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Assessing the Functional Role of Motor Response During the Integration Process

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The aim of this study was to provide evidence that actions performed by an individual influence the sensorimotor memory processing and, in particular, the integration process. We conducted 3 experiments that highlighted the multimodal aspect of memory traces. The 1st experiment consisted of a short-term priming paradigm based on 2 phases: a learning phase, consisting of the association between a shape and a sound, and a test phase, examining the priming effect of the shape seen in the learning phase on the processing of target tones. The participants' motor response became a factor in Experiments 2 and 3, allowing us to observe its influence on the integration between the shape and the sound. In Experiment 1, we showed that (a) the prime associated with the sound in the learning phase had an effect on target processing and (b) the component reactivated by the prime was perceptual in nature (i.e., auditory). Experiment 2 showed that the participants' responses were faster when the association of a shape and a sound had been learned with a motor response rather than without. Experiment 3 showed that the integration process required the individual to act while learning the association between the shape and the sound; otherwise no integration effect was observed. Our results highlight the role of motor responses as a necessary criterion for the integration process to take place.

Keywords: memory traces, integration, binding, action, sensorimotor components

The fact that human beings are constantly performing actions has only recently been taken into account in studies aiming at understanding the way humans learn and perceive their environment (Chemero, 2009; Engel, Maye, Kurthen, & König, 2013; Zimmer et al., 2001). This major step in cognitive research is underpinned by a relatively new conception of human memory and perception and in particular how the latter depend on interactions between the body and its environment (Clark & Chalmers, 1998; Wilson, 2002). In this context, the integration process (also called "binding process," depending on the theoretical framework), which is at the interplay between individuals' major cognitive functions, is often held responsible for the perception of a multisensory environment (King, 2005) by unifying their perceptions of the different aspects of our cognitive experiences. Indeed, the integration process binds the various sensorimotor units and their consecutive activations in a single percept, or event (Hommel, 2004), and holds together individuals' former and current experiences (Versace et al., 2014). The existence of such a process and its implication in multisensory perception has been well demonstrated by the phenomenon of perception bias. A well-known example of these biases is the McGurk effect (McGurk & MacDonald, 1976), which suggests the integration of auditory and visual perception (King & Calvert, 2001). By showing that participants tended to perceive /da/ when they see someone pronouncing the syllable /ga/ and hear the sound /ba/, McGurk and MacDonald (1976) demonstrated the ability of one sensory system to modify the processing of another sensory system. Many other examples of the integration process have been demonstrated with various sensory modalities across different cognitive functions (on memory and perception, see Brunel, Labeye, Lesourd, & Versace, 2009; Versace, Labeye, Badard, & Rose, 2009; Versace et al., 2014; on perception and action, see Corveleyn & Coello, 2014; Hommel, 2004; Tucker & Ellis, 1998, 2001; on perception and emotion, see Brouillet, Heurley, Martin, & Brouillet, 2010; Milhau, Brouillet, & Brouillet, 2015; on memory and emotion, see Damasio, 1994; on memory and action, see Brouillet et al., 2015; Glenberg, 1997; Zimmer et al., 2001). The integration process is thereby considered a main pillar of our cognitive system.

Yet, a question remains regarding the difficulty of separating sensory and motor dimensions when considering what should be integrated into a unitary event or episodic memory trace. According to Hommel's theory of event coding (TEC; Hommel, Müsseler, Aschersleben, & Prinz, 2001), the perception of the world is a process of actively acquiring information, and there is therefore no reason to draw any distinction between motor and sensory features. In other words, perceiving an object (such as an apple, for instance) would involve not only sensory aspects (e.g., shape, color, taste) but also motor responses (e.g., grasp, eye saccade). During perception, motor components are linked with sensory components in what Hommel calls an *event-file* (Hommel, 1998; see Zmigrod & Hommel, 2013, for a review). Using the event-file paradigm, Hommel and collaborators showed various integration phenomena between unisensory features (visual: Hommel, 1998;

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auditory: Zmigrod, Spapé, & Hommel, 2009) and multisensory features (Zmigrod & Hommel, 2011). Classically, in this paradigm, participants see a single object as prime (S1) and probe (S2). Results have shown that performance is equally good if all the features are repeated or changed between S1 and S2 (Hommel, 1998; see Zmigrod & Hommel, 2013, for a review). However, the performance is significantly altered in the case of partial repetitions (i.e., if one feature is repeated while the others are changed). Because an event-file is supposed to be reactivated whenever at least one feature is repeated, this cost observed during the S2 processing has been interpreted as evidence that an integrated event-file was created during the S1 processing (see Hommel, 2004). This effect has been observed irrespective of the sensorimotor modification between S1 and S2 (see Hommel, 1998; Zmigrod et al., 2009). In sum, TEC assumed that motor responses should be considered intrinsically linked with sensory features into an event-file (Hommel, 2004, 2015; see also Versace et al., 2014). However, the question remains as to whether motor and sensory components are functionally equivalent regarding the integration process.

Recent studies have shown that the integration process depends on temporal and spatial aspects of the situation (see Zmigrod & Hommel, 2013, for a review), as well as on the relation between the sensory features (see Parise & Spence, 2009). However, Zmigrod and Hommel (2011) showed that an integration effect could still be observed even when participants perceived two perceptual features (a color and a sound) presented asynchronously (see also Hommel, 1998). This result may seem relatively counterintuitive because synchronous presentation was thought to be a critical condition for the integration process (see Zmigrod & Hommel, 2013, for a review). Zmigrod and Hommel (2001) interpreted their effect as evidence of a modulation of the temporal integration window. An alternative explanation could be that responding to a stimulus produces an integration between its sensory components, irrespective of the temporal relation between the components. For instance, Corveleyn, Lopez-Moliner, and Coello (2012) showed that performing a motor action directly influenced the temporal order judgment between features that were seemingly unrelated and presented asynchronously (see also Parise & Spence, 2009, with cross-modal correspondence). In their experiment, Corveleyn and colleagues asked the participants to decide which attribute of a stimulus changed second (i.e., color or position, Experiment 1) and manipulated the condition under which the participants made their judgment. The results showed that when the participants performed a motor action (i.e., reaching the target-stimulus with their finger) while the attribute was changing, it considerably reduced the perceived temporal asynchrony between the visual changes. The authors suggested that motor action overcomes the temporal constraint associated with the integration of sensory components.

In line with Corveleyn et al. (2012), we assumed here that the motor action should be considered as an integration criterion, as well as the temporal and spatial aspects of the stimuli (see for instance Zmigrod & Hommel, 2013). Our objective was to test whether and how performing a motor response during learning affects the integration process. More specifically, our work investigated for the first time whether performing a motor response to multisensory stimuli has a direct consequence on the integration of the stimuli. To do so, we worked with task-relevant and nonspecific motor responses, meaning that the motor actions (a) were related to the task in which the participants were involved (i.e., task-relevant) and (b) were different between the learning and the test phases (i.e., nonspecific) to highlight a general and functional effect of the motor response on the integration process. We used a short-term priming protocol inspired by Brunel et al. (2009), where the authors highlighted the relevance of the integration process in explaining the cognitive ability to create multisensory episodic memory traces. This previous study did not allow testing whether performing an action affected the integration process, because participants had to systematically perform a motor response during the whole learning phase. The originality of the present study is to explicitly incorporate the motor response as a factor in three experiments to investigate its influence on the integration of multisensory stimuli.

Our Experiment 1 used the paradigm of Brunel et al. (2009, Experiment 1). During the first phase (the learning phase), participants had to learn different associations between two visual shapes and a white noise, one shape being associated with white noise and the other one with silence (see Figure 1). During the second phase (the test phase), participants had to categorize pure sounds, while being previously primed with the visual shapes of the learning phase (see Figure 1). The duration of the prime was manipulated to highlight the intrinsic sensorimotor characteristics of the components coded in the memory trace. If one considers that the activated auditory memory component keeps all of its encoded characteristics (duration and frequency), in the case where the prime duration is the same as that of the white noise that was associated with the shape during the learning phase, the activation of the auditory component should facilitate the processing of the auditory target. In fact, a white noise is a sound with an intensity equal to that of all frequencies within a broad range of frequencies (Kuo, 1996); thus, it contains auditory frequencies that are the same as those of the target sounds. The facilitation effect could therefore be explained by the preactivation of a sensory modality that aids subsequent processing in the same modality and does so to a greater extent when the frequencies of the auditory target are present in the reactivated white noise. In contrast, when the prime duration is shorter than that of the white noise associated with the shape during the learning phase, the activation of the auditory component should interfere with the processing of the auditory target. The interference effect could then be due to the temporal overlap between the reactivation of the previously associated white noise and the target sound (see the test phase in Figure 1): Participants would still be processing the reactivated white noise when asked to categorize the pure tones, which would lead to an auditory conflict between the integrated sound and a concurrent auditory coding process (Brunel et al., 2009; Hommel et al., 2001). In sum, we expected to find that only the prime shape previously associated with white noise would have an effect on the sound classification and that this effect would be modulated by the duration of the prime: A facilitation effect was expected if the prime duration were the same between the learning and the test phase (500 ms), whereas an interference effect was expected if the prime duration were shorter in the test than in the learning phase (100 ms).

In line with these predictions, there is increasing evidence in the literature that the sensorimotor characteristics are kept in memory traces, so that the reactivation of memory components is either able to facilitate (see Pecher, Zeelenberg, & Barsalou, 2004; Van

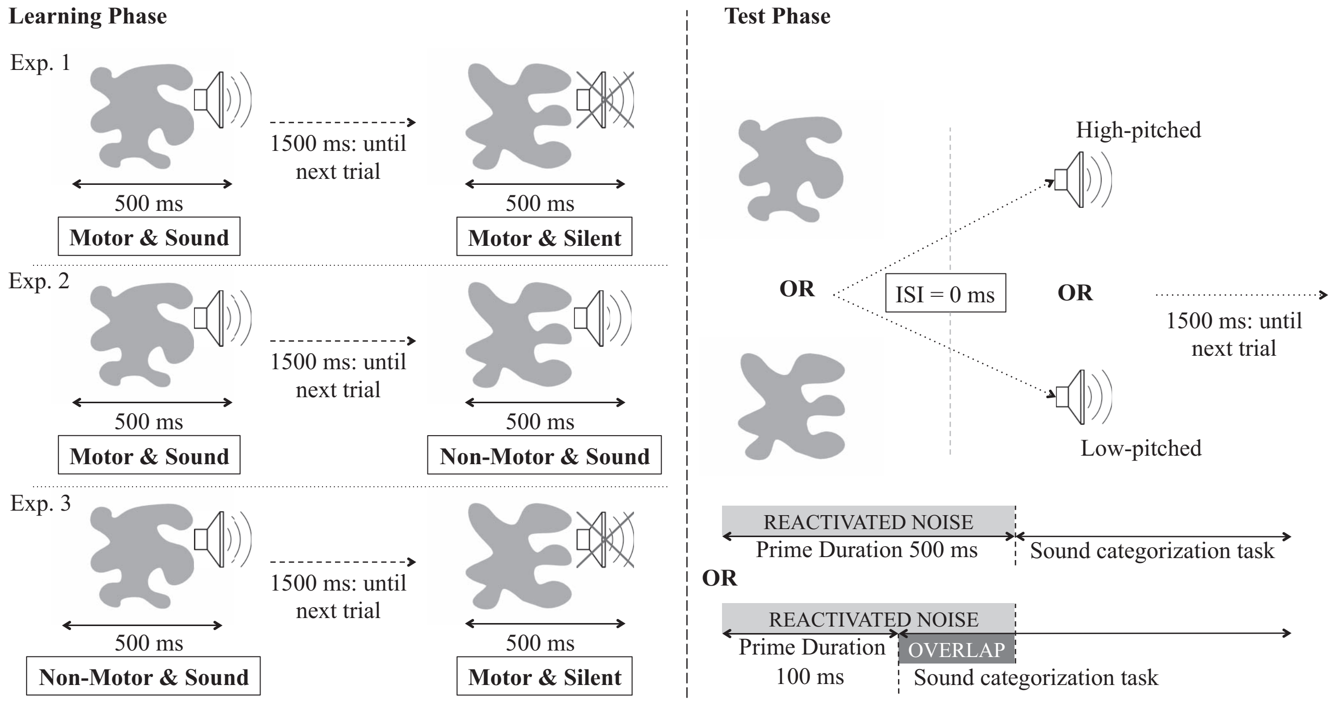

Figure 1. Schematic representation of the experimental protocol. Organization of the trials in the learning phase and in the test phase for each experiment. Exp. = experiment; ISI = interstimulus interval.

Dantzig, Pecher, Zeelenberg, & Barsalou, 2008) or interfere (see Vermeulen, Corneille, & Niedenthal, 2008) with ulterior processing of stimuli that share the same perceptual characteristics as the reactivated ones. The originality of our procedure was to manipulate and predict these two patterns within a single paradigm. Also, this procedure allowed testing whether the perceptual nature of the auditory component is maintained in the memory trace, by observing the effect of the priming shape's duration on target processing. An amodal perspective would consider that each memory trace that codes for white noise does not possess any sensorimotor characteristics (in particular, nothing related to frequency or duration). In such a case, there is no reason to predict any interference or facilitation as a function of the prime duration; rather, a facilitation effect irrespective of the prime duration would be expected, due to a mere spread of activations between amodal representations (i.e., from the representation of the prime to the representation of the "sound").

Experiment 2 was designed to manipulate the presence or absence of a motor response during the learning phase; that is, participants had to respond to only one of the two shapes, although both were presented with white noise (see Figure 1). If the motor response were functionally relevant to the integration process, one would expect that pairing a white noise to a visual shape would lead to the integration of the two only when followed by a motor response. Conversely, the absence of a motor response would impair the integration process, meaning that the non-motor, noise-paired shape would behave like the silent shape in Experiment 1. The success of the integration was then tested by presenting the previously noise-paired shapes as primes, with the expectation that the one learned with a motor response would either speed up (facilitation) or slow down (interference) the following pure tone categorization task, depending on the prime duration, in the same way as in Experiment 1.

Experiment 3 was designed to test whether the motor response could be considered as an integration criterion. In this experiment, participants performed a motor response with the shape paired with silence, whereas no motor response was performed with the shape that was systematically paired with white noise (see Figure 1). In this experiment, we expected two distinct patterns of results. If the motor response were functionally relevant but not necessary to the integration process, one should observe the same pattern of results as seen in both previous experiments. This would mean that one would observe a facilitation or an interference effect depending on the prime duration (as in Experiment 1 and 2), because the experiment would then boil down to opposing a noise-paired shape to a silent shape (the motor response not playing a critical role). However, if the motor response were a necessary criterion for the integration process, one should not observe any priming effect, meaning that one then would not expect to see any difference between the two conditions.

Experiment 1

Method

Participants. Forty-eight right-handed voluntary participants were recruited for this experiment (41 female; $M = 20.35$, $SD = 3.7$, age range = 17–38). All of them were students at Paul Valery University in Montpellier, France, and had normal or corrected-to-normal vision.

Stimuli and material. The visual stimuli were of two different shapes (i.e., blobs), with the same surface area and the same number of growths (equally distributed from a vertical symmetrical axis), and both shapes fitted in a 12 × 12 cm square (see Figure 1). They were created using AutoCAD to control such characteristics (AutoCAD, 2014). The two particular shapes used for this experiment were chosen from among eight shapes: We performed a similarity test on the eight shapes presented in pairs and rated them on a 7-point Likert scale ranging from 1 (*identical pairs*) to 7 (*most dissimilar pairs*). We analyzed the results using a multidimensional scaling analysis and chose the most dissimilar shapes on each dimension. The shapes could be in one of four different colors: red, green, purple, and blue. Those colors, although meaningless for the purpose of the task, were chosen using a CIE*LAB referential to be different but perfectly equidistant between themselves.

The auditory stimuli consisted of a white noise during the learning phase and two pure tones during the subsequent phase of the experiment: a high-pitched one of 312 Hz and a low-pitched one of 256 Hz. The auditory stimuli were created using Audacity software (Audacity, 2015). They were presented in monophony using Sennheiser HD 419 headphones and had a duration of either 100 ms or 500 ms. The experiment was conducted on a Fujitsu microcomputer (ESPRIMO Mobile V6535; Fujitsu Technology Solutions) using E-Prime software Version 2.0 (Schneider, Eschman, & Zuccolotto, 2002) to create and manage the experiment. Except for the visual stimuli used, this first experiment was identical to the one conducted by Brunel et al. (2009, Experiment 1).

Procedure and design. After filling in a written consent form, each participant performed the experiment individually during a session that lasted approximately 15 min in total. The experiment consisted of two phases.

During the first phase, referred to as the learning phase, each trial consisted of the presentation of one of the two shapes for 500 ms, with one of them being presented simultaneously with white noise, whereas the other was presented without noise (see procedure in Figure 1). For half of the participants, one shape was presented with white noise and the other was presented without sound, whereas the opposite arrangement was used for the other half of the participants. Each shape was presented 40 times (i.e., 10 times for each of the different colors) in a random order. During the instructions, the participants were told that a particular shape was associated with a particular key on the keyboard (the *Q* and *M* keys, with opposite order for half of the participants). The participants were then told to identify which shape had been presented by pressing the appropriate key on the keyboard, without paying attention to the color of the shape. All the visual stimuli were presented in the center of the screen, and the intertrial interval was 1,500 ms long. Participants completed a total of 80 trials, and the 16 first served as a training phase. It is important to note that all noise-paired shape or silent shape associations required a motor response during the learning phase.

The second phase consisted of a short-term priming paradigm (see the procedure in Figure 1). The participants were told to perform a sound categorization task and had a short training phase (four trials) to be able to fully discriminate the two sounds. For half of the participants, the prime (i.e., one of the two shapes of the learning phase) was presented for a period of 100 ms, whereas it was presented for 500 ms for the other half of the participants. The prime was immediately followed by a target sound that was either the high-pitched one or the low-pitched one. Then the participants had to judge as quickly and accurately as possible whether the target sound was low-pitched or high-pitched and indicate their choice by pressing the appropriate key on the keyboard. All the participants were instructed to keep their eyes open during the whole phase. The target sound occurred immediately upon the disappearance of the prime, which had a duration of either 100 ms or 500 ms in the two groups of participants, respectively. All the visual stimuli were presented in the center of the screen, and the intertrial interval was 1,500 ms. In sum, each participant saw a total of 100 trials during the second phase, 50 with each target sound, among which 25 were presented with a prime corresponding to the previously learned noise-paired shape and 25 were presented with a prime corresponding to a previously learned silent shape. The order of the different experimental conditions was randomized. The 100 experimental trials were preceded by the four practice trials. The time delay between the learning, and the test phase never exceeded 15 s.

Results and Discussion

Learning phase. We performed Student tests and Wilcoxon's tests on the error rates and Student tests on the latencies for the two different shapes' associations. We found no significant effect between our treatments. These results are consistent with the idea that participants performed the task accurately (the overall error rate was 2.1%) and that the systematic association between a sound and a shape did not impact the visual nature of the task (see Gallace & Spence, 2006, for a similar interpretation). The same pattern of results was found throughout the learning phase in all experiments (respectively, 1.5% and 3.4% for Experiment 2 and Experiment 3). This phase led participants to integrate the visual shape and the auditory tone within a single memory trace. As a consequence, the visual prime shape should have been able to influence the processing of the target tone during the test phase (see also Brunel, Carvalho, & Goldstone, 2015; Brunel, Goldstone, Vallet, Riou, & Versace, 2013; Brunel et al., 2009; Brunel, Lesourd, Labeye, & Versace, 2010).

Test phase. The mean correct response latencies and the mean error rates were calculated across participants and for each experimental condition (see Table 1). Latencies below and above two standard deviations were removed (the same cutoff was used throughout all the experiments and never led to the exclusion of more than 9% of the data). We performed an analysis of variance (ANOVA) on error rates and latencies, with subjects as a random variable, prime type (prime associated or not associated with a white noise in the learning phase) as a within-subject factor, and prime duration (100 ms or 500 ms) as a between-subjects factor. For the latencies, we expected a significant Prime Type × Prime Duration interaction, which is what we found in our analyses, $F(1, 46) = 12.19$, $p = .001$, $\eta_p^2 = .21$, where η_p^2 was calculated as $(SS_{between})/(SS_{between} + SS_{error})$ (SS stands for Sum of Squares; see Figure 2). There was no significant main effect or any significant interaction of the error rates between our treatments. This result could be explained by a ceiling effect because the overall error rate was 4%.

Table 1
Mean Reaction Times (RTs) and Mean Error Rates (ERs) in Each Experimental Condition

	Learning phase				Test phase: Prime duration 100 ms				Test phase: Prime duration 500 ms			
Prime type	RT (ms)	*SE* (ms)	ER (%)	*SE* (%)	RT (ms)	*SE* (ms)	ER (%)	*SE* (%)	RT (ms)	*SE* (ms)	ER (%)	*SE* (%)
Experiment 1												
Motor & Sound	425	20	2.1	.6	713	38	2.7	.8	690	35	6.5	2.3
Motor & Silent	427	18	2.1	.6	701	37	2.3	1	711	36	4.5	2
Experiment 2												
Motor & Sound			1.8	.4	730	48	4	1.4	627	25	2.5	1.1
Non-Motor & Sound			1.1	.5	716	47	3.1	.9	642	27	2.6	1.1
Experiment 3												
Motor & Silent			3.9	1.4	740	45	4.7	1.4	594	32	3.7	1.3
Non-Motor & Sound			2.9	1.4	742	43	4.6	1	599	32	4.2	1.1

The priming effects were reversed for the two different prime durations, which was consistent with Brunel et al. (2009, Experiments 1 and 2a). The Student tests used for comparisons showed that with a prime duration of 500 ms, the responses were significantly faster when the prime consisted of the shape that had been associated with white noise during the encoding phase (hereafter referred to as Motor & Sound prime) than when the prime consisted of the shape that had not been associated with noise (hereafter referred to as Motor & Silent prime), $t(23) = 2.85$, $p < .01$, $d = 0.58$ (i.e., Cohen's d = mean difference ÷ standard devia-

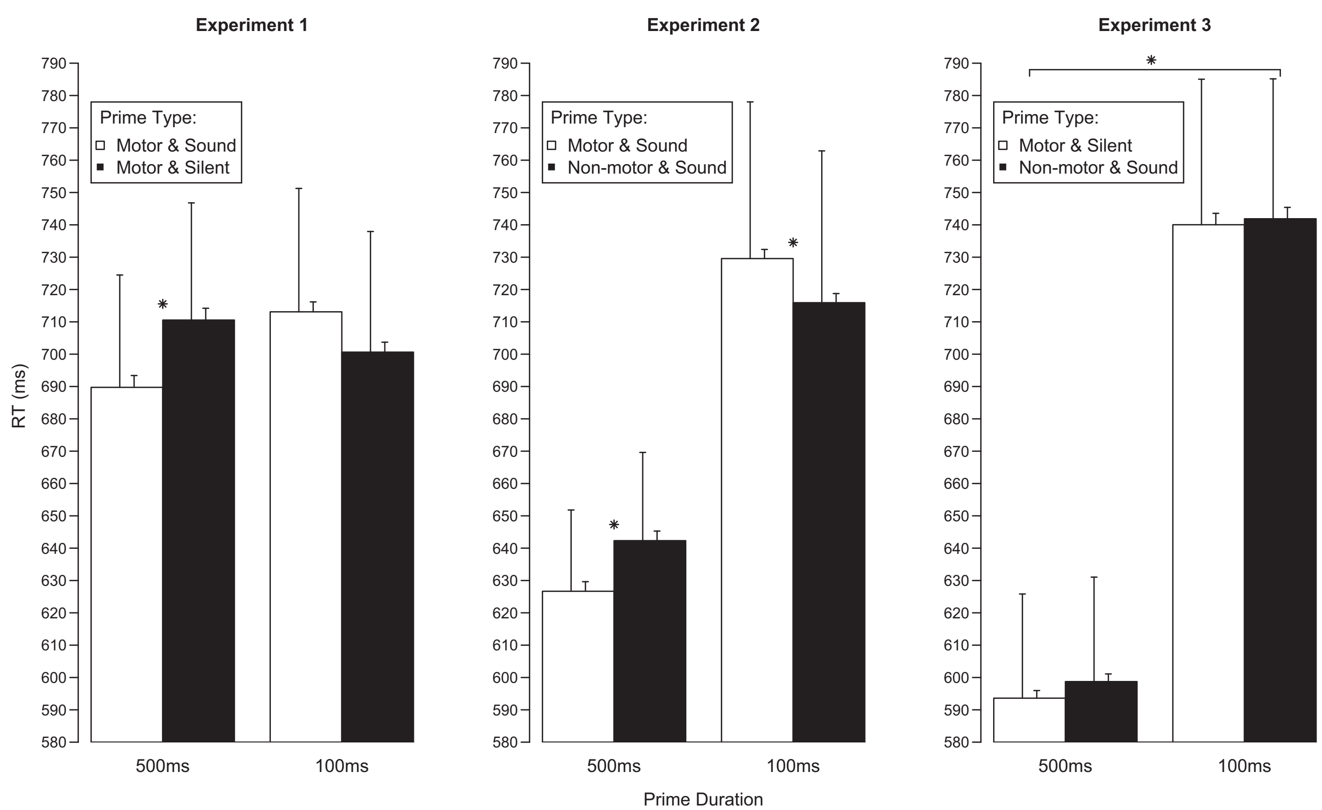

Figure 2. Average of the mean reaction times (RTs) for each prime type and for the two prime durations (500 ms and 100 ms). Raw data correspond to the mean RT of each participant (for a given prime type and prime duration). Each bar represents the average of these mean RTs across participants. On each mean, the left error bar indicates one SEM calculated between-subjects, and the right error bar one SEM calculated within-subject (Loftus & Masson, 1994). * $p < .05$.

tion). In contrast, when the prime duration was 100 ms, the responses were marginally significantly faster with the Motor & Silent prime than with the Motor & Sound prime, $t(23) = 2.03$, $p = .054$, $d = 0.41$.

Those results show that an association between the shape and the white noise was indeed constructed by the participants during the learning phase, because the shape in the test phase did affect target processing. What is of major interest here is that we replicated not only the facilitation effect with a 500-ms prime duration (equal duration in the learning and the test phases) but also the interference effect with a 100-ms prime duration (prime duration shorter in the test phase than in the learning phase). This shows that the perceptual nature of the auditory component was indeed kept in the memory trace, because if this component were coded under an amodal form, there would be no reason to observe an interference with the short prime duration.

In Experiment 2, we manipulated the participants' motor response during the learning phase to see whether it had an impact on the integration of the auditory and visual stimuli. If our hypothesis were verified, we would expect the shape learned with a sound but no motor response in Experiment 2 to behave like the silent shape did in Experiment 1; that is, we should observe the same pattern of results in Experiment 1 and 2.

Experiment 2

Method

Participants. Forty-eight right-handed voluntary participants were recruited for this experiment (29 female; $M = 20.37$, $SD = 1.8$, age range = 18–25). All of them were students at Paul Valery University in Montpellier and had normal or corrected-to-normal vision.

Stimuli, material, procedure, and design. The stimuli and material were identical to those of the first experiment. The procedure was similar to that of the first experiment except for two aspects of the learning phase: The two shapes were noise-paired (instead of just one of the two shapes), and the participants were asked to perform a go/no-go task (instead of having a key dedicated to a specific shape) that consisted of pressing the appropriate key for only one of the two shapes, whereas the other one was left unanswered (see the procedure in Figure 1). The test phase was identical to the one in the first experiment.

Results and Discussion

We performed an ANOVA on error rates and latencies of the test phase, with subjects as a random variable, prime type (prime associated or not associated with a motor response in the learning phase) as a within-subject factor, and prime duration (100 ms or 500 ms) as a between-subjects factor. For the latencies, we expected a replication of the pattern of results observed in Experiment 1, that is to say, a significant Prime Type × Prime Duration interaction, which is indeed what we found, $F(1, 46) = 12.81$, $p < .001$, $\eta_p^2 = .22$. There was no significant main effect or any significant interaction of the error rates between our treatments, with an overall error rate of 3%.

The priming effects were reversed for the different prime durations, which was consistent with our results for Experiment 1. The Student tests used for comparisons showed that with an prime duration of 500 ms, the responses were significantly faster when the prime consisted of the shape that had been associated with a white noise and a motor response during the encoding phase (Motor & Sound prime) than when the prime consisted of the shape that had been associated with a white noise but no motor response (Non-Motor & Sound prime), $t(23) = 2.6$, $p < .05$, $d = 0.54$. In contrast, with a prime duration of 100 ms, the responses were significantly faster with the Non-Motor & Sound prime than with the Motor & Sound one, $t(23) = 2.4$, $p < .05$, $d = 0.49$ (see Figure 2).

Our aim in Experiment 2 was to highlight the functional role of the participants' motor response during the learning phase on the integration process. As observed in Experiment 1, the presentation of the shape on its own in the test phase had a significant effect on target processing. Because the white noise was always associated with both shapes during the learning phase, only the motor response performed on one of the two shapes can be held responsible for this effect. As in Experiment 1, we observed a facilitation effect with the long prime duration and an interference effect with the short one, which means that the duration of the shape in the learning phase had a different effect whether the participants performed a motor response or not. The fact that the observed effects are opposite at the two prime durations rules out an interpretation of the results that would be based on simple motor priming; indeed, in such a case, the effects would be equivalent for the Motor & Sound prime at both prime durations. Because only the duration of the sound reactivated by the prime can therefore be held responsible for the priming effect, we have good reasons to believe that the Non-Motor & Sound prime did not reactivate any sound. It seems here that the participants did not integrate the visual and the auditory components as well in the Non-Motor & Sound prime condition as in the Motor & Sound one.

To eliminate the possibility that the motor response could be considered just another component integrated within the trace, we performed a third experiment with a shape that was associated with white noise but no motor response (Non-Motor & Sound prime) and a shape that was not associated with white noise but on which the participants had to perform a motor response (Motor & Silent prime). If the motor response were acting as a criterion for the integration process and were not just another component of the trace, we would not expect any difference between the two learning conditions on target processing. Indeed, the participants would lack the motor response to integrate the sound and the shape in the Non-Motor & Sound prime condition, and they would have no sound to integrate with the shape in the Motor & Silent one.

Experiment 3

Method

Participants. Forty-eight right-handed voluntary participants were recruited for this experiment (35 female; $M = 19.85$, $SD = 4.7$, age range = 17–50). All of them were students at Paul Valery University in Montpellier and had normal or corrected-to-normal vision.

Stimuli, material, procedure, and design. The stimuli and material were identical to those in the first and second experiments. The procedure was similar to that in the first and second experiments except for two aspects of the learning phase: Only one of the two shapes was noise-paired, and the participants were asked to perform a go/no-go task that consisted of pressing the appropriate key for only one of the two shapes (the Motor & Silent one), whereas the other one was left unanswered (the Non-Motor & Sound one; see the procedure in Figure 1). The test phase was identical to those in the first and second experiments.

Results and Discussion

We performed an ANOVA on error rates and latencies of the test phase, with participants as a random variable, prime type (prime associated or not associated with a motor response during the learning phase) as a within-subject factor, and prime duration (100 ms or 500 ms) as a between-subjects factor. Regarding the latencies, we were interested in the significance of the Prime-Type × Prime Duration interaction. A significant interaction would mean that a priming effect can still be observed without performing a motor response. A non-significant interaction would indicate that the motor response might be a necessary condition for such priming effect to occur. Our analyses revealed no significant main effect of prime type ($F < 1$) and no significant Prime Type × Prime Duration interaction effect ($F < 1$), but a significant effect of prime duration, $F(1, 46) = 7.05$, $p < .05$, $\eta_p^2 = .13$. In fact, the responses were significantly faster when the prime was learned with a duration of 500 ms than with a duration of 100 ms, regardless of the prime type (see Figure 2). The pattern of priming effect that we consistently observed across the previous experiments was not observed anymore. Furthermore, we did not find any difference between the prime type conditions, which suggests no priming effect. This result allowed us to rule out the possibility that the priming effects of the Motor & Silent prime and of the Non-Motor & Sound prime are equivalent, because in such a case we would have observed opposite effects at the two prime durations. There was no significant main effect or any significant interaction of the error rates between our treatments, with an overall error rate of 4.3%.

Complementary Analysis: Priming Effect Sizes

Because no significant effect of the interaction between prime type and prime duration was found in Experiment 3, this could be interpreted as evidence of a lack of integration. Indeed, we argue that the priming effect that we observed during the test phase is a direct outcome of an integration that occurred during learning. Because the pattern of priming effect (i.e., interference for the 100-ms prime duration and facilitation for the 500-ms one) seemed consistent across Experiment 1 and Experiment 2 (see also Brunel et al., 2015, 2009, 2010;), we decided to run an additional analysis on the priming effect sizes obtained in each experiment. This allowed a direct comparison of the pattern of priming effects across the experiments. Thus, consistent with our hypothesis and the results of the previous experiments, we expected a significant Experiment Type × Prime Duration interaction. In other words, the contrast between the 100-ms prime duration and the 500-ms one should be significant for Experiments 1 and 2 but not for Experiment 3. This would indicate that performing a motor response to an audiovisual stimulus is critical to the creation of an integrated trace or event in memory and thus to the observation of any priming effect during the test phase. In our experiments, without motor response, an audiovisual stimulus seen during learning produced the same effect as did a visual stimulus. To compute the priming effect sizes, we subtracted for each participant the mean reaction time (RT) of the sound primes (i.e., Motor & Sound, Motor & Sound, Non-Motor & Sound from, respectively, Experiments 1, 2, and 3) from the mean RT of the silent (or equivalent) primes (i.e., Motor & Silent, Non-Motor & Sound, Motor & Silent from, respectively, Experiments 1, 2, and 3). In that case, negative values indicate an interference and positive values a facilitation. We performed an ANOVA on the priming effects, with participants as a random variable, and experiment type (1, 2, and 3) and prime duration both as between-subjects factors. Our analyses revealed a significant effect of the factor prime duration, $F(1, 138) = 18.87$, $p < .05$, $\eta_p^2 = .12$. More important, however, was the Prime Duration × Experiment Type interaction effect, $F(2, 138) = 3.46$, $p < .05$, $\eta_p^2 = .05$ (see Figure 3).

First, as one can see in Figure 3, the pattern of priming effect and the size of the priming effect seemed consistent across Experiments 1 and 2. However, it completely disappeared when Experiment 3 was considered. Second, as expected, the Student tests used for comparison between the prime durations of each experiment showed a significant effect for Experiment 1, $t(23) = 44.71$, $p < .05$, $d = 1$, and Experiment 2, $t(23) = 45.89$, $p < .05$, $d = 1.03$, but not for Experiment 3 ($p < 1$).

General Discussion

The present study addressed, for the first time, the role of the motor response in the multisensory integration process. We used a

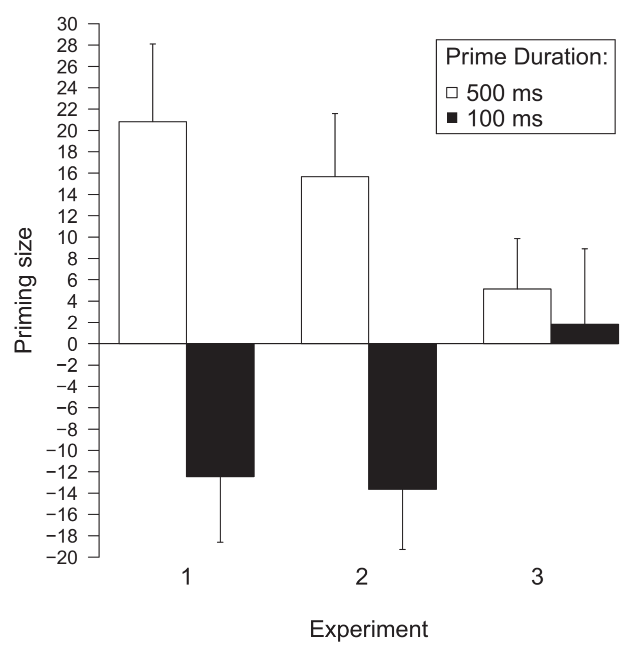

Figure 3. Average of the mean priming size across all participants for the two prime durations (500 ms and 100 ms) in the three experiments. The mean priming size is calculated for each participant as the difference between the mean reaction time (RT) of one prime type and the mean RT of the other. Error bars indicate one SEM calculated between-subjects.

two-phase short-priming protocol (i.e., a learning phase and a test phase), which allowed testing the integration of multisensory stimuli and was thus particularly well suited to testing the role of motor responses in the integration process. The principle was as follows: In the learning phase, participants learned a new multisensory event. The test phase consisted of a short-term priming procedure in which the participants had to categorize pure tones according to their pitch (i.e., high- or low-pitched tones).

The results of our Experiment 1 are consistent with those for Brunel and collaborators (2009, Experiments 1 and 2a), confirming that the stimuli we used were integrated under the same conditions and that their perceptual nature was preserved into the memory trace. We observed a facilitation effect (faster RTs in response to the auditory probe) when the prime and the visual stimulus previously learned were presented with identical time duration. However, when the time duration used for priming was shorter than that used during learning, it led to an interference effect (longer RTs in response to the auditory probe). Those results confirmed that the integration of the audiovisual stimuli was successful during the learning phase, because the visual priming did indeed reactivate the sound and facilitate the target processing. More important, the interference effect observed with the short prime duration also showed that the perceptual nature of the sensory components was preserved: When primed, the participants were still processing the sound while they had to respond to the target, which resulted in an overlap of both sound treatments and in longer response times. This experiment did not allow testing whether the motor response had an influence on processing, which is why we manipulated the participants' motor response during the learning phase in the following experiment.

In Experiment 2, participants were exposed to the same visual shapes as in Experiment 1, each with a sound, but they had to respond to only one of the two shapes. The results confirmed our hypothesis. The Non-Motor & Sound prime behaved the same way as the Motor & Silent prime did in Experiment 1, and this was in both prime durations. The fact that this pattern of results is similar to the one observed in Experiment 1 shows that the integration between the sound and the shape in the Non-Motor & Sound prime condition was not effective. An alternative explanation could be that the Non-Motor & Sound prime did influence the processing of the target tones but with a much weaker effect than for the Motor & Sound one. In such a case, performing a motor response would strengthen the integration process, producing stronger traces over time, but this would not necessarily mean that it is a necessary criterion for the integration process to take place. Experiment 3 aimed precisely at disentangling those two alternative explanations. To do so, we compared a Non-Motor & Sound prime (as in Experiment 2) to a Motor & Silent prime (as in Experiment 1). If performing a motor response would help but not be necessary to integrate the sound and the shape, we would have observed the same patterns of results as in Experiments 1 and 2. In fact, no difference was observed on target processing between both prime conditions, which suggests that performing a motor response during multisensory learning was a necessary criterion for the participants to integrate both the visual shape and the white noise.

Conclusion

In conclusion, our results are consistent with the views on the integration process discussed in previous studies: The integration of the stimuli on the one hand and the action planned or realized on the other hand is necessary to generate an event-file (theory of event coding; Hommel et al., 2001), and such a process should be held responsible for one's ability to create a continuity between past and present experiences (Act-In; Versace et al., 2014). Our results might be taken to a more applied level, because they seem to match other findings about the implications of motor components or motor activity in education-related matters, such as letter knowledge (James & Atwood, 2009; Kersey & James, 2013; Wamain, Tallet, Zanone, & Longcamp, 2012) or thematic relation processing (Pluciennicka, Wamain, Coello, & Kalénine, 2015). To sum up, the present study brings two major contributions to the understanding of the integration process.

First, our results indicate that the absence of a motor response during learning interferes with the binding of various stimuli from different sensory modalities. It may at first sight seem contradictory with the fact that well-known effects, such as the McGurk and the ventriloquist effects, seem to reveal integration effects without requiring a motor response. However, in these cases, the motor implication could well be only simulated (for a review, see Buccino, Binkofski, & Riggio, 2004; Calvo-Merino, Grèzes, Glaser, Passingham, & Haggard, 2006). In fact, the McGurk and the ventriloquist effects rely on both hearing and seeing someone producing some syllables, which can induce a motor simulation for the viewer: What was thought to be an audiovisual integration would turn out to be a visuomotor and auditory integration. Another nonexclusive interpretation could be that prior knowledge about the relation between the different components of a stimulus can help in the observation of integration effects (Brunel et al., 2015; Parise & Spence, 2009). This explanation could account for the bounce-stream effect, for example, because studies on this subject use an auditory component, which is perfectly consistent with the consequence of bouncing two objects. These interpretations about the role of motor simulation or about prior knowledge would need to be tested to be confirmed; such a test could not be investigated in our study, because we used stimuli for which we did not expect any motor simulation and because the relation between the components of the stimuli (i.e., between the shapes and the white noise) was arbitrary.

Second, our results, together with those of previous studies (see Engel et al., 2013, for a review), suggest that the motor response should be considered critical. Hommel (1998; Hommel et al., 2001) showed that a specific motor response could be a component integrated within a memory trace (i.e., an event-file); here, our results show that it is not "just" another sensory component. Even though our study was not designed to investigate specifically what kind or which aspect of the motor response was playing a critical role, the execution of a nonspecific motor response in direct relation with the stimuli seems central to the integration process. Indeed, because the sensory components and the motor activity are tightly coupled, they should not be dealt with in isolation. It is therefore meaningful to take the motor aspects into account when speaking of sensory components. This last point allows reconsidering the relevance of the distinction between the sensory and motor components, beyond the descriptive perspective. In sum, our study suggests that a multisensory integration could often be a sensorimotor one. However, it is noteworthy that we did not test for the specificity of the motor response. By comparing specific and nonspecific motor responses in multimodal integration's learning, further research could attempt to disentangle such benefits of nonspecific motor responses on the integration process from the component-related aspects of the motor activity.

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