



The relationship between feature binding and consciousness: Evidence from asynchronous multi-modal stimuli

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ABSTRACT

Processing the various features from different feature maps and modalities in coherent ways requires a dedicated integration mechanism (“the binding problem”). Many authors have related feature binding to conscious awareness but little is known about how tight this relationship really is. We presented subjects with asynchronous audiovisual stimuli and tested whether the two features were integrated. The results show that binding took place up to 350 ms feature-onset asynchronies, suggesting that integration covers a relatively wide temporal window. We also asked subjects to explicitly judge whether the two features would belong to the same or to the different events. Unsurprisingly, synchrony judgments decreased with increasing asynchrony. Most importantly, feature binding was entirely unaffected by conscious experience: features were bound whether they were experienced as occurring together or as belonging to a separate events, suggesting that the conscious experience of unity is not a prerequisite for, or a direct consequence of binding.

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We perceive the world through several sensory modalities and process the numerous features of the events we perceive in various cortical maps (e.g., Kaas & Hackett, 1999; Zeki & Bartels, 1999). Many authors have noted that these processing characteristics are likely to create all sorts of binding problems: how does the brain know which of the currently coded features belong to the same event (von der Malsburg, 1999) and how do we integrate all these different features into one coherent conscious representation (Treisman, 2006). It is true that one can argue whether having a coherent conscious experience of a multi-featured event really requires the actual binding of the corresponding feature codes. After all, all these codes are located in the same brain and, if we assume that conscious states are lawfully related to brain states, this may be sufficient to guarantee coherence. And yet, given that we can process (though not necessarily attend to) several objects, and control multiple actions concurrently, a whole number of binding problems needs to be solved in any case. And given that our conscious experience is commonly restricted to only some, often just one of these objects and actions, consciousness is likely to rely on at least some form of feature binding.

Even though there is no really comprehensive theory of the relationship between feature binding and consciousness, several authors have claimed that these two processes are tightly related (for an overview, see Engel & Singer, 2001). For instance, Treisman (2003) assumes that feature integration is a necessary precondition for coherent conscious perception, and that focused attention is required and responsible for creating feature bindings. Along the same lines, Crick and Koch (1990) and Engel and Singer (2001) have claimed that feature binding, and the neural processes underlying it, is an essential precondition for conscious awareness. At the same time, however, there is increasing evidence that attention is not

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necessary for binding (see Hyun, Woodman, & Luck, 2009) and that feature binding and conscious awareness, or the processes underlying them, can be dissociated. For instance, Wojciulik and Kanwisher (1998) observed that explicit feature binding (i.e., reporting the relationship between multiple features) is impaired in Balint's syndrome while implicit feature binding is not. In healthy subjects, Mitroff, Scholl, and Wynn (2005) found dissociations between the conscious awareness and measures of the implicit integration of the spatiotemporal parameters and identities of moving objects. For instance, participants reported seeing a "streaming" visual object while their behavior suggested a (apparently implicit) binding of this object to the feature "bouncing". These and other observations raise doubts in the idea that feature binding is strongly related to the construction of conscious awareness.

In the present study, we were interested to test whether the consciously perceived coherence or belongingness of two features (operationalized as perceived temporal simultaneity or "occurrence at the same time") would be systematically related to implicit measures of the binding of the same two features. We varied the temporal relationship between these two features, assuming that people would be less likely to perceive them as belonging to the same event as the temporal interval between them increases. We also assessed the degree of binding between the two features by means of the event file paradigm of Hommel (1998), a variant the object-preview design developed by Kahneman, Treisman, and Gibbs (1992). If conscious awareness would be a direct consequence of feature binding, or even represent the mechanism producing it (as suggested by the global workspace model of Baars (1988)), one would expect that binding would occur only for features that are perceived as belonging to the same event but not for features perceived as belonging to separate events. This was the main hypothesis being tested in Experiment 2 of the present study. The purpose of Experiment 1 was to introduce the multimodal version of the event-file design that we used to assess feature binding in Experiment 2, and to demonstrate that it works with the particular stimuli and parameters chosen.

1. Experiment 1

An elegant way to test whether people spontaneously bind the codes of the perceptual features of a given event was developed by Kahneman et al. (1992). In a nutshell, these authors presented participants with two visual displays in a row, a task-irrelevant prime display with a number of objects in different locations followed by a probe display with a to-be-identified object. The main finding was that performance was better if the probe object had already appeared in the prime display and, more importantly, that this priming effect was particularly strong if the location of the object was also the same as in the prime display. This observation was taken to suggest that encountering the object in the prime display had led to a binding between object identity and location codes, so that repeating the complete conjunction allowed for a reuse of the same object representation (object file).

Further studies with a stripped-down version of this task revealed that at least part of the effect might not reflect benefits related to the reuse of object representations but, rather, cognitive conflict due to the retrieval of misleading object files. Hommel (1998) presented participants with single-object prime (S1) and probe (S2) displays that repeated or alternated the shape, the color, and/or the location of the stimulus. It turned out that performance was equally good if two or more stimulus features were repeated and if all features were alternated, suggesting that the opportunity to reuse an object file might not provide a particular advantage. However, performance was impaired if one feature was repeated but another alternated, suggesting that the effect reflects interference produced by partial repetitions. If, for instance, participants encounter a red square after having seen a red circle, the repetition of the red color might retrieve the just-created binding of RED and CIRCLE, which creates conflict between the reactivated CIRCLE feature and the actually relevant SQUARE feature (Hommel, 2004).

Further evidence for this binding-retrieval scenario was obtained in an fMRI study (Keizer et al., 2008). Subjects were presented with visual primes and probes that consisted of two blended pictures showing a face and a house. Either the face or the house moved in one of two possible directions, and participants responded to the direction of the probe irrespective of which object moved. Of particular interest were the conditions where the prime showed a moving house and the probe a moving face: when the direction of motion in these two events was the same (i.e., the motion feature was repeated) the parahippocampal place area—which is known to code for visual house stimuli (Epstein & Kanwisher, 1998)—was activated more than when the motion directions differed. Apparently, repeating the motion feature induced the retrieval of the entire previous binding that included this motion, which in this task also included the picture of a house. As demonstrated by Kühn, Keizer, Colzato, Rombouts, and Hommel (2011), the same scenario holds for more complex bindings involving information about stimulus-related actions. Given that the apparently automatic retrieval of apparently complete sets of previous feature co-occurrences presupposes some sort of binding between the representations of those features, we can thus conclude that the prime–probe technique provides a conservative (as binding may take place even in the absence of retrieval) but valid measure of feature binding.

Recent studies provided evidence that the interactions between feature–repetition effects have been demonstrated for visual features generalize to auditory (Mondor, Hurlburt, & Thorne, 2003; Zmigrod & Hommel, 2009) and tactile features (Zmigrod, Spapé, & Hommel, 2009), as well as to intermodal combinations of visual and auditory or auditory and tactile features (Zmigrod et al., 2009). This suggests that people spontaneously integrate co-occurring features from various sensory modalities. In the present study, we adopted the design of Zmigrod et al. (2009), which combines visual stimuli varying in color with auditory stimuli varying in pitch (see Fig. 1). However, given that the design of Experiment 2 required the

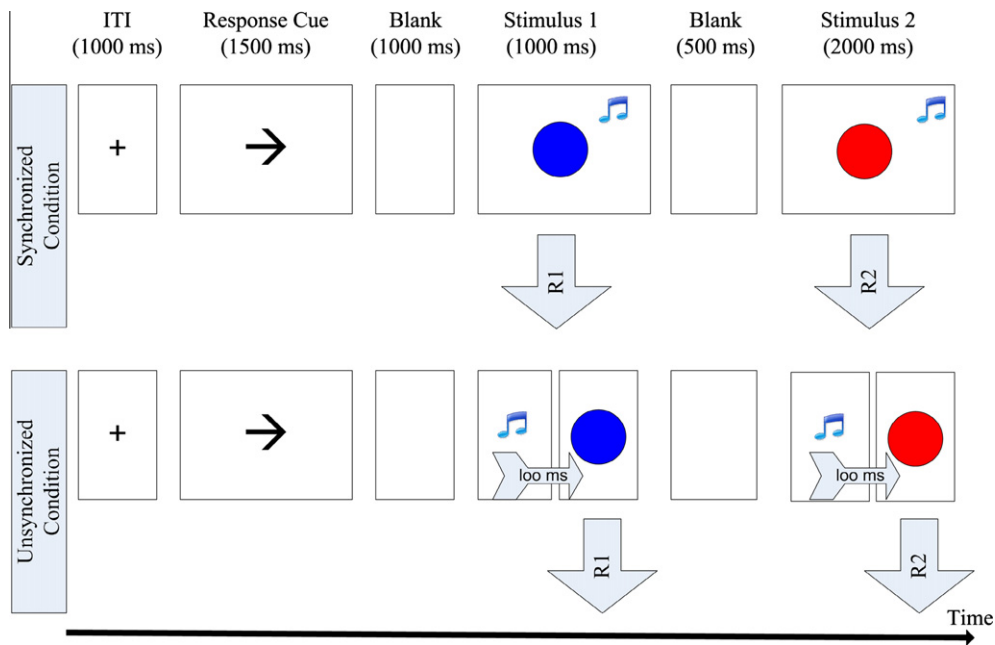


Fig. 1. Experiment 1, overview of the display and the timing of events for the synchronous condition. In the asynchronous condition, the sound preceded the onset of the color by 100 ms.

presentation at different temporal asynchronies, we wondered to which degree feature binding would be affected by temporal asynchrony. Studies on multimodal perception suggest that stimuli that appear within a temporal window of up to about 100 ms (Lewald, Ehrenstein, & Guski, 2001) or even 200 ms (van Wassenhove, Grant, & Poeppel, 2007) are still perceived as being part of the same event. Lewkowicz (1996) has coined this temporal criterion for perceived coherence the “intersensory temporal synchrony window” and has claimed that this window is shorter for frequent multimodal events than unfamiliar or less frequent ones.

Our main question in Experiment 1 was whether at least some degree of asynchrony would be tolerated by the binding process assessed by our task. We thus compared performance in the standard, synchronous version of the task, which amounted to a replication of Zmigrod et al. (2009), with performance in a modified version, where the visual color feature appeared 100 ms after the offset of the auditory feature. As shown in Fig. 1, each trial started with the presentation of a response cue in the form of a directional arrow, indicating whether a left or right response (R1) was required to the mere onset of S1 (regardless of its features).¹ S2, another audio-visual stimulus, appeared 500 ms after responding to S1. S2 required a binary choice reaction (R2) to the color of the visual feature of S2 (red vs. blue). The two stimulus features varied independently, so that color- and pitch-repetition effects could be analyzed.

1.1. Method

1.1.1. Participants

Twenty-two participants (4 men) were recruited by advertisement for this experiment and were paid or received a course credit for a 25 min session. Their mean age was 21 years (range 18–30 years). The participants were naïve as to the purpose of the experiment, and they reported not having any sight or hearing problem. They were randomly assigned to two groups, a synchronous ($N = 11$) and an asynchronous ($N = 11$) feature-presentation group.

1.1.2. Apparatus and stimuli

The experiment was controlled by a Pentium 3 computer attached to a 17-inch CRT monitor. Participants faced the monitor at a distance of about 60 cm along with headphones. The auditory feature of the stimuli S1 and S2 were composed of two pure tones of 1000 Hz and 3000 Hz with duration of 50 ms and presented at approximately 70 dB SPL. The visual features of

¹ Having participants respond to S1 (as in the standard setup of Hommel (1998)) was not a strict requirement for the logic of Experiment 1. However, given that we needed a response to S1 in Experiment 2, including such a response in Experiment 1 already made the two experiments more similar and, thus, easier to compare. Moreover, previous studies have shown that people do not only bind stimulus features but stimulus and response features as well (Hommel, 1998, 2004), so that we were interested to look into these effects for explorative purposes. However, given that, in addition to the standard stimulus-response-interaction effects reported earlier (Zmigrod et al., 2009), no interaction with the synchrony manipulation was obtained, we do not present response-related effects for the sake of clarity.

Table 1

Experiment 1: means of mean reaction times for responses to stimulus 2 (RT_{R2} in ms) and error rates (in parentheses) as a function of the presentation type (synchronous vs. asynchronous), and the relationship between the stimuli features (S1–S2) for color and pitch.

S1 asynchrony	Color repeated		Color alternated	
	Pitch repeated	Pitch alternated	Pitch repeated	Pitch alternated
0	419 (8.3)	443 (7.5)	452 (5.9)	449 (7.8)
100	417 (6.0)	430 (7.1)	456 (6.5)	424 (10.2)

the stimuli S1 and S2 were a blue or a red circle of about 10 cm in diameter. In the synchronous group, the visual and the auditory features were presented at the same time; however, in the asynchronous group, the auditory feature was presented 100 ms before the visual feature. Responses to S1 and to S2 were made by clicking on the left or the right mouse button with index and middle fingers, respectively. Response cues were presented in the middle of the screen (see Fig. 1) with a right or left arrow indicating a left and right mouse click, respectively.

1.1.3. Procedure and design

The experiment was composed of a practice block with 15 trials and an experimental block with 128 trials. The order of the trials was random. Participants were to carry out two responses per trial: the first response (R1) was a left or right mouse click to the onset of the visual feature of S1 (ignoring its identity) as indicated by the direction of an arrow in the response cue. The second response (R2) was a left or right mouse click to the value of the color dimension of S2. The responses' mapping was counterbalanced between participants. The participants were instructed to respond as quickly and accurately as possible.

The sequence of events in each trial is shown in Fig. 1. A response cue with a right or left arrow appeared for 1000 ms to signal R1, which was to be carried out as soon as the color of S1 appeared. The duration between the response cue and S1 was 1000 ms. S2 came up 500 ms after R1, with the color signaling the second response (R2). In the case of incorrect or absent response an error message was presented on the screen.

1.2. Results & discussion

Trials with incorrect R1 responses (0.1%), as well as missing ($RT > 1200$ ms) or anticipatory ($RT < 100$ ms) R2 responses (0.2%) were excluded from analysis. The mean reaction time for corrected R1 was 222 ms ($SD = 72.5$). From the remaining data, mean reaction times (RTs) and error rates (PEs) for R2 were analyzed as a function of the three variables: the relationship (repetition vs. alternation) between S1 and S2 with regard to color and to pitch, and the presentation type (synchronous vs. asynchronous) (see Table 1 for mean RTs and PEs). ANOVAs were performed by using a mixed design with repeated measures on color and pitch repetition and with presentation type as between-group variable.

The analysis of the error rates did not reveal any significant effect. For RTs, there was a significant interaction between repetition vs. alternation of pitch and repetition vs. alternation of color, $F(1, 20) = 22.28$, $p < .0001$. As shown in Table 1, responses delayed if one feature was repeated but the other alternated, which is the standard interaction indicative of feature binding (Zmigrod et al., 2009). Importantly, however, this interaction was not modified by presentation type, $p > 1$ suggesting binding was unaffected by asynchronous presentation. This was confirmed by separate ANOVAs, which indicated that the color-by-pitch interaction was significant with both synchronous presentation, $F(1, 10) = 10.42$, $p < .01$, and asynchronous presentation, $F(1, 10) = 12.54$, $p < .005$. We can thus conclude that visual and auditory stimulus features are spontaneously integrated with both perfectly synchronous and slightly asynchronous stimulus onsets, suggesting that intermodal feature integration is using temporarily extended feature-integration windows (Lewald et al., 2001).

2. Experiment 2

Experiment 1 provided evidence that binding effects can be observed with synchronous as well as asynchronous presentation of perceptual features from different modalities, but these findings do not tell us anything about the conscious experience of the participants. Experiment 2 aimed to directly assess this experience by asking participants to judge whether the tone and the color making up S1 would appear at the same time or constitute different events. Given that processing and responding to S2 might affect this experience, we had participants make the judgment online, as a response to the presentation of S1. As Experiment 1 suggests that minor temporal gaps are tolerated by the binding mechanism, we also included larger gaps (of up to 350 ms) in Experiment 2.

One possible problem that might result from introducing larger gaps is that the gap itself might be perceived as coded as a feature of S1. If so, it is conceivable that even strongly asynchronous S1 features are still integrated into the same event representation but this representation is no longer retrieved at S2 processing, simply because the asynchronous S1 and the synchronous S2 are no longer perceived as similar. In other words, the manipulation of synchrony of S1 features may not only affect the likelihood of relating these features to the same event but also introduce a novel feature (i.e., synchrony) that

would always mismatch with S2. Without a match, however, the representation of S1 would no longer have the chance to affect S2 processing, and the absence of any effect might be mistaken to imply a lack of S1 feature binding. To test whether this is a real problem, we presented the S2 features (color and pitch) synchronously, as in Experiment 1, or asynchronously (350 ms gap), as in the largest gap condition of S1. This allowed us to test whether the targeted effects of S1 synchrony would depend on the relationship or similarity between S1 and S2 synchrony.

The synchrony-match issue aside, our main interest was whether spontaneous feature binding, as indicated by the color-by-pitch interactions observed in Experiment 1, would depend on whether the corresponding S1 features would be perceived as belonging to the same event. If so, we would expect a reliable interaction between color- and pitch-repetition effects in trials where participants judge the features as belonging together but no interaction in trials where the two features are perceived as belonging to separate events. The main function of manipulating S1 feature synchrony was to introduce some systematic variability in the judgment, and we expected same-event judgments to become less frequent as the asynchrony increases.

2.1. Method

2.1.1. Participants

Twenty participants (1 man) were recruited by advertisement for this experiment and were paid or received a course credit for a 50 min session. Their mean age was 21 years (range 18–30 years), and they fulfilled the same criteria as in Experiment 1.

2.1.2. Apparatus and stimuli

The apparatus and the stimuli were as in Experiment 1, with the following exceptions. The sound of the first stimulus compound (S1) appeared 0, 50, 150, 250, or 350 ms before the onset of the color. The sound of the second stimulus compound (S2) appeared either 0 or 350 ms before the color. The response cue no longer signaled R1 but contained the judgment-to-key mapping for the response to S1. The participants were instructed to judge whether the sound and the color of S1 appeared “at the same time (together)” or “not at the same time (separately)” and to press the left or right key accordingly.

2.1.3. Procedure and design

The procedure and the design were as in Experiment 1, with the following exceptions (see Fig. 2). All manipulations were carried out within subjects. There was a practice block of 12 trials and an experimental block with 368 trials. The order of the trials within the blocks was random. Participants were to carry out two responses per trial: a simultaneity judgment of sound and color of S1 (R1) and a left or right response (R2) to the color of S2, as in Experiment 1. The mapping of the stimuli to responses was balanced across participants. In the case of a response omission or an incorrect R2, an error message was presented on the screen.

2.2. Results & discussion

Trials with missing R1 responses (5.5%), as well as missing (RT > 1500 ms) or anticipatory (RT < 100 ms) R2 responses (0.6%) were excluded from all the analyses. In the following, we will first address the integration effects for all trials regardless of the subjective experience and examine the impact of the S1 and S2 synchrony manipulations, then report the impact of asynchrony on the synchrony judgments, and finally address the impact of this judgment on the integration effects.

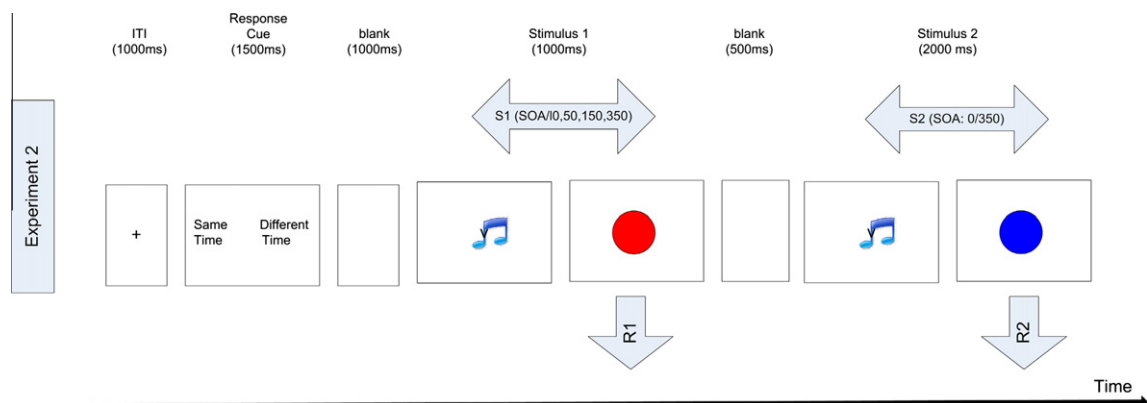


Fig. 2. Overview of the display and the timing of events in Experiment 2.

2.2.1. Binding effects

Mean RTs and error rates for R2 were analyzed by mean of a four-way ANOVA as a function of S1 asynchrony (0, 50, 150, 250, or 350 ms), S2 asynchrony (0, 350 ms), the relationship between S1 and S2 color (repetition vs. alternation), and the relationship S1 and S2 pitch (repetition vs. alternation) (see Table 2).

The analysis of the error rates did not reveal any significant effect. The RTs yielded a significant interaction between color and pitch repetition in RTs, $F(1, 19) = 20.10$, $p < .0001$, comparable to that obtained by Zmigrod et al. (2009) and in Experiment 1. Importantly this interaction was not modified by S1 asynchrony or S2 asynchrony, $F_s < 1$. This shows that multimodal feature binding tolerates temporal asynchronies of at least 350 ms, which implies a rather broad temporal integration window. The only other reliable effect was a main effect of S2 asynchrony in RTs, $F(1, 19) = 57.25$, $p < .0001$, indicating faster performance if the sound preceded the visual presentation by 350 ms (488 ms) than with synchronous presentation (544 ms). Very likely, this observation represents a kind of alerting effect, through which the task-irrelevant tone enhanced the preparation for processing the color stimulus. Importantly, however, there was no indication that the match between S1 and S2 asynchrony would matter.

2.2.2. Synchrony judgment

As shown in Fig. 3, the likelihood of judging the visual and the auditory feature to occur at the same time decreases as the temporal asynchrony increases. This confirms that our manipulation worked as expected.

2.2.3. Impact of conscious experience on binding

We sorted the trials according to the outcome of the synchrony judgment and analyzed RTs by means of a three-way ANOVA with experience (synchronous vs. asynchronous) and pitch and color repetition (vs. alternation) as factors. The only significant result was an interaction between color and pitch, $F(1, 19) = 25.76$, $p < .0001$, indicative of multimodal binding. This interaction was not modified by subjective experience, $F < 1$ (see Fig. 4). That is, feature integration effects were observed irrespective of whether participants perceived the sound and the color as one or as two different events.

Table 2

Experiment 2: means of mean reaction times for responses to stimulus 2 (RT_{R2} in ms) and error rates (in parentheses) as a function of S1 asynchrony (in ms) and S2 asynchrony (in ms), and the S1–S2 relationship with respect to color and pitch.

S1 asynchrony	S2 asynchrony	Color repeated		Color alternated	
		Pitch repeated	Pitch alternated	Pitch repeated	Pitch alternated
0	0	512 (4.0)	552 (6.1)	536 (7.8)	536 (7.1)
	350	457 (9.6)	491 (8.5)	509 (7.3)	478 (6.9)
50	0	505 (6.9)	536 (6.7)	560 (7.4)	547 (9.1)
	350	465 (6.1)	487 (7.3)	518 (11.3)	461 (4.3)
150	0	528 (8.1)	556 (2.7)	585 (13.9)	543 (6.8)
	350	457 (6.1)	504 (6.4)	462 (4.2)	511 (3.9)
250	0	541 (6.0)	553 (4.5)	578 (5.0)	546 (3.9)
	350	483 (5.3)	517 (6.1)	491 (9.0)	483 (5.3)
350	0	531 (5.5)	528 (4.3)	561 (5.0)	554 (7.4)
	350	476 (5.8)	513 (5.8)	524 (4.6)	481 (7.8)

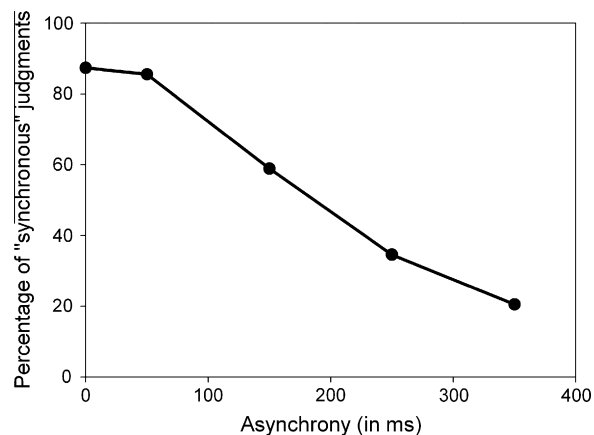


Fig. 3. Percentage of "synchronous" judgments as a function of S1 color-tone asynchrony in Experiment 2.

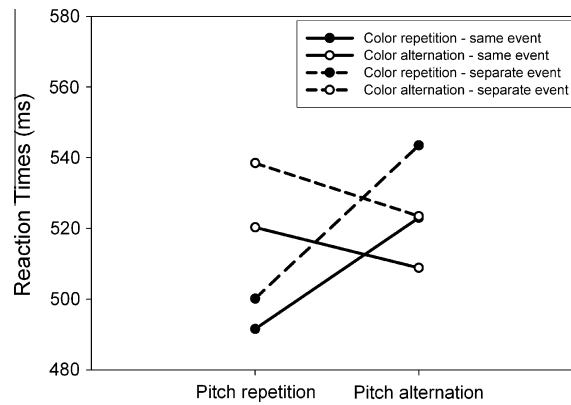


Fig. 4. R2 reaction times in Experiment 2 as a function of repetition vs. alternation of the color and the pitch of S1 and S2, and the perceived simultaneity of color and pitch.

3. General discussion

The main question of the present study was whether intermodal feature binding and the conscious perception of multimodal features as belonging to the same event are related. If they would, the probability of feature binding should have been correlated with the probability of perceiving the bound features as belonging to the same perceptual event or, more specifically, as occurring at the same time. And yet, our findings do not provide any evidence for such a relationship. In fact, binding effects were entirely unrelated to conscious perception and did not even decrease in size when the bound features were perceived as separate events.

This observation fits with previous reports of dissociations between binding effects and conscious perception (Mitroff et al., 2005; Wojciulik & Kanwisher, 1998) and challenges, or at least helps to refine theoretical accounts that claim or suggest a tight relationship between binding and consciousness. On the one hand, one can argue that the fact that binding is not necessarily reflected in conscious perception is not inconsistent with the assumption that feature integration is a necessary precondition for coherent conscious perception (Crick & Koch, 1990; Engel & Singer, 2001; Treisman, 2003). It is possible that binding is a necessary first step which however needs to be followed up by other processes to generate a conscious impression (LaRock, 2007; van Leeuwen, 2007). In our study, binding might have taken place while these other processes did not, so that we were able to measure binding after effects independent of conscious experience. However, not only would such an approach beg the question of what these other processes might be and why they failed to take place in the present study, but we would also need to explain why participants were able to make synchrony judgments that apparently reflected their conscious experience. If a conscious representation was constructed while binding took place, why was the outcome of binding not reflected in the conscious representation? Even more difficult to apply to our findings is the idea that integration across specialized modules requires a processing state that is correlated with conscious awareness (Baars, 1988; Dehaene & Naccache, 2001). If integration is impossible without such a conscious state, how is it possible that the outcome of binding processes is not reflected in conscious awareness?

These considerations suggest that binding seems to operate independently of conscious awareness, which again implies that it solves processing problems other than the construction of conscious representations. As pointed out already, our ability to carry out multiple actions at (about) the same time requires some sort of feature integration, so that concurrently active action routines “know” which objects they are to process. Given the evidence that conscious awareness does not seem to play an important role in online-controlling such actions (Hommel, 2000, 2007), it makes a lot of sense that feature integration operate independently of consciousness. Moreover, various authors have claimed that the human brain is proactive and constantly generating unconscious predictions about upcoming events (Bar, 2009; Neisser, 1976; Schubotz, 2007; Zacks, Speer, Swallow, Braver, & Reynolds, 2007). These kinds of predictions must rely on memory traces that integrate the features belonging to the same event, suggesting that they require feature binding as well. Hence, the processes responsible for constructing conscious representations are by no means the only possible clients will feature-binding operations and, as our findings suggest, they may not even be the most important ones.

One may wonder why integration processes are so much more tolerant with respect to temporal asynchronies between stimulus features than conscious judgments are: whereas the judgments were very sensitive to any increase in asynchrony, there was no evidence for any impact of even the longest asynchrony (350 ms) on feature integration. On the one hand, there are good reasons for integration processes not to be particularly picky with respect to the timing of features coded by different sensory channels. The channels available to humans differ rather dramatically with respect to the speed with which stimulus features are registered, detected, and identified—just compare the high speed of auditory processing with the very low speed of processing smell. Moreover, the travel times of information stimulating the different senses can differ dramatically as well, the more the greater the spatial distance of the perceived event. Properly integrating multimodal

feature information about a single event can thus not afford using too tight temporal integration windows. From this perspective, finding that intermodal feature integration can tolerate an asynchrony of 350 ms should not be that surprising. On the other hand, however, there is evidence that temporal integration windows are not fixed but sensitive to the temporal rate at which stimulus events appear (Akyürek, Toffanin, & Hommel, 2008). Given the rather low temporal event rate in the present study, this implies that a higher rate might induce a smaller integration window and, thus, reduce the tolerance for temporal asynchrony. If so, such a manipulation would make the data representing feature integration and conscious judgments more similar without—in view of our present findings—necessarily showing that binding and conscious experience rely on the same mechanism.

References

- Akyürek, E. G., Toffanin, P., & Hommel, B. (2008). Adaptive control of event integration. *Journal of Experimental Psychology: Human Perception and Performance*, 34, 569–577.
- Baars, B. J. (1988). *A cognitive theory of consciousness*. New York: Cambridge University Press.
- Bar, M. (2009). The proactive brain: Memory for predictions. *Philosophical Transactions of the Royal Society B*, 364, 1235–1243.
- Crick, F., & Koch, C. (1990). Towards a neurobiological theory of consciousness. *Seminars in the Neurosciences*, 2, 263–275.
- Dehaene, S., & Naccache, L. (2001). Towards a cognitive neuroscience of consciousness: Basic evidence and a workspace framework. *Cognition*, 79, 1–37.
- Engel, A. K., & Singer, W. (2001). Temporal binding and the neural correlates of sensory awareness. *Trends in Cognitive Science*, 5, 16–25.
- Epstein, R., & Kanwisher, N. (1998). A cortical representation of the local visual environment. *Nature*, 392, 598–601.
- Hommel, B. (1998). Event files: Evidences for automatic integration of stimulus–response episodes. *Visual Cognition*, 5, 183–216.
- Hommel, B. (2000). The prepared reflex: Automaticity and control in stimulus–response translation. In S. Monsell & J. Driver (Eds.), *Control of cognitive processes: Attention and performance XVIII* (pp. 247–273). Cambridge, MA: MIT Press.
- Hommel, B. (2004). Event files: Feature binding in and across perception and action. *Trends in Cognitive Sciences*, 8, 494–500.
- Hommel, B. (2007). Consciousness and control: Not identical twins. *Journal of Consciousness Studies*, 14, 155–176.
- Hyun, J., Woodman, G. F., & Luck, S. J. (2009). The role of attention in the binding surface features to locations. *Visual Cognition*, 17, 10–24.
- Kaas, J. H., & Hackett, T. A. (1999). ‘What’ and ‘Where’ processing in auditory cortex. *Nature Neuroscience*, 2, 1045–1047.
- Kahneman, D., Treisman, A., & Gibbs, B. J. (1992). The reviewing of object files: Object specific information. *Cognitive Psychology*, 24, 175–219.
- Keizer, A. W., Nieuwenhuis, S., Colzato, L. S., Theeuwisse, W., Rombouts, S. A. R. B., & Hommel, B. (2008). When moving faces activate the house area: An fMRI study of object file retrieval. *Behavioral and Brain Functions*, 4, 50.
- Kühn, S., Keizer, A., Colzato, L. S., Rombouts, S. A. R. B., & Hommel, B. (2011). The neural underpinnings of event-file management: Evidence for stimulus-induced activation of, and competition among stimulus–response bindings. *Journal of Cognitive Neuroscience*, 23, 896–904.
- LaRock, E. (2007). Disambiguation, binding, and the unity of visual consciousness. *Theory Psychology*, 17, 747–777.
- Lewald, J., Ehrenstein, W. H., & Guski, R. (2001). Spatio-temporal constraints for auditory–visual integration. *Behavioural Brain Research*, 121, 69–79.
- Lewkowicz, D. J. (1996). Perception of auditory–visual temporal synchrony in human infants. *Journal of Experimental Psychology: Human Perception and Performance*, 22, 1094–1106.
- Mitroff, S. R., Scholl, B. J., & Wynn, K. (2005). The relationship between object files and conscious perception. *Cognition*, 96, 67–92.
- Mondor, T. A., Hurlburt, J., & Thorne, L. (2003). Categorizing sounds by pitch: Effects of stimulus similarity and response repetition. *Perception & Psychophysics*, 65, 107–114.
- Neisser, U. (1976). *Cognition and reality*. San Francisco: Freeman.
- Schubotz, R. I. (2007). Prediction of external events with our motor system: Towards a new framework. *Trends in Cognitive Sciences*, 11, 211–218.
- Treisman, A. (2003). Consciousness and perceptual binding. In A. Cleeremans (Ed.), *The unity of consciousness: Binding, integration, and dissociation* (pp. 95–113). Oxford: Oxford University Press.
- Treisman, A. (2006). Object tokens, binding and visual memory. In H. Zimmer, A. Mecklinger, & U. Lindenberge (Eds.), *Handbook of binding and memory: Perspectives from cognitive neuroscience*. New York: Oxford University Press (pp. 315–338).
- van Leeuwen, C. (2007). Synchrony, binding, and consciousness: How are they related? *Theory Psychology*, 17, 779–790.
- van Wassenhove, V., Grant, K. W., & Poeppel, D. (2007). Temporal window of integration in bimodal speech. *Neuropsychologia*, 45, 598–607.
- von der Malsburg, C. (1999). The what and why of binding: The modeler’s perspective. *Neuron*, 24, 95–104.
- Wojciulik, E., & Kanwisher, N. (1998). Implicit visual attribute binding following bilateral parietal damage. *Visual Cognition*, 5, 157–181.
- Zacks, J. M., Speer, N. L., Swallow, K. M., Braver, T. S., & Reynolds, J. R. (2007). Event perception: A mind–brain perspective. *Psychological Bulletin*, 133, 273–293.
- Zeki, S., & Bartels, A. (1999). Toward a theory of visual consciousness. *Consciousness & Cognition*, 8, 225–259.
- Zmigrod, S., & Hommel, B. (2009). Auditory event files: Integrating auditory perception and action planning. *Attention, Perception, and Psychophysics*, 71, 352–362.
- Zmigrod, S., Spapé, M., & Hommel, B. (2009). Intermodal event files: Integrating features across vision, audition, tactition, and action. *Psychological Research*, 73, 674–684.