracting participants' mean reaction time in congruent trials from their mean reaction time in incongruent trials during the target task. Values in brackets are 95% confidence intervals.

and was significantly lower than chance in Experiment 3 (Table 2). This was taken as evidence for an absence of awareness. Yet one could argue that chance-level performance for discriminating audiovisual primes could have still been obtained if participants had consciously perceived the masked stimuli yet were unable to judge the relations between the auditory and visual digits because of memory failure. This alternative explanation stems from the fact that the task of assessing the relations of the items in the prime pair always came after the task of assessing the items in the target pair. Accordingly, there was a time lag between the end of the stimuli sequence and the primes task. This time lag could have led participants to forget what the primes were (and therefore perform at chance), even if they did manage to consciously perceive them.

To exclude this possibility, we conducted three additional control experiments, in which there was no task involving the target pairs. Instead, participants were instructed to judge the relations between the visual and auditory digit primes immediately after the stimuli sequence and ignore the targets completely. Note that this instruction, together with the absence of any task involving the target, could have motivated participants to allocate more attentional resources to the prime pair, thereby enhancing its chances of being consciously perceived (Lavie, 2006). Yet even under these stringent conditions, participants' performance was still at chance when judging the semantic relations between the auditory and visual digits (see Supplemental Experiments 6–8).

In addition, because the objective measure we used specifically probed the capacity to judge the relations between the auditory and visual primes, participants could have still performed at chance even if they had perceived one of the stimuli consciously. Therefore, in Experiment 3, it could be argued that participants had partial access to either the auditory or the visual prime

(in Experiments 1 and 2, this was always the case, because only one sensory modality was masked). However, this concern is mitigated by participants' reports after the experiment that they did not perceive any of the digits. More important, the fact that chance-level performance was found in the first two experiments confirms that each modality was indeed effectively masked. Thus, it seems less plausible that one of the two primes was consciously perceived in Experiment 3.

Reaction times. In our analysis of reaction times, we found that as in the conscious conditions, there was a main effect of targets' semantic relations (all $ps < .003$); that is, responses were faster for pairs of identical targets than for pairs of different targets (mean difference > 60 ms; see Table 4). Although we found no main effect of prime-target congruency in Experiments 1, 2, and 3 ($ps = .54$, .33, and .40, respectively), interactions between targets' semantic relations and prime-target congruency were found in all three experiments ($ps = .02$, .02, and .03, respectively). In Experiments 1 and 3, this interaction stemmed from congruency priming for identical but not for different targets, whereas in Experiment 2 it reflected the opposite situation of congruency priming in different but not identical targets (Fig. 2, Table 4).

To account for the possibility that the residual visibility of the prime could have driven congruency priming, we relied on Greenwald's regression method (Greenwald, Klinger, & Schuh, 1995) and conducted a linear regression at the group level between the amplitude of congruency priming and the accuracy in the objective measure of awareness (primes task). It revealed no relations between priming and awareness (Experiment 1: adjusted $R^2 = -.03$, $p = .48$; Experiment 2: adjusted $R^2 = -.04$, $p = .75$; Experiment 3: adjusted $R^2 = -.03$, $p = .48$). Finally, to detect potential differences of reaction times in the primes task, we ran a 2 × 2 repeated measure ANOVA with relation and primes congruency as within-subjects

Table 4. Main Effects of Targets' Semantic Relations and Congruency Priming in the Unconscious Conditions of Experiments 1, 2, 3, and 4

Experiment	Effect of targets' semantic relations		Congruency priming for identical targets		Congruency priming for different targets	
	M	*F* test	*M*	*t* test	*M*	*t* test
Experiment 1	89 [42, 136]	$F(1, 16) = 20.49$, $p < .001$, $\eta^2 = .56$	47 [4, 90]	$t(16) = 2.18$, $p = .04$	−17 [−68, 34]	$t(16) = 0.92$, $p = .37$
Experiment 2	61 [14, 108]	$F(1, 21) = 11.54$, $p = .003$, $\eta^2 = .35$	−11 [−35, 13]	$t(21) = 1.10$, $p = .28$	37 [2, 72]	$t(21) = 2.25$, $p = .035$
Experiment 3	95 [40, 150]	$F(1, 20) = 14.82$, $p = .001$, $\eta^2 = .43$	59 [0, 118]	$t(20) = 2.18$, $p = .04$	−32 [−75, 11]	$t(20) = 1.17$, $p = .26$
Experiment 4	79 [42, 116]	$F(1, 20) = 26.38$, $p = .001$, $\eta^2 = .56$	25 [−17, 67]	$t(21) = 0.84$, $p = .41$	4 [−22, 30]	$t(21) = 0.05$, $p = .96$

Note: Main effects of targets' semantic relations were calculated by taking the mean reaction-time difference (in ms) between different and identical targets. Congruency-priming scores were calculated by subtracting participants' mean reaction time in congruent trials from their mean reaction time in incongruent trials during the target task. Values in brackets are 95% confidence intervals.

factors. No effect reached significance in the unconscious conditions of Experiments 1 through 3 (all *p*s > .2). As this effect is commonly found in the field of unconscious cognition, we should note that congruency effects were found only for reaction times (and not for response biases or accuracies), probably because unconscious stimuli have a weak impact on overt responses (see Kouider & Dehaene, 2007, for a review).

Taken together, our results show that multisensory integration can take place when participants are unaware of one, and even both, of the integrated stimuli. Even though the unconscious priming effects we found were
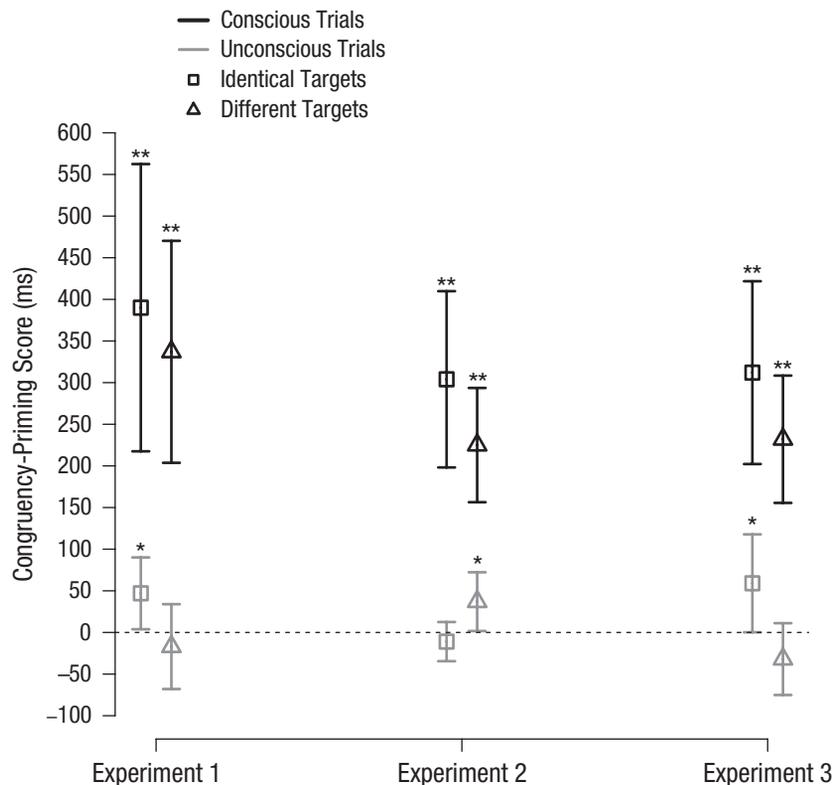
Fig. 2. Mean congruency-priming scores in Experiments 1, 2, and 3, separately for trial type and for the relation between items in target pairs. Congruency-priming scores were calculated by subtracting participants' mean reaction time in congruent trials from their mean reaction time in incongruent trials during the target task. Error bars represent 95% confidence intervals. Asterisks indicate conditions in which the mean congruency-priming score was significantly different from zero (*p* < .05, **p* < .001).

relatively large (around 50 ms, corresponding to ~5% of the total reaction time), their amplitude was nevertheless much lower compared with the conscious effects (around 300 ms, corresponding to ~25% of the total reaction time). Such smaller effect sizes are typical of unconscious processes, both with respect to perceptual aftereffects and higher-level cognitive functions (e.g., Blake, Tadin, Sobel, Raissian, & Chong, 2006). Here, we are facing the conundrum of whether conscious access has a causal role in the decrease of priming or whether this decrease is simply due to the reduced stimulus strength imposed by masking. The latter hypothesis is challenged by the fact that masking did not affect multisensory integration in an additive manner: The amplitude of priming was not smaller when masking was applied to both the auditory and visual primes, compared with when it was applied to either the auditory or the visual prime separately (Table 4).

An aspect of our results that remains unclear is why unconscious congruency priming was found for identical targets in Experiments 1 and 3, and for different targets in Experiment 2, in which masking was applied to the auditory prime. In a control experiment, we ruled out the possibility that this may stem from a failure in unconscious auditory processing (see Supplemental Experiment 5 for auditory semantic priming). Several differences between Experiment 2 and Experiments 1 and 3 could possibly account for this pattern of results. First, Experiment 2 was the only experiment in which the visual prime was consciously perceived (in Experiment 1, the auditory prime was consciously perceived, and in Experiment 3, both primes were suppressed from awareness). This could have led to differential processing of semantic relations, in line with the modality-appropriateness framework (Welch & Warren, 1980), according to which multisensory integration varies as a function of the perceptual strength of the relevant stimuli.

Second, in Experiment 2, there was a decrease of sound intensity between the conscious and unconscious conditions (i.e., a 20-dB change). Such a change in stimulus energy was previously found to invert semantic priming (Wentura & Frings, 2005). In addition to stimulus energy, the difference in duration between the auditory and visual components of the prime pairs also might have led to this difference between experiments: Although the visual digits were presented for 50 ms, the auditory ones lasted 300 ms. Previous studies have shown that in the visual domain, prime duration can invert the direction of priming effects (Barbot & Kouider, 2012; Faivre & Kouider, 2011). Accordingly, this might have given rise to the pattern of results observed here. Finally, the priming effect we found in Experiment 2 may have partly been driven by the repetition of the target's congruency across trials, as priming was marginally larger in trials in which two or more congruent or incongruent targets were subsequently presented than in trials in which target congruency alternated ($p = .05$). No such carryover effects from one trial to another were found in the other experiments (all $ps > .19$). Future studies may be able to shed more light on the different mechanisms that come into play during multisensory integration of a supraliminal stimulus with a subliminal one, and of two subliminal stimuli.

Experiment 4

Experiment 4 examined the role of conscious training in enabling unconscious multisensory integration. To do this, we masked both the visual and the auditory primes, and no conscious training was performed. Instead, participants performed two blocks of 96 unconscious trials, which means they never consciously saw or heard the prime pairs.

As in Experiments 1, 2, and 3, participants could accurately discriminate the semantic relations of the audiovisual targets but not of the audiovisual primes (Table 2). We found a main effect of targets' semantic relations, with faster responses for identical than for different targets (Table 4). However, we did not find a main effect of prime-target congruency, $F(1, 21) = 0.47$, $p = .50$, $\eta^2 = .02$, nor an interaction between the two regressors, $F(1, 21) = 0.56$, $p = .46$, $\eta^2 = .03$. To further assess whether the lack of priming stemmed from insufficient sensitivity of our experimental design or from a genuine lack of effect, we computed Bayes factors (referred to as B hereafter; see Jeffreys, 1961; Dienes, 2011; $0.33 < B < 3$ suggests insensitivity, and $B < 0.33$ implies no effect). The priming effects were modeled as uniformly distributed between 0 ms and 59 ms (i.e., the biggest unconscious priming effect found across all experiments). We found that B was equal to 0.21 for identical targets and 0.23 for different targets, which provides substantial evidence for the null hypothesis. The lack of any congruency effect suggests that in Experiment 4, no multisensory integration of the prime pairs took place. Notably, unconscious training was not sufficient to enable multisensory integration, as no difference in priming was found between the first and second part of the experiment ($p > .3$). Similar results were found when comparing the first with the second half of trials in the unconscious conditions in Experiments 1, 2, and 3 (all $ps > .19$). This suggests that conscious training is needed for subsequently integrating the subliminal prime pairs, possibly by enabling task-related strategies (though here, direct stimulus-response mapping is unlikely considering the large number of possible combinations in our experimental design). Finally, a 2 × 2 repeated measures ANOVA with relation and prime congruency as within-subjects factors revealed no difference of reaction times in the primes task ($p > .2$).

Discussion

In a series of four experiments, we investigated the role of consciousness in multisensory integration by systematically manipulating the conscious accessibility of audiovisual stimuli with masking. The results of Experiment 1 confirmed that an invisible visual stimulus can be integrated with a consciously perceived stimulus (here, in the auditory domain), in line with previous studies (see Alsius & Munhall, 2013; Chen & Spence, 2010, 2011; Ngo & Spence, 2010; Palmer & Ramsey, 2012, for similar conclusions with different experimental setups). The results of Experiment 2 then showed that such integration can take place also for a subliminal auditory stimulus and a consciously perceived visual one. Most crucially, Experiment 3 revealed that multisensory integration can occur even when both stimuli are subliminally presented using masking. This is, to our knowledge, the first demonstration of multisensory integration in complete unawareness, with strict measures of stimulus discriminability in awake participants (see Arzi et al., 2012, for multisensory integration during sleep).

Our findings are of special interest when considering the central role commonly assigned to consciousness in information integration (Dehaene & Changeux, 2011; Mudrik, Faivre, & Koch, 2014; Tononi, 2008, 2011). Some researchers (e.g., Baars, 2002) have even specifically postulated that consciousness is necessary for multisensory integration, claiming that global broadcasting of information during conscious access is required for the integration of incoming signals from different sensory modalities. Yet others have claimed that multisensory integration can take place even without such global access. Two possible mechanisms can underlie such unconscious integration. According to the global-neuronal-workspace theory (Dehaene & Changeux, 2011; Dehaene & Naccache, 2001), multisensory integration can be performed by multimodal encapsulated neurons that are not connected to the global workspace (Dehaene, 2014). Such neurons have been described at relatively low-level structures in the brain, including subcortical regions like the superior colliculus (see Meredith & Stein, 1986; Stein & Stanford, 2008, for a review).

Other researchers have claimed that multisensory integration can occur shortly after stimulus onset via feedforward connections between sensory cortical areas (Schroeder & Foxe, 2005); such rapid, early integration arguably takes place unconsciously. In the context of the present study, then, we can conjecture that visual and auditory primes were first processed in their corresponding sensory cortices, the congruency between the auditory and the visual digits being subsequently discriminated either through connections to a bimodal area involved in the processing of numeracy (e.g., intraparietal sulcus; see

Piazza & Izard, 2009) or through direct communications between the visual and auditory cortices.

Our results shed new light on the enabling role of consciousness in multisensory integration. We found that participants were able to integrate the subliminal visual and auditory stimuli when they had previously performed the task consciously (Experiment 3) but not when they had previously performed the task unconsciously (Experiment 4). This suggests that conscious but not unconscious training enabled multisensory integration. Plus, we found that effect sizes between the conscious and unconscious conditions differed greatly. Considering these three points, we suggest two nonmutually exclusive mechanisms explaining the facilitating effect of consciousness during multisensory integration. One is that the conscious processing of audiovisual pairs in the conscious condition facilitated the independent, unisensory processing of both the auditory and the visual digits—but not necessarily their integration. Applied to our study, this would entail that following conscious training, the unconscious processing of each component of the prime pair is improved, which subsequently facilitates their unconscious integration. In the absence of conscious training, on the other hand, the unconscious processing of each component is weak, leading to the failure (or even absence) of unconscious integration. In line with this interpretation, multisensory experiences are known to induce long-lasting facilitatory effects on subsequent unisensory processes (e.g., see Thelen & Murray, 2013, for a review). This mechanism would be supported by experiments showing that conscious training increases the magnitude of unisensory priming effects (e.g., semantic priming within a sensory modality) beyond that of multisensory ones (e.g., audiovisual congruency priming).

Another possibility is that conscious training facilitates integrative processes themselves, and not only the unisensory processing of the integrated components. In other words, conscious exposure to the stimuli and context of the task enables the mechanisms by which audiovisual digits are compared. Only after these mechanisms have been consciously laid down can they be activated automatically, in the absence of awareness. This interpretation is supported by the view that consciousness is needed for establishing novel strategies and adapting to new stimuli sets and tasks (Dehaene & Naccache, 2001) and that multisensory integration is highly adaptive to contextual factors (van Atteveldt, Murray, Thut, & Schroeder, 2014). Our results do not allow us to conclude which of these two interpretations is more accurate, hereby calling for further research. For instance, evidence for unconscious multisensory integration following conscious training on another set of audiovisual primes (e.g., using the odd digits "1," "3," "7," "9" in the training and the even ones "2," "4," "6," "8" in the experimental phase) would support the latter interpretation and render the former less likely.

Conclusions

Our findings reveal that the relations between conscious and unconscious integrative processes are more complex than sometimes assumed (Mudrik et al., 2014). Typically, the role of consciousness in cognitive functions is described in an all-or-none manner: Either it is necessary for a process or not, without comparing performances during conscious and unconscious processing. Here, we suggest that consciousness may serve as an enabling factor, allowing for the establishment of novel networks that are subsequently used during unconscious multisensory integration (Crick & Koch, 2003; Dehaene & Naccache, 2001). Further studies are needed in order to generalize this hypothesis, possibly by manipulating the number, novelty, and temporal dynamics of multimodal stimuli, their complexity and ecological value, and the level of stimulus-response mapping. Only then will researchers be able to provide a comprehensive account of the role of consciousness in integrative processes.

Supplemental Material

Additional supporting information can be found at http://pss.sagepub.com/content/by/supplemental-data

Open Practices

All data and materials have been made publicly available via Open Science Framework and can be accessed at https://osf.io/usfa5/?view_only=1f2e1994fc6247548499f47de64a2650. The complete Open Practices Disclosure for this article can be found at http://pss.sagepub.com/content/by/supplemental-data. This article has received badges for Open Data and Open Materials. More information about the Open Practices badges can be found at https://osf.io/tvyxz/wiki/view/ and http://pss.sagepub.com/content/25/1/3.full.

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