Cross-Sensory Mapping of Feature Values in the Size-Brightness Correspondence can be more Relative than Absolute

Laura Walker and Peter Walker

Lancaster University

Author Note

Laura Walker, Department of Psychology, Lancaster University; Peter Walker, Department of Psychology, Lancaster University.

This research was supported by a Lancaster University Postgraduate Studentship awarded to Laura Walker. The order of authorship is alphabetic.

Correspondence concerning this article should be addressed to Laura Walker, Department of Psychology, Lancaster University, Lancaster, LA1 4YF, UK. Email: l.walker1@lancaster.ac.uk

Abstract

A role for conceptual representations in cross-sensory correspondences has been linked to the relative (context-sensitive) mapping of feature values, whereas a role for sensory-perceptual representations has been linked to their absolute (context-insensitive) mapping. Demonstrating the relative nature of the automatic mapping underlying a cross-sensory correspondence therefore offers one way of confirming its conceptual basis. After identifying several prerequisites for relative and absolute mappings, we provide the first compelling demonstration that an automatically induced congruity effect based on a cross-sensory correspondence (i.e., that between haptic size and visual brightness) can be largely contingent on the relative mapping of the two features, thereby implying a conceptual basis for the correspondence. Participants in a speeded classification task were faster to classify a visual stimulus as brighter or darker when this required them to press a hidden response key that, incidentally, was relatively small or big, respectively. Importantly, the same levels of brightness (Experiment 1) and key size (Experiment 2) at different times corresponded to contrasting levels of the other feature depending on the context provided by the alternative stimuli with which they appeared. For example, the same medium key was congruent with a brighter stimulus when paired with a bigger key, but was congruent with a darker stimulus when paired with a smaller key. Reflecting on the broader implications of this finding, it is noted that the involvement of cross-sensory correspondences in some forms of sound symbolism in language also requires the relative coding of stimulus features.

Keywords: size-brightness correspondence, cross-sensory correspondences, speeded classification, relative and absolute mapping, context-sensitive feature coding

Cross-Sensory Mapping of Feature Values in the Size-Brightness Correspondence can be more Relative than Absolute

That there exist systematic associations between the basic features of stimuli from different sensory channels is well known. Sounds that are higher in auditory pitch, for example, are found to correspond reliably to smaller (Gallace & Spence, 2006), sharper (Parise & Spence, 2009), brighter (Hubbard, 1996), thinner (Evans & Treisman, 2010), and spatially higher visual stimuli (Parise, Knorre, & Ernst, 2014; Rusconi, Kwan, Giordano, Umiltà, & Butterworth, 2006), to faster and more rapidly ascending visual objects (Collier & Hubbard, 2001), to more elevated tactile sensations (Occelli, Spence, & Zampini, 2009), and to (the names of) foodstuffs having sweet and sour tastes (Crisinel & Spence, 2009, 2010a, 2010b), to name but a few.

Such *cross-sensory correspondences* sometimes appear to reflect mappings between the sensory-perceptual representations of feature values across different sensory domains. On other occasions, however, the mappings could reflect the fact that extreme feature values from different sensory domains share the same verbal labels (e.g., *high* and *low* auditory pitch corresponding with *high* and *low* visuo-spatial elevation), potentially giving the illusion of a correspondence (e.g., Ben-Artzi & Marks, 1995). In his tutorial review, Spence (2011) notes instances where correspondences also appear to reflect mappings among conceptual representations, although the extent to which this is the case remains to be determined. Following Karwoski, Odbert, and Osgood (1942), P. Walker and L. Walker (2012) recently proposed that all cross-sensory correspondences can have a conceptual basis, supplementing whatever other bases are available. In particular, they claim that there exists a core set of systematic associations connecting stimulus features encoded in different sensory channels, and that these cross-sensory correspondences are observed because there is crosstalk (cross-activation) between correspondingly positioned feature values on different conceptual dimensions. The representation of feature values along these dimensions is assumed to be conceptual because the values concern abstracted aspects of the stimulus features, such as their status as the *brighter*, *smaller*, or *higher* feature value in a context-defined set of feature values (or, indeed, specification of their ordinal position in this set). For this reason the absolute value of a feature is not sufficient to specify its status within the set of values against which it is being compared. Such specification requires the relevant set of values to be determined and the stimulus feature under consideration to be compared against them. The representation of feature values is also assumed to be conceptual when they are abstracted further to transcend the sensory channel through which the features are encoded, thereby embracing features from different sensory domains (see L. Walker, P. Walker, & Francis, 2012; P. Walker, 2012; P. Walker, L. Walker, & Francis, 2015). On the assumption that cross-sensory correspondences can have a conceptual basis of this kind, P. Walker and L. Walker predicted a novel correspondence between haptic size and surface brightness. They went on to demonstrate the existence of this correspondence, with the details of their results containing additional, indirect evidence for the role of conceptual processing.

Participants in P. Walker and L. Walker's (2012) study were presented with individual circles at one of six levels of luminance on a mid-grey background. Three levels appeared brighter than the background, and three appeared darker, and participants were required to classify each circle as quickly and accurately as possible according to whether it appeared to be brighter or darker than the background. Participants confirmed their decision by pressing one of two hidden response keys with their left and right hand. As a task-irrelevant aspect of the situation, the response keys differed in size, so that on any given trial the key needing to be pressed was either the smaller or the bigger of the two keys available. P. Walker and L. Walker observed the congruity effect predicted from the size-brightness correspondence, with participants classifying brighter (darker) circles more quickly when the key needing to be pressed was the smaller (bigger) of the two. Their results also contained evidence, albeit indirect, that the size-brightness congruity effect originated from processes taking place after the brightness classification of each circle. Particularly pertinent in the context of the present study was their finding that variations in perceived surface brightness within each task-defined category of brightness (i.e., within those levels of brightness that were perceived to be brighter than the mid-grey background, and within those levels of brightness that were perceived to be darker than the mid-grey background) did not interact with key size to yield a congruity effect. That is, participants did not respond more quickly when higher (lower) levels of perceived brightness within a task-defined category of brightness were paired with the smaller (bigger) key. This indicates that the size-brightness congruity effect reflects context-sensitive interactions among representations at or beyond the level at which visual stimuli are categorised for the purpose of response selection. As P. Walker (2012, p. 1805) stated, this accords with Martino and Marks' (2001) claim that cross-sensory correspondences can be based on the context-sensitive coding of stimulus features, providing that context-sensitivity refers not only to the other stimuli being presented, but also to the specific requirements of the task (e.g., how the stimuli are being classified).

Absolute and Relative Cross-Sensory Mappings

As alluded to above, cross-sensory correspondences can reflect two types of mappings. The first are mappings based on absolute feature values, with particular values on one feature dimension equalling particular values on the other (as has been suggested for the mapping between visual brightness and auditory loudness, see Lewkowicz & Turkewitz, 1980). The second are mappings based on relative feature values, with individual mappings adapting to the context provided by, for example, the other values within the particular set being explored. Marks (1987, p. 385) notes that whereas relative mappings seem especially compatible with correspondences rooted in higher level, conceptual processes, absolute mappings seem more compatible with correspondences rooted in lower level, sensory-perceptual processes. If true, then demonstrating more directly that the size-brightness congruity effect derives from the relative, context-sensitive mapping of feature values along these two dimensions would provide converging evidence that the size-brightness correspondence, and, by implication, other cross-sensory correspondences (see, e.g., L. Walker, P. Walker, & Francis, 2012), can reflect interactions among conceptual representations, as P. Walker and L. Walker (2012) suggested.

The extent to which the mapping of stimulus features across sensory domains is absolute or relative has been assessed in several studies in the belief that the type of mapping indicates the level of processing at which the correspondence takes effect (see Chiou & Rich, 2012; Gallace & Spence, 2006; Guzman-Martinez, Ortega, Grabowecky, Mossbridge, & Suzuki, 2012; Lunghi & Alais, 2013; Lunghi, Binda, & Morrone, 2010; Marks, 1974, 1987, 1989; Marks, Szczesiul, & Ohlott, 1986; Orchard-Mills, van der Burg & Alais, 2013; Orchard-Mills, Alais, & van der Burg, 2013). In line with Marks' (1987) observation (see above), the consensus view from these studies is that absolute mappings indicate interactions at sensory-perceptual levels of representation, whereas relative mappings indicate interactions at conceptual levels of representation.

The nature of cross-sensory mappings has sometimes been explored using tasks in which participants make explicit comparisons of stimuli from different modalities. In general, such tasks have confirmed the preponderance of relative mapping (e.g., Marks, 1974, 1989), though one study provided evidence for an equal mix of absolute and relative mapping (Marks et al., 1986). Such studies of cross-modality matching might not be best placed to allow absolute mapping to be revealed. One reason is that cognitive processes are sufficiently flexible to override any absoluteness in the underlying correspondence, most likely by generating rules for mapping that are relational in nature. For example, depending on the specific feature value (e.g., the level of pitch) of the first presented stimulus that is to be altered until it matches a reference stimulus in another domain, people might make very different inferences about the range of values available for mapping (e.g., Marks, 1974; Marks et al., 1986). In addition, people are free to make many different types of association to the stimuli being matched, and it might be these that provide the basis on which mapping occurs, rather than the stimuli themselves. For example, people might associate a white surface either with meringue, or with the ice of an iceberg, with dramatic consequences for how surface brightness maps onto size and heaviness. It is perhaps because of this cognitive flexibility that studies of cross-modality matching have tended to reveal relative, rather than absolute mapping. By the same token, however, where studies of cross-modality matching reveal absolute mapping this would provide a strong indication that the underlying correspondence itself relies primarily on absolute mapping.

In view of the considerations outlined above, it can be argued that studies that do not require participants to make explicit judgements about how stimuli from different domains compare, but instead examine the nature of cross-sensory mappings occurring automatically (for example, through automatically induced congruity effects), are more likely to reveal the true nature of the mapping underlying a correspondence. Such studies reveal how mappings can be both absolute and relative, sometimes in the same task situation (as in Marks et al., 1986), sometimes in different task situations. In the latter case, the pertinent studies were designed to provide evidence for one type of mapping, either absolute (Guzman-Martinez, et al., 2012; Lunghi et al., 2010; Lunghi & Alais, 2013) or relative (Chiou & Rich, 2012; Gallace & Spence, 2006; Marks, 1987; Orchard-Mills, Alais, & van der Burg, 2013; Orchard-Mills, van der Burg, & Alais, 2013), and it therefore remains uncertain whether the alternative type of mapping might also have been influential, however modestly.

Evidence for an automatic contribution from relative cross-sensory mappings has come in different forms. First, it has been reported that mappings can change according to the particular sample of feature values being examined (e.g., when more extreme feature values are added to those already being assessed, or when the range of values is shifted towards one extreme or the other) (Chiou & Rich, 2012; Marks, 1987, 1989; Marks et al., 1986), or according to the direction in which the same ordered set of feature values is assessed (e.g., from highest to lowest, or lowest to highest; Orchard-Mills, Alais, & van der Burg, 2013). Second, it has been reported that a prerequisite for observing a cross-sensory congruity effect is that more than a single feature value appears in a block of trials (i.e., there have to be other feature values being sampled that provide a context; see Gallace & Spence, 2006). Third, specifying the ordinal position of individual feature values being sampled from the two domains has been sufficient for their mapping (Orchard-Mills, van der Burg, & Alais, 2013), even when these positions are conveyed verbally and, therefore, without any absolute feature values being specified. In contrast, evidence for the absolute nature of cross-sensory mappings includes their insensitivity to these same manipulations (Guzman-Martinez et al, 2012), their tight tuning along other feature dimensions (e.g., narrow orientation tuning when visual and haptic gratings are being cross-referenced on the basis of their spatial frequency; see Lunghi et al., 2010), and their alignment on the basis of objective feature values in the two domains, such as the true (distal) spatial frequency of a Gabor stimulus, rather than its proximal (retinal) spatial frequency (see, e.g., Guzman-Martinez et al., 2012; Lunghi & Alais, 2013; Lunghi et al., 2010).

Although evidence for both absolute and relative automatic cross-sensory mappings exists, there has as yet been little consideration of the factors determining which type of mapping will predominate in a particular situation. A systematic inspection of the studies cited above, however, reveals two likely prerequisites for absolute mapping. First, the domains being cross-referenced should provide equivalent information about the same measurable feature of a stimulus and should be spatio-temporally coincident (or close to such), consistent with them originating from the same object (see, e.g., Guzman-Martinez et al., 2012; Lunghi & Alais, 2013; Lunghi et al., 2010). Second, and alternatively, both domains should carry information about the intensity of stimulation (e.g., auditory amplitude and visual luminance), and this should provide the basis for their cross-referencing, irrespective of whether or not they are arranged to be spatio-temporally coincident (see, e.g., Marks, 1987). Those studies providing evidence for absolute mapping appear to satisfy at least one of these two prerequisites, and the implication of this for the mapping of haptic size to perceived surface brightness is clear: Because these two domains do not provide equivalent information about the same measurable feature of an object, and because they are not both concerned with stimulus strength, neither prerequisite for absolute mapping is satisfied. On this basis alone, therefore, their mapping is expected to be relative, which is, of course, consistent with the automatic congruity effect they induce reflecting interactions among conceptual, rather than sensory-perceptual, representations.

Further to the factors identified above, in three of the five studies in which participants were not required to explicitly compare different stimuli, the relative mapping of cross-sensory features was still deemed to be under strategic control (Chiou & Rich, 2012; Orchard-Mills, van der Burg, & Alais, 2013; Orchard-Mills, van der Burg, & Alais, 2013). This strategic mapping of stimulus features does not appear to be a prerequisite for relative mapping, however, because in the remaining two studies there was little opportunity, or incentive, for participants to cross-reference the sensory features (they involved a speeded classification task in which the criterial feature was accompanied by an uninformative, task-irrelevant feature) (Gallace & Spence, 2006; Marks, 1987). This leaves the way open for the non-strategic (i.e., automatic) size-brightness congruity effect identified by P. Walker and L.

Walker (2012) to reflect the relative, rather than the absolute, mapping of feature values along these two dimensions, which would in turn provide additional support for their claim that this and other cross-sensory correspondences can reflect interactions among conceptual representations.

Only two studies currently purport to demonstrate the involvement of relative mapping in the automatic induction of congruity effects based on cross-sensory correspondences. In the first of these, Marks (1987) asked participants to classify black and white stimuli according to their perceived surface brightness while ignoring a task-irrelevant tone of either 220 or 360 Hz. He observed a significant interaction between pitch and perceived surface brightness, such that responses were relatively fast to the black stimulus when it was accompanied by the 220 Hz tone, rather than the 360 Hz tone, but to the white stimulus when it was accompanied by the 360 Hz tone, rather than the 220 Hz tone. Of particular interest, the magnitude of the interaction between these visual and auditory stimuli was reduced in another experiment where more extreme tones, of 100 Hz and 800 Hz, were added to the ensemble of incidental sounds. Marks argued that this was likely due to the fact that the 220 and 360 Hz tones were now no longer the lowest and highest pitched sounds presented in the task, but instead had *relatively* intermediate values. Nevertheless, he regarded this evidence as supporting only a “tentative” (*Ibid.,* p. 390), albeit reasonable, conclusion for the involvement of relative mapping in the pitch-brightness correspondence. One reason for this uncertainty centred on unresolved concerns about the adequacy with which hand-decision assignments had been taken into account. A further issue, however, is that a significant pitch-brightness congruity effect involving the 220 and 360 Hz tones remained in place, albeit at a reduced strength (from 12.5 ms to 4.0 ms), when the two more extreme tones were added to the stimulus ensemble (and there was no statistical evidence offered to confirm that the reduction in strength was itself significant).

In the second of these two studies, Gallace and Spence (2006) also demonstrated the involvement of relative mappings in a task designed to detect the automatic induction of a congruity effect deriving from the cross-sensory correspondence between auditory pitch and visual size. They asked participants to classify the second of two successively presented circles according to whether it was bigger or smaller than the first (the size of which was fixed). As a task-irrelevant stimulus, an auditory tone of either 300 or 4500 Hz accompanied the second circle. In some blocks of trials the incidental sound was always either the 300 Hz tone or the 4500 Hz tone. In other blocks of trials, however, the two tones were mixed, with one of the tones being selected for a trial independently of the relative size of the second circle. In this way, the pitch of the tone was uninformative regarding the correct classification of the circle. Because Gallace and Spence observed a congruity effect induced by the pitch-size correspondence only when both tones appeared within a block of trials, they reasoned that the mapping of feature values across these two dimensions is relative in nature. That is, for the mapping to induce a congruity effect a context needs to be present in which multiple feature values in both stimulus domains appear. Gallace and Spence nevertheless attached some caution to this conclusion, pointing out that by presenting two tones rather than a single tone they introduced uncertainty regarding the pitch of the tone that would appear on any given trial. They noted that this in itself could have been the critical difference between the two conditions, rather than the availability of a context for the relative coding of the stimulus feature values. Interestingly, the same caution also applies to Marks' (1987) study, although in that case the introduction of two additional, more extreme, values for pitch served to increase the stimulus uncertainty that was already present in the task.

In contrast to the automatic induction of cross-sensory congruity effects reported by Marks (1987) and Gallace and Spence (2006), the mapping between auditory pitch and visuo-spatial elevation examined by Chiou and Rich (2012) was deemed to be under strategic control. It could also have arisen because contrasting feature values in the two domains share the same verbal labels (*high* and *low* auditory pitch, *high* and *low* visuo-spatial elevation). These two aspects reduce the significance of the study in the present context. However, the strategy adopted by Chiou and Rich to confirm the involvement of relative mapping in the pitch-elevation congruity effect very effectively avoids changes in stimulus uncertainty being confounded with changes in stimulus context. Participants in their Experiment 3 performed a speeded detection task requiring them to press the same response key whenever a visual target was displayed in the upper or lower location on a computer screen. Each visual target was preceded by a non-predictive tone of high or low auditory frequency. The range of high and low frequency tones was manipulated across two experimental sections, such that the same (900 Hz) tone was the high pitched sound in one section, but the low pitch sound in the other.[1] Measuring response detection times to visual targets in the congruent (high tone-upper position, low tone-lower position) and incongruent (high tone-lower position, low tone-upper position) conditions, Chiou and Rich found that the same 900 Hz tone elicited attentional shifts in opposite directions depending on the context provided by the frequency range within which it was presented (i.e., whether it was presented with a 100 Hz tone, so that it was relatively high in frequency, or a 1700 Hz tone, so that it was relatively low in frequency). As the absolute frequency of the tone was identical in both contexts, they concluded that the attentional cueing effect caused by the correspondence between pitch and visuo-spatial elevation reflected the relative, context-sensitive mapping of the features at a post-categorical level of processing. Because the same number of alternative stimuli were sampled throughout, and because the same stimulus behaved in contrasting ways according to the context provided by the other stimuli with which it appeared, this is an especially persuasive demonstration of the involvement of relative mapping in correspondence-induced congruity effects. With this in mind, the same experimental strategy was adopted in the present study.

The Present Study

The aim of the present study was to provide more direct evidence that the automatically induced size-brightness congruity effect demonstrated by P. Walker and L. Walker (2012) can be driven by the relative mapping of feature values across these two stimulus domains and, by implication, that the size-brightness correspondence is rooted in interactions among conceptual representations. Doing so would, of course, provide the most compelling evidence to date that an automatically induced congruity effect based on a cross-sensory correspondence can reflect the relative mapping of features across sensory domains.

In two experiments, a version of the speeded classification task used by P. Walker and L. Walker (2012) is adopted to determine whether the absolute feature values that behave as bright (Experiment 1) and small (Experiment 2) in one context (in terms of how they contribute to the congruity effect) can behave as dark and big in another context, where the context is provided by the other feature values appearing in the task.

Experiment 1: Size-Brightness Correspondence with Relative Values of Brightness

In Experiment 1, participants performed a speeded brightness classification task. On each trial they classified one of four possible visual stimuli (taken from the total sample of six) according to whether it was perceived to be brighter or darker than the background against which it was displayed (see Figure 1). In some blocks of trials the background was relatively dark. In other blocks of trials, however, the background was relatively bright. The change in the brightness of the background was such that the two test stimuli of intermediate luminance were brighter than the relatively dark background but darker than the relatively bright background. These two stimuli were always included as test stimuli, being accompanied by the two stimuli from the remaining four whose perceived brightness contrasted in the opposite direction relative to the background. In total, therefore, six test stimuli were used in this experiment, with the four darkest stimuli appearing in blocks of trials for which the background was relatively dark, and the four brightest stimuli appearing in blocks of trials for which the background was relatively bright. In this way, the two stimuli of intermediate luminance appeared against both backgrounds, as the two brighter stimuli with the darker background, but as the two darker stimuli with the brighter background (see Figure 1).

Participants indicated their classification decision by pressing the left or right of two response keys that, incidentally, differed in size. If the cross-sensory mapping of size to brightness is contingent on the relative values of brightness of the four test stimuli as they appear against a particular background (i.e., in a block of trials), then an equivalent size-brightness congruity effect should be observed whichever of the two backgrounds is used. Specifically, whichever of the two backgrounds is used, the two test stimuli perceived to be darker than the background should behave as such and form a congruent relationship with the bigger of the two keys, whereas the two test stimuli perceived to be brighter than the background should behave as such and form a congruent relationship with the smaller of the two keys. This means, of course, that the two stimuli of intermediate luminance in the total set of six should behave as brighter stimuli when appearing against the darker background (thereby forming a congruent relationship with the smaller key), but as darker stimuli when appearing against the brighter background (thereby forming a congruent relationship with the bigger key). This will mean that the two stimuli of intermediate luminance should be classified relatively more quickly and accurately on the smaller key when they appear against the darker background, but relatively more quickly and accurately on the bigger key when they appear against the brighter background.

Method

Participants

Thirty-two Lancaster University students (21 females and 11 males) aged between 18 and 37 (mean age = 20.2 years) volunteered to participate in exchange for course credit. All but four of the participants were right-handed by self report.

Task, Materials, and Apparatus

Participants completed 192 trials, in each of which they were required to decide whether a visual stimulus was brighter or darker than the background against which it appeared. The visual stimuli consisted of six, solid 4.5 cm diameter circles that varied in luminance from very light grey through to very dark grey (100, 96, 40, 16, 3, and 2.5 cd/m^2). The circles were presented individually at the centre of a 20" computer screen (Apple PowerMac G5, Dual 2GHz), running version 2.1.1 of the PsyScript experiment generator programme. In separate blocks of trials, either the four darkest circles from the six available were displayed against the darker of the two backgrounds, or the four brightest circles from the six available were displayed against the brighter of the two backgrounds. In both cases, two of the four circles were perceived to be brighter than the background, and two were perceived to be darker than the background. The two alternative levels for the luminance of the background (8 cd/m^2 and 63 cd/m^2) were chosen to ensure that the two circles of intermediate luminance (i.e., 16 and 40 cd/m^2) were perceived to be brighter than the darker background, but darker than the brighter background (see Figure 1).

Participants indicated their classification decision by pressing one of two response keys that, incidentally, differed in size. The response keys comprised two smoothed, wooden balls mounted onto micro-switches. The small ball had a diameter of 2.5 cm and the big ball had a diameter of 7.5 cm. The physical resistance of the two switches was adjusted until the authors judged that equal force was needed to close them. This required a higher level of resistance to be set for the big key (1000 gm) than for the small key (250 gm). The small key was also raised 3.75 cm from the table by a wooden block to ensure that the two balls were perceived (haptically) to be equally high spatially. A thick black cloth was used to cover the response keys at all times during the experiment, as a result of which participants never saw them.

Experimental Design

Along with Key Size, two aspects of perceived surface brightness were treated as separate factors in the design. The first, *Circle Brightness Relative to Background*, refers to the brightness feature on which response selection was based, and relates to whether a circle was perceived to be brighter or darker than the background against which it appeared. The second, *Background Brightness*, refers to the context provided by the brightness of the background (i.e., darker vs. brighter background), and links to whether the two circles of intermediate brightness should, at different times, be classified as "brighter" or "darker". The experiment therefore involved a 2 x 2 x 2 repeated-measures design, with Key Size (small vs. big), Circle Brightness Relative to Background ("brighter" vs. "darker"), and Background Brightness (brighter vs. darker), all as within-participant factors. The dependent variables were the speed (in milliseconds) and accuracy (percent correct) of participants' responses to each circle.

Procedure

Participants were informed that they would complete 192 trials, in each of which a circle would be presented at the centre of the computer screen. They were told that their task was to decide as quickly and accurately as possible whether the circle was brighter or darker than the background against which it appeared. Half of the participants (12 right-handers and four left-handers) were asked to press the left-hand key when the circle was brighter than the background and the right-hand key when the circle was darker than the background. The remaining participants (16 right-handers) were assigned to the opposite hand-brightness mapping (i.e., left-hand key for “darker” and right-hand key for “brighter”).

All participants completed four blocks of trials and were given a 1-minute break between blocks. In a block of 48 trials, either the four brightest of the six available circles, or the four darkest of the six available circles appeared 12 times each, in a randomly determined order that was generated afresh for each block of trials for each participant. In two blocks of trials (either Blocks 1 & 2 or Blocks 3 & 4), the two circles of intermediate luminance were accompanied by the darkest two circles and appeared against the darker of the two backgrounds. In the other two blocks of trials (either Blocks 3 & 4 or Blocks 1 & 2), the two circles of intermediate luminance were accompanied by the two brightest circles and appeared against the brighter of the two backgrounds.

Each circle remained visible until participants had made their classification decision and was followed by a blank interval of 3 seconds before the next circle was presented. The order in which the brighter and darker backgrounds (and the related sets of visual stimuli) were used was counterbalanced across participants. Participants did not receive feedback about the speed or accuracy of any of their responses.

At the end of each block of trials, the experimenter surreptitiously switched the left-right positions of the two response keys so that participants performed the proceeding block using the opposite (key) size-brightness mapping. Thus, across the four blocks of trials, participants alternately pressed the smaller key for “brighter” and the bigger key for “darker” (a congruent mapping) or the smaller key for “darker” and the bigger key for “brighter” (an incongruent mapping). Which of these two mappings was used in the first block of trials was counterbalanced across participants.

Results

The data were the speed and accuracy of participants' responses to the circles. Mean correct response times (RTs) and accuracy levels obtained for the brighter and darker circles were calculated separately for the smaller and bigger keys (see Table 1). An alpha level of .05 was used in all statistical analyses reported here.

Response Accuracy

The overall mean level of response accuracy was 98.7% (SD = 2.5%). The level of correct responding was significantly higher for congruent trials than for incongruent trials for both levels of background brightness (i.e., whether the two circles of intermediate luminance were perceived to be relatively brighter or relatively darker than the background), Wilcoxon Signed Ranks Test $z = -2.79$, $p = .005$, and Wilcoxon Signed Ranks Test $z = -2.32$, $p = .02$, for the darker and brighter backgrounds, respectively, both two-tailed.

Response Times

Participants' mean correct RTs to the two brighter and two darker circles in each trial block were calculated. RTs from incorrect trials were excluded from the analysis, and any RTs greater than 2.5 SDs above a participant's mean correct RT were replaced with the cut-off value. The resulting data were submitted to a 2 x 2 x 2 repeated-measures analysis of variance (ANOVA) with Key Size (small vs. big), Circle Brightness Relative to Background ("brighter" vs. "darker"), and Background Brightness (brighter vs. darker) as within-participant factors.

The overall mean correct RT was 615 ms (SD = 149 ms). There was a significant main effect of Key Size, $F(1, 31) = 40.98$, $MSE = 0.003$, $p < .001$, $\eta_p^2 = 0.57$, with participants responding more quickly on the big key (592 ms) than on the small key (638 ms). There was not a significant main effect of Background Brightness, $F(1, 31) = 2.07$, $p = .16$, and no significant main effect of Circle Brightness Relative to Background, $F(1, 31) = 1.34$, $p = .26$.

There was a significant interaction between Key Size and Circle Brightness Relative to Background, $F(1, 31) = 7.94$, $MSE = 0.01$, $p = .008$, $\eta_p^2 = 0.20$, the nature of which was consistent with the predicted congruity effect. The overall mean correct RTs for congruent trials (e.g., smaller key with brighter circle) and incongruent trials (e.g., bigger key with brighter circle) were 603 and 628 ms, respectively. Paired-samples *t*-tests confirmed that this difference in response times to congruent and incongruent trials remained significant whether the level of Within-Category Circle Brightness (i.e., whether the circle was the brighter or darker of a pair of circles sharing the same level of categorical brightness relative to the background, see Figure 1) was low or high, $t(31) = -2.71$, $p = .01$, and $t(31) = -2.47$, $p = .02$, respectively, both two-tailed (see Figure 2). The size-brightness congruity effect therefore appears to be very robust.

There was not a significant interaction between Key Size and Background Brightness, $F(1, 31) = 0.13$, $p = .72$, indicating that participants responded more quickly on the big key than on the small key irrespective of whether the background was relatively bright or relatively dark. Most importantly, the lack of a significant three-way interaction between Key Size, Circle Brightness Relative to Background, and Background Brightness, $F(1, 31) = 1.80$, $p = .19$, indicates that an equivalent Key Size x Circle Brightness Relative to Background interaction was observed whichever of the two backgrounds was used and, therefore, regardless of how the two circles of intermediate luminance are interpreted. This confirms that the predicted size-brightness congruity effect is largely determined by the relative, rather than the absolute, mapping of perceived brightness onto key size.

Classifying the Two Circles of Intermediate Luminance When they Appeared against the Brighter and Darker Backgrounds

Because the two circles of intermediate luminance appeared on both backgrounds, albeit in separate blocks of trials for each participant, their classification affords an opportunity to confirm directly that it was the perceived brightness of a circle relative to the brightness of the background that determined the size of the response key with which it became congruent. The mean RTs for these two circles, at each level of background brightness, were submitted to a 2 x 2 repeated-measures ANOVA with Key Size (small vs. big) and Background Brightness (brighter vs. darker) as within-participant factors (see Figure 1).

The overall mean correct RT was 630 ms (SD = 151 ms). The analysis revealed a significant main effect of Key Size, $F(1, 31) = 36.35$, $MSE = 0.003$, $p < .001$, $\eta_p^2 = 0.54$, with participants again responding more quickly on the big key (602 ms) than on the small key (659 ms). The main effect of Background Brightness was not significant, $F(1, 31) = 0.34$, $p = .57$. However, the interaction between Key Size and Background Brightness approached significance, $F(1, 31) = 3.79$, $MSE = 0.004$, $p = .06$, $\eta_p^2 = 0.11$, with the nature of the suggested interaction being consistent with the predicted congruity effect.

The overall mean level of correct responding (98.4%) was too high to permit the equivalent analysis of response accuracy. However, a simplified analysis revealed that the mean percentage of correct responses was significantly higher for congruent trials (99.0%) than for incongruent trials (97.8%), Wilcoxon Signed Ranks $z = -2.41$, $p = .01$, two-tailed.

Brightness Contrast. The two circles of intermediate luminance have a special place in the argument that the mapping between size and brightness observed here is largely relative. This is because, despite their absolute values of luminance being held constant across the two backgrounds against which they appear, they switch their correspondence to contrasting sizes of response key according to the brightness of the background. However, it is only their luminance as measured physically (as cd/m^2) that is held constant, and we know that simultaneous brightness contrast causes the same visual stimulus to be perceived as brighter when it appears against a darker background, and darker when it appears against a brighter background. Though Figure 1 provides only an approximate reproduction of the levels of luminance involved in the present experiments, the reader will most likely experience this contrast-induced change in perceived brightness (i.e., the two intermediate circles will appear modestly brighter against the darker background than against the brighter background). Acknowledging this difference between objective luminance (as measured physically) and perceived brightness, there is a sense in which the brightnesses of the intermediate circles are not being kept constant across the two backgrounds. This introduces a confound between the absolute levels of perceived brightness of these circles and their categorical brightness, both of which change in the same way according to the background against which the circles appear (e.g., not only is a circle categorically brighter than a darker background, but its perceived brightness is raised through simultaneous brightness contrast). Does this confound provide an alternative explanation for our results? Might it be an absolute mapping between perceived brightness and key size that is determining the pattern of results being interpreted here as evidence for relative mapping? We believe not.

The simultaneous contrast-induced change in perceived brightness of either of the two intermediate circles across the two levels of background brightness (i.e., the difference in the perceived brightness of the 16 d/m^2 circle and the 40 cd/m^2 circle when each of these was presented against the brighter background vs. the darker background; see Figure 1) is very modest compared to the difference in the level of perceived brightness between these two circles, and indeed, the difference in the level of perceived brightness between any of the paired circles (i.e., between the 3 cd/m^2 circle and the 2.5 cd/m^2 circle, and between the 100 cd/m^2 circle and the 96 cd/m^2 circle; see Figure 1). And yet, an analysis of the results that includes Within-Category Circle Brightness as an additional within-participant factor, reveals no significant interaction between Within-Category Circle Brightness, Circle Brightness Relative to Background, and Key Size, $F(1, 31) = 0.02$, $p = .90$, or between Within-Category Circle Brightness, Circle Brightness Relative to Background, Key Size, and Background Brightness, $F(1, 31) = 1.02$, $p = .32$. These outcomes confirm that, regardless of the brightness of the background, any differences in perceived brightness between two paired circles did not interact with key size. That is, responses were no faster to the circle within a pair that was perceived to be the brighter (darker) of the two when it was linked to the small (big) key than the big (small) key. Given that the differences in perceived brightness within the pairs of circles were much more pronounced than any changes in perceived brightness induced through simultaneous contrast, the latter does not undermine the interpretation of the results being offered here.

Discussion

The results of Experiment 1 replicate those of P. Walker and L. Walker (2012) by providing evidence for a cross-sensory correspondence between (haptic) size and (visual) brightness. When participants in a speeded classification task were asked to classify circles according to their perceived brightness they did so more quickly and accurately when pressing a small key to confirm that a circle was bright, and a big key to confirm that a circle was dark, than vice versa. Of particular importance here, an equivalent size-brightness congruity effect was observed when the relative perceived brightness of the circles was switched across blocks of trials by varying the context provided by the brightness of the background on which they appeared. This meant that, in separate blocks of trials, the two circles of intermediate luminance behaved as brighter circles when appearing against the darker background (thereby forming a congruent relationship with the small key), but as darker circles when appearing against the brighter background (thereby forming a congruent relationship with the big key). In the context of the speeded brightness classification task, and the automatically induced congruity effect this reveals, the correspondence-based mapping of size and brightness appears to be largely contingent on context-sensitive, relative levels of perceived brightness, rather than on context-insensitive, absolute levels of perceived brightness.

Experiment 2: Size-Brightness Correspondence with Relative Values of Size

Experiment 1 provides evidence indicating that the correspondence-based cross-sensory mapping of size to brightness can be largely based on context-sensitive, relative levels of perceived brightness, rather than on context-insensitive, absolute levels. In Experiment 2, an analogous procedure is used to assess whether the same is also true of size, that is, is it the relative values for size across the two response keys that interacts with brightness, rather than the absolute values? Participants again classified circles according to whether they were perceived to be brighter or darker than the background on which they appeared (which in Experiment 2 did not vary) by pressing the left or right of two response keys that, incidentally, differed in size. In contrast to Experiment 1, three different sizes of response key were available, though it was only the two smaller keys, or the two bigger keys, that were used in any given block of trials. The *relative* size of the medium response key was manipulated across separate blocks of trials by pairing it with either the smallest key or the biggest key from the three keys available, thereby ensuring that it was variously either the bigger key, or the smaller key, being used by participants, respectively (see Figure 3). If the cross-sensory mapping of size to brightness depends on the relative size of the two keys being used in a block of trials, then an equivalent size-brightness congruity effect should be observed regardless of whether the two smaller keys are being used, or the two bigger keys. Specifically, regardless of their absolute size, the smaller key being used should form a congruent relationship with circles that are perceived to be brighter than the background, and the bigger key being used should form a congruent relationship with circles that are perceived to be darker than the background. This means of course that the medium key should behave as a smaller key when it is paired with the biggest of the three keys (in which case it will be congruent with brighter circles), but as a bigger key when, in separate blocks of trials, it is paired with the smallest of the three keys (in which case it will be congruent with darker circles). The change in the relative size of the medium key across trial blocks will mean that responses on this key will be relatively quick and accurate to brighter circles, than to darker circles, when it is paired with the biggest key, but relatively quick and accurate to darker circles, than to brighter circles, when it is paired with the smallest key.

Method

Participants

Thirty-two Lancaster University students (20 females and 12 males) aged between 18 and 28 (mean age = 21.3 years) volunteered to participate in exchange for course credit. All but four of the participants were right-handed by self report. None of the participants had been involved in Experiment 1.

Task, Materials, and Apparatus

The task, materials, and apparatus were similar to those used in Experiment 1, with the exception that the six circles now varied in luminance from white through to black (340, 230, 150, 42, 17, and 2 cd/m^2) and were always presented against the same mid-grey background (90 cd/m^2). Participants again classified each circle according to whether it was perceived to be either brighter or darker than the background by pressing either the left or right of two response keys that, incidentally, differed in size. Three smoothed, wooden balls mounted onto micro-switches were available for use as response keys. The smallest and biggest of these keys were those used in Experiment 1. The medium sized key created for this experiment was 5 cm in diameter and was raised 2 cm from the table by a wooden block to ensure that all three keys were perceived (haptically) to be equally high spatially. The physical resistance of the medium key was set between that of the smallest and biggest keys at 625 gm.

Experimental Design

The experimental design was based on that used in Experiment 1. However, the varying context now related to whether it was the two smaller keys from the set of three that were used as response keys, or the two bigger keys. That is, it related to whether the medium size key was paired with the smallest key, or the biggest key. The experiment therefore involved a 2 x 2 x 2 repeated-measures design with Size of Correct Key (smaller key vs. bigger key needing to be pressed), Key Pairing (medium key paired with smallest vs. biggest key), and Circle Brightness Relative to Background ("brighter" vs. "darker"), all as within-participant factors. The dependent variables were the speed (in milliseconds) and accuracy (percent correct) of participants' responses to each circle.

Procedure

The procedure was equivalent to that described in Experiment 1, except that in each of four blocks of trials the medium key was paired with either the smallest key or the biggest key from the three available. Whether the medium key was paired with the smallest key in the first half of the experiment (i.e., Blocks 1 & 2) and the biggest key in the second (i.e., Blocks 3 & 4), or vice versa, was counterbalanced across participants. Half of the participants (13 right-handers and three left-handers) were asked to press the left-hand key when the circle was perceived to be brighter than the background and the right-hand key when the circle was perceived to be darker than the background. The remaining participants (15 right-handers and one left-hander) were assigned to the opposite hand-brightness mapping (i.e., left-hand key for “darker” and right-hand key for “brighter”).

Results

The data were the speed and accuracy of participants’ responses to the circles. Mean correct RTs and accuracy levels obtained for the bright and dark circles were calculated separately for the smaller and bigger of the two keys used in each block of trials (see Table 2).

Response Accuracy

The overall mean level of response accuracy was 98.5% (SD = 3.1%). The level of correct responding was not significantly higher for congruent trials than for incongruent trials for either key pairing (i.e., whether the medium key was the smaller of the two keys, or the bigger), Wilcoxon Signed Ranks Test $z = -0.43$, $p = .67$, and Wilcoxon Signed Ranks Test $z = -0.58$, $p = .56$, for the medium key paired with the biggest and smallest key, respectively, both two-tailed.

Response Times

Participants’ mean correct RTs to the three brighter and three darker circles in each trial block were calculated. RTs from incorrect trials were excluded from the analysis, and any RTs greater than 2.5 SDs above a participant’s mean correct RT were replaced with the cut-off value. The resulting data were submitted to a 2 x 2 x 2 repeated-measures ANOVA, with Size of Correct Key (smaller key vs. bigger key needing to be pressed), Key Pairing (medium key paired with smallest vs. biggest key), and Circle Brightness Relative to Background (“brighter” vs. “darker”) as within-participant factors.[2]

The overall mean correct RT was 667 ms (SD = 197 ms). There was a significant main effect of Size of Correct Key, $F(1, 31) = 7.96$, $MSE = 0.004$, $p = .008$, $\eta_p^2 = 0.20$, with participants responding more quickly on the smaller key (656 ms) than on the bigger key (678 ms). There was not a significant main effect of Key Pairing, $F(1, 31) = 3.12$, $p = .09$. However, there was a significant Size of Correct Key x Key Pairing interaction, $F(1, 31) = 54.25$, $MSE = 0.004$, $p < .001$, $\eta_p^2 = 0.64$. This indicated that participants' responses were slower on the medium key (696 ms) than on either the smallest key (638 ms) or the biggest key (638 ms).

The main effect of Circle Brightness Relative to Background was significant, $F(1, 31) = 12.99$, $MSE = 0.01$, $p = .001$, $\eta_p^2 = 0.30$, with participants classifying the darker circles (647 ms) more rapidly than the brighter circles (686 ms). There was also a significant interaction between Size of Correct Key and Circle Brightness Relative to Background, $F(1, 31) = 13.13$, $MSE = 0.01$, $p = .001$, $\eta_p^2 = 0.30$, the nature of which was consistent with the predicted congruity effect. The mean correct RTs for congruent and incongruent trials were 646 and 686 ms, respectively. Paired-samples *t*-tests confirmed that the difference in response times to congruent and incongruent trials remained significant across low, medium, and high levels of within-category circle brightness, $t(31) = -2.51$, $p = .02$, $t(31) = -3.70$, $p = .001$, and $t(31) = -2.37$, $p = .02$, respectively, all two-tailed (see Figure 4).

There was not a significant interaction between Key Pairing and Circle Brightness Relative to Background, $F(1, 31) = 2.41$, $p = .13$, indicating that participants classified the darker circles more rapidly than the brighter circles irrespective of whether the medium key was paired with the biggest key (so that it was relatively small) or the smallest key (so that it was relatively big). Most importantly, the lack of a significant three-way interaction between Size of Correct Key, Key Pairing, and Circle Brightness Relative to Background, $F(1, 31) = 1.78$, $p = .19$, indicates that an equivalent Size of Correct Key x Circle Brightness Relative to

Background interaction was observed both when the two smaller keys were used and when the two bigger keys were used (i.e., regardless of how the medium size key was interpreted). This confirms that the predicted size-brightness congruity effect is largely determined by the relative size of the key needing to be pressed, rather than by its absolute size.

Responding with the Medium Key when it was Paired with either the Smallest Key or the Biggest Key

Because the medium key was one of the two response keys on all trials for each participant, there was the opportunity to confirm directly that it was the size of the medium key relative to the size of the key with which it was paired that determined whether it was congruent with the brighter or darker circles being classified. The mean RTs of the medium key alone, for each of the key pairings, were submitted to a 2 x 2 repeated-measures ANOVA with Key Pairing (medium key paired with smallest vs. biggest key) and Circle Brightness Relative to Background ("brighter" vs. "darker") as within-participant factors (see Figure 3).

The overall mean correct RT was 696 ms (SD = 185 ms). The analysis revealed a significant main effect of Key Pairing, $F(1, 31) = 8.66$, $MSE = 0.01$, $p = .006$, $\eta_p^2 = 0.22$, in which participants responded on the medium key more quickly when it was paired with the biggest key (673 ms) than when it was paired with the smallest key (718 ms). There was also a significant main effect of Circle Brightness Relative to Background, $F(1, 31) = 19.31$, $MSE = 0.01$, $p < .001$, $\eta_p^2 = 0.38$, with participants classifying darker circles (667 ms) more rapidly than brighter circles (724 ms). Finally, there was a significant interaction between Key Pairing and Circle Brightness Relative to Background, $F(1, 31) = 15.07$, $MSE = 0.01$, $p = .001$, $\eta_p^2 = 0.33$, the nature of which was consistent with the predicted size-brightness congruity effect (with mean RTs of 669 ms and 723 ms for congruent and incongruent pairings, respectively). That is, participants responded relatively quickly on the medium key when its size relative to the other key being used was congruent with the perceived brightness of the circle relative to the background against which it appeared.

The overall mean level of correct responding (98.6%) was too high to permit the equivalent analysis of response accuracy. However, a simplified analysis failed to reveal a significant difference in the percentage of correct responses across congruent (98.6%) and incongruent (98.5%) trials, Wilcoxon Signed Ranks $z = -0.06$, $p = .95$, two-tailed.

Discussion

The results of Experiment 2 support those of Experiment 1 by demonstrating that the congruity effect automatically induced by the size-brightness correspondence also can be largely dependent on context-sensitive, relative values of size, rather than on context-insensitive, absolute values of size. Performance on a speeded classification task was once again faster (though not more accurate) when participants pressed the smaller of two keys to confirm that a circle was perceived to be brighter than the background against which it appeared, and the bigger of two keys to confirm that a circle was perceived to be darker than the background, than vice versa. Crucially, an equivalent size-brightness congruity effect was observed regardless of whether the two keys being used were the two smaller keys or the two bigger keys of the three keys available. This meant that, in separate blocks of trials, the same medium key behaved as a smaller key when it was paired with the biggest of the three keys (thereby forming a congruent relationship with the brighter circles), but as a bigger key when it was paired with the smallest of the three keys (thereby forming a congruent relationship with the darker circles). Thus, for the cross-sensory congruity effect under investigation, the absolute size of the smaller and bigger keys being used by participants is clearly less important than is their size relative to each other.

General Discussion

The results of the two experiments in the present study provide direct evidence that the cross-sensory mapping of (haptic) size to (visual) brightness in the size-brightness correspondence is largely contingent on the relative values of these two features on their respective dimensions, as compared to their absolute values. Consistent with previous research by P. Walker and L. Walker (2012), participants in two speeded brightness classification tasks were faster and more accurate at classifying circles as bright when this required them to press the smaller of two keys, and as dark when this required them to press the bigger of two keys, than vice versa. More importantly, the same values of luminance (Experiment 1) and key size (Experiment 2) were at different times found to correspond to contrasting values on the other feature dimension depending on the context provided by the alternative stimuli with which they were being presented. That is, in separate blocks of trials, the two circles of intermediate luminance were classified relatively more quickly and accurately on the smaller key when they appeared against a darker background, but relatively more quickly and accurately on a bigger key when they appeared against a brighter background. Similarly, the same medium sized key was variously found to elicit relatively faster responses to either darker or brighter circles depending on whether it was paired with the smallest or the biggest of the three keys available for use in the experiment, respectively.

Given the consensus view reflected in the studies of cross-sensory mapping reviewed in the Introduction, wherein relative mappings are taken to indicate interactions at conceptual levels of representation, the present results provide valuable converging evidence for P. Walker and L. Walker's (2012) claim that the size-brightness congruity effect can originate at levels of processing at or beyond the level at which stimuli are categorised for the purpose of response selection (i.e., the congruity effect is post-categorical), and, in turn, for their suggestion that all cross-sensory correspondences can have a basis in the conceptual representation of basic stimulus features (see also L. Walker, P. Walker, & Francis, 2012; P. Walker, L. Walker, & Francis, 2015). Were the size-brightness congruity effect to arise at pre-categorical levels of processing, then particular feature values on these two dimensions would have corresponded with each other irrespective of their relationship to other task-relevant stimuli (cf. Marks, 1987). This was not the case in the present study.

By avoiding confounding changes in stimulus context with changes in stimulus uncertainty (i.e., by ensuring that the same number of alternative stimuli were sampled regardless of context), and by fully accounting for any effects of hand-decision assignment, the present study provides the most persuasive evidence to date that an automatically induced congruity effect based on a cross-sensory correspondence can be driven by the relative mapping of feature values across the two stimulus domains. This is especially compelling because the same stimuli behaved in contrasting ways according to the context provided by the other stimuli with which they appeared. That is, the size-brightness congruity effect reversed, rather than just diminished in strength, when the context in which the same stimuli appeared was changed.

The suggestion that a correspondence induced congruity effect can have a basis in the post-categorical coding of basic stimulus features complements other accounts which posit that cross-sensory correspondences can take effect at early (i.e., pre-categorical) levels of processing, allowing them to impact directly on multisensory perceptual integration. Using Bayesian integration theory as a framework within which to model cross-sensory correspondences, Spence (2011) (see also Parise & Spence, 2009) suggested that correspondences arising from the internalisation of the statistics of the natural environment (*statistical correspondences*) can form part of the sensory system's prior knowledge that certain stimuli "go together". This prior knowledge (the coupling prior) strengthens the coupling between the stimuli, which in turn enhances the perceptual fusion of the sensory signals.

Evidence in support of such an early processing account comes from a study exploiting the temporal ventriloquism effect (Morein-Zamir, Soto-Faraco, & Kingstone, 2003) to show that the cross-sensory mapping of smallness to high pitch (which is readily observed in the natural environment; see, e.g., Grassi, 2005) can enhance the auditory capture of vision in time. Parise and Spence (2008) asked participants to make temporal order judgements (TOJs) regarding the sequence in which two circles (one small, one big) were displayed to the left and right sides of a computer screen, whilst ignoring two auditory tones (300 and 4500 Hz), one presented 150 ms before the first visual stimulus, and the other 150 ms after the second visual stimulus. In accordance with their belief that cross-sensory correspondence will strengthen the sensory attraction between temporally proximate auditory-visual stimuli, they found that TOJs were more sensitive (i.e., the temporal separation of the two visual stimuli became more apparent) when the relative size of each circle was congruent with the pitch of the most adjacent tone. It was as if the congruity caused the visual and auditory stimuli to be perceived to occupy closer moments in time. In Bayesian terms, this suggests that repeated exposure to co-occurrences between these two feature dimensions strengthened the coupling between congruent auditory-visual pairs, thus leading to an illusory blending of the temporal location of the adjacent visual and auditory stimuli (in this case creating an expansion of the perceived temporal interval between the two visual stimuli) (but see Keetels & Vroomen, 2011). All of this said, of course, it is possible that low level (statistical) correspondences will come to be reflected at a higher, conceptual level, thereby allowing such congruity effects also to emanate from the context-sensitive, post-categorical coding of contrasting feature values. Indeed, as Marks (1989, p. 587) commented in relation to the correspondence between loudness and brightness, “(…) even if loudness and brightness find their basic resemblance in common physiological processes, they may subsequently come to owe their communality to a common semantic code (…)”.

That the representation of natural co-occurrences need not be restricted to the absolute feature values captured by lower levels of stimulus encoding is apparent from other observations. For example, when researchers have selected stimulus values to demonstrate and explore correspondences, they have not normally taken steps to match corresponding stimuli on the basis of their absolute feature values, but have relied instead on their relative contrast. Thus, the highest pitched sounds and pointiest shapes in one study might be lower in pitch and less pointy than the highest pitched sounds and pointiest shapes in another study.[3] The relevance of relative stimulus contrast can also be seen in the language used to talk about statistical correspondences. For instance, when discussing the co-occurrence between size and pitch, Spence (2011, p. 985), like Marks (1989, p. 587), employed the comparative form for adjectives to remark that “in nature (...) the *larger* the object, the *lower* the frequency it makes when struck, dropped, sounded, etc. [emphasis added]”.

The functional significance of the context-sensitive coding of stimulus feature values becomes especially apparent when the contribution of cross-sensory correspondences to sound symbolism in language is considered. Thus, a case can be made for cross-sensory correspondences underpinning some forms of sound symbolism. For example, because higher pitched sounds are perceived to be smaller, sharper, brighter, thinner, faster, and lighter in weight than are lower pitched sounds (Tarte, 1982; P. Walker, & Smith, 1984; L. Walker, P. Walker, & Francis, 2012), reflecting the correspondences among these feature dimensions, words with vowel sounds containing relatively high acoustic frequencies (i.e., front/close vowels rather than back/open vowels) seem appropriately sound symbolic as names for concepts with corresponding attributes (e.g., *gleam*, *tweet*, *mini*) (Berlin, 1994;

Klink, 2000; Klink & Wu, 2014; Lowry & Shrum, 2007; Newman, 1933; Sapir, 1929). Indeed, Monaghan, Mattock, and Walker (2012) show how people are able to learn names for novel shapes contrasting in their pointiness/curvedness more easily when the front/close vs. back/open status of the vowel in the word is congruent with the pointiness of the shape it names. That is, they find it easier to learn the name for a pointy (curved) shape when it contains a vowel sound with relatively high (low) acoustic frequencies. Crucially, in this and other instances of sound symbolism involving the front/close vs. back/open nature of vowel sounds, it is the acoustic frequencies of the vowel sounds relative to the word as a whole and, more importantly perhaps, relative to the overall acoustic profile of the speaker's voice that are salient. It is assumed, for example, that particular instances of sound symbolism in language will occur whatever the fundamental frequency of a speaker's voice (e.g., whether the speaker is male or female), confirming that cross-sensory correspondences can support sound symbolism only to the extent that the coding of the acoustic frequencies embedded in a spoken word is context (voice) sensitive.

References

Ben-Artzi, E. & Marks, L. E. (1995). Visual-auditory interaction in speeded classification: Role of stimulus difference. *Perception and Psychophysics, 57,* 1151-1162. doi: 10.3758/BF03208371

Berlin, B. (1994). Evidence for pervasive synesthetic sound symbolism in ethnozoological nomenclature. In L. Hinton, J. Nichols, & J. J. Ohala (Eds), *Sound Symbolism,* pp. 76-93. New York: Cambridge University Press.

Chiou, R., & Rich, A. N. (2012). Cross-modality correspondence between pitch and spatial location modulates attentional orienting. *Perception*, *41*, 339-353. doi: 10.1068/p7161

Collier, W. G., & Hubbard, T. L. (2001). Judgements of happiness, brightness, speed, and tempo change of auditory stimuli varying in pitch and tempo. *Psychomusicology*, *17*, 36-55.

Crisinel, A-S., & Spence, C. (2009). Implicit association between basic tastes and pitch. *Neuroscience Letters*, *464*, 39-42. doi: 10.1016/j.neulet.2009.08.016

Crisinel, A-S., & Spence, C. (2010a). As bitter as a trombone: Synesthetic correspondences in nonsynesthetes between tastes/flavors and musical notes. *Attention, Perception, & Psychophysics*, *72*, 1994-2002. doi: 10.3758/APP.72.7.1994

Crisinel, A-S., & Spence, C. (2010b). A sweet sound? Food names reveal implicit associations between taste and pitch. *Perception*, *39*, 417-425. doi: 10.1068/p6574

Evans, K. K., & Treisman, A. (2010). Natural cross-modal mappings between visual and auditory features. *Journal of Vision*, *10*, 1-12. doi: 10.1167/10.1.6

Gallace, A., & Spence, C. (2006). Multisensory synesthetic interactions in the speeded classification of visual size. *Perception & Psychophysics*, *68*, 1191-1203. doi: 10.3758/BF03193720

Grassi, M. (2005). Do we hear size or sound? Balls dropped on plates. *Perception & Psychophysics*, *67*, 274-284. doi: 10.3758/BF03206491

Guzman-Martinez, E., Ortega, L., Grabowecky, M., Mossbridge, J., & Suzuki, S. (2012). Interactive coding of visual spatial frequency and auditory amplitude-modulation rate. *Current Biology, 22,* 383-388. doi: 10.1016/j.cub.2012.01.004

Hubbard, T. L. (1996). Synesthesia-like mappings of lightness, pitch, and melodic interval. *American Journal of Psychology*, *109*, 219-238. doi: 10.2307/1423274

Karwoski, T. F., Odbert, H. S., & Osgood, C. E. (1942). Studies in synesthetic thinking: II. The role of form in visual responses to music. *The Journal of General Psychology, 26,* 199-222.

Keetels, M., & Vroomen, J. (2011). No effect of synesthetic congruency on temporal ventriloquism. *Attention, Perception, & Psychophysics*, *73*, 209-218. doi: 10.3758/s13414-010-0019-0

Klink, R. R. (2000). Creating brand names with meaning: The use of sound symbolism. *Marketing Letters, 11,* 5-20. doi: 10.1023/A:1008184423824

Klink, R. R., & Wu, L. (2014). The role of position, type, and combination of sound symbolism imbeds in brand names. *Marketing Letters, 25,* 13-24. doi: 10.1007/s11002-013-9236-3

Lewkowicz, D. J., & Turkewitz, G. (1980). Cross-modal equivalences in early infancy: Auditory-visual intensity matching. *Developmental Psychology, 16,* 597–607. doi: 10.1037/0012-1649.16.6.597

Lowry, T. M. & Shrum, L. J. (2007). Phonetic symbolism and brand name preference. *Journal of Consumer Research, 34,* 406-414. doi: 10.1086/518530

Lunghi, C. & Alais, D. (2013). Touch interacts with vision during binocular rivalry with a tight orientation tuning. *PLoS ONE, 8(3),* e58754. doi: 10.1371/journal.pone.0058754

Lunghi, C., Binda, P., & Morrone, M. C. (2010). Touch disambiguates rivalrous perception at early stages of visual analysis. *Current Biology, CB, 20(4),* R 143-R144. doi: 10.1016/j.cub.2009.12.015

Marks, L. E. (1974). On associations of light and sound: The mediation of brightness, pitch, and loudness. *American Journal of Psychology*, *87*, 173-188.

Marks, L. E. (1987). On cross-modal similarity: Auditory-visual interactions in speeded discrimination. *Journal of Experimental Psychology: Human Perception and Performance*, *13*, 384-394. doi: 10.1037/0096-1523.13.3.384

Marks, L. E. (1989). On cross-modal similarity: The perceptual structure of pitch, loudness, and brightness. *Journal of Experimental Psychology: Human Perception and Performance, 15,* 586-602. doi: 10.1037/0096-1523.15.3.586

Marks, L. E., Szczesiul, R., & Ohlott, P. (1986). On the cross-modal perception of intensity. *Journal of Experimental Psychology: Human Perception and Performance, 12,* 517-534. doi: 10.1037/0096-1523.12.4.517

Martino, G., & Marks, L. E. (2001). Synesthesia: Strong and weak. *Current Directions in Psychological Science*, *10*, 61-65.

Monaghan, P., Mattock, K., & Walker, P. (2012). The role of sound symbolism in language learning. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *38*, 1152-1164. doi: 10.1037/a0027747

Morein-Zamir, S., Soto-Faraco, S., & Kingstone, A. (2003). Auditory capture of vision: Examining temporal ventriloquism. *Cognitive Brain Research*, *17*, 154-163. doi: 10.1016/S0926-6410(03)00089-2

Newman, S. S. (1933). Further experiments in phonetic symbolism. *American Journal of Psychology, 45,* 53-75.

Occelli, V., Spence, C., & Zampini, M. (2009). Compatibility effects between sound frequency and tactile elevation. *NeuroReport*, *20*, 793-797. doi: 10.1097/WNR.0b013e32832b8069

Orchard-Mills, E., Alais, D., & van der Burg, E. (2013). Cross-modal associations between vision, touch, and audition influence visual search through top-down attention, not bottom-up capture. *Attention, Perception and Psychophysics, 75,* 1892-1905. doi: 10.3758/s13414-013-0535-9

Orchard-Mills, E., van der Burg, E., & Alais, D. (2013). Amplitude-modulated auditory stimuli influence selection of visual spatial frequencies. *Journal of Vision, 13(3),* 6, 1-17. doi: 10.1167/13.3.6

Parise, C.V., Knorre, K., & Ernst, M. O. (2014). Natural auditory scene statistics shapes human spatial hearing. *Proceedings of the National Academy of Sciences of the USA*, *111*, 6104-6108. doi: 10.1073/pnas.1322705111

Parise, C., & Spence, C. (2008). Synesthetic congruency modulates the temporal ventriloquism effect. *Neuroscience Letters*, *442*, 257-261. doi: 10.1016/j.neulet.2008.07.010

Parise, C. V., & Spence, C. (2009). ‘When birds of a feather flock together’: Synesthetic correspondences modulate audiovisual integration in non-synesthetes. *PLoS ONE*, *4*, doi:10.1371/journal.pone.0005664

Rusconi, E., Kwan, B., Giordano, B. L., Umiltà, C., & Butterworth, B. (2006). Spatial representation of pitch height: The SMARC effect. *Cognition*, *99*, 113-129. doi: 10.1016/j.cognition.2005.01.004

Sapir, E. (1929). A study of phonetic symbolism. *Journal of Experimental Psychology, 12,* 225-239.

Spence, C. (2011). Crossmodal correspondences: A tutorial review. *Attention, Perception, & Psychophysics*, *73*, 971-995. doi: 10.3758/s13414-010-0073-7

Spence, C., & Deroy, O. (2012). Crossmodal correspondences: Innate or learned? *i-Perception*, *3*, 316-318. doi: dx.doi.org/10.1068/i0526ic

Tarte, R. D. (1982). The relationship between monosyllables and pure tones: An investigation of phonetic symbolism. *Journal of Verbal Learning and Verbal Behavior, 21,* 352-360. doi: 10.1016/S0022-5371(82)90670-3

Walker, P. & Smith, S. (1984). Stroop interference based on the synaesthetic qualities of auditory pitch. *Perception, 13,* 75-81.

Walker, P. (2012). Cross-sensory correspondences and crosstalk between dimensions of connotative meaning: Visual angularity is hard, high-pitched, and bright. *Attention, Perception, & Psychophysics*, *74*, 1792-1809. doi: 10.3758/s13414-012-0341-9

Walker, P., Bremner, J. G., Mason, U., Spring, J., Mattock, K., Slater, A., & Johnson, S. P. (2010). Preverbal infants' sensitivity to synaesthetic cross-modality correspondences. *Psychological Science*, *21*, 21-25. doi: 10.1177/0956797609354734

Walker, P., & Walker, L. (2012). Size-brightness correspondence: Crosstalk and congruity among dimensions of connotative meaning. *Attention, Perception, & Psychophysics*, *74*, 1226-1240. doi: 10.3758/s13414-012-0297-9

Walker, L., Walker, P., & Francis, B. (2012). A common scheme for cross-sensory correspondences across stimulus domains. *Perception, 41,* 1186-1192. http://dx.doi.org/10.1068/p7149

Walker, P., Walker, L., & Francis, B. (2015). The size-brightness correspondence: Evidence for crosstalk among aligned conceptual feature dimensions. *Under Review.*

Footnotes

[1] This is a similar strategy to the one adopted by Lawrence Marks and his colleagues to study context effects in cross-modality matching (see Marks, 1989; Marks, Szczesiul, & Ohlott, 1986).

[2] An initial analysis of the data, which included Within-Category Circle Brightness as an additional within-participant factor, showed that there were no significant interactions between Within-Category Circle Brightness, Circle Brightness Relative to Background, and Size of Correct Key, $F(1.62, 50.26) = 0.86$, $p = .41$, or between Within-Category Circle Brightness, Circle Brightness Relative to Background, Size of Correct Key, and Key Pairing, $F(2, 62) = 0.56$, $p = .57$. These outcomes confirm that neither when the medium key was paired with the smallest key, nor when it was paired with the biggest key, did variations in circle brightness within each task-defined category of brightness (i.e., within those levels of brightness that were brighter than the mid-grey background, and within those levels of brightness that were darker than the mid-grey background) interact with key size to yield a congruity effect. In other words, irrespective of whether the medium key was the smaller or the bigger of the two keys available, participants did not respond more quickly when higher (lower) levels of brightness within a task-defined category of brightness were paired with the smaller (bigger) key. In line with P. Walker and L. Walker's (2012) findings, this provides additional evidence that the size-brightness congruity effect reflects context-sensitive interactions among representations at or beyond the level at which visual stimuli are categorised for the purpose of response selection.

[3] While there are no known co-occurrences in the natural environment through which the pitch-sharpness correspondence could be acquired directly, it is plausible that this correspondence is mediated by a broader understanding of the physical properties of objects

(see Spence & Deroy, 2012). For example, Walker et al. (2010) noted that sensitivity to the mapping of high pitch to pointiness might be driven in part by the realisation that because pointier objects tend to be formed from harder materials they are more likely than are curved objects to make a higher pitched sound when struck.

Table 1

Mean Correct RTs (SEMs in parentheses) and Accuracy Levels (percent correct) According to Key Size, Circle Brightness Relative to Background, and Background Brightness

		Circle Brightness Relative to Background	
Background Brightness	Key Size	“brighter”	“darker”
Brighter	Small	619	***675***
		(29)	***(29)***
		99.3	***97.3***
	Big	**612**	*595*
		(30)	*(25)*
		98.6	*99.0*
Darker	Small	*643*	**614**
		(27)	**(21)**
		99.0	**98.3**
	Big	***609***	554
		(24)	(22)
		98.3	100

Note. Normal font entries relate to congruent conditions, bold entries relate to incongruent conditions. Also, italicised entries relate to the two circles of intermediate brightness that appeared as stimuli in every block of trials.

Table 2

Mean Correct Response Times (SEMs in parentheses) and Accuracy Levels (percent correct) According to Circle Brightness Relative to Background, Key Pairing, and Size of Correct Key

		Circle Brightness Relative to Background	
Key Pairing	Size of Correct Key	“brighter”	“darker”
Medium & Smallest	Smaller	633 (29) 98.3	**634** **(31)** **98.4**
	Bigger	***774*** ***(42)*** ***98.6***	*663* *(27)* *99.0*
Medium & Biggest	Smaller	*674* *(24)* *98.3*	***672*** ***(32)*** ***98.4***
	Bigger	**664** **(32)** **98.3**	612 (27) 98.8

Note. Normal font entries relate to congruent conditions, bold entries relate to incongruent conditions. Also, italicised entries relate to the medium key, which was one of the two keys available on all trials.

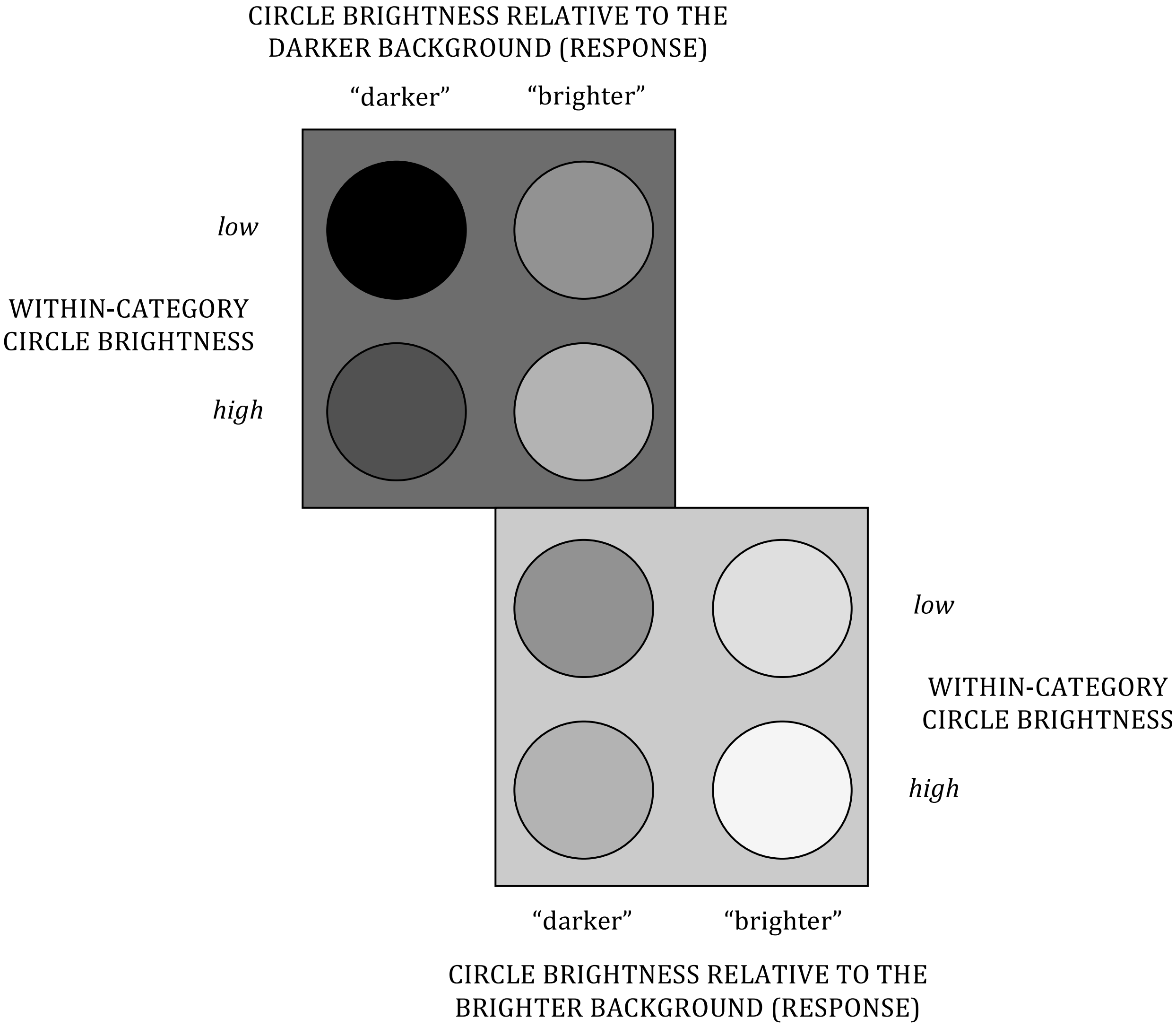

Figure 1. The circles varying in luminance used in Experiment 1 according to the context provided by the brightness of the background against which they appeared. Note that though the perceived brightness of each circle might not appear here exactly as it did in the experiment, the direction of its contrast with the background is preserved.

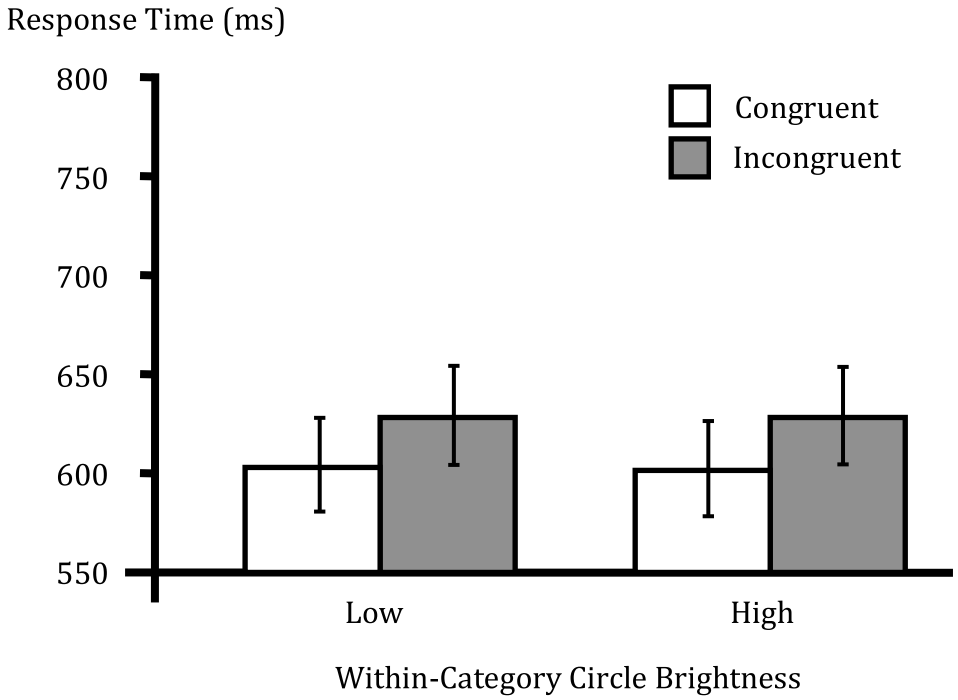

Figure 2. Mean correct response times for congruent and incongruent combinations of Circle Brightness Relative to Background and Key Size at each level of Within-Category Circle Brightness. Error bars show standard error of the mean.

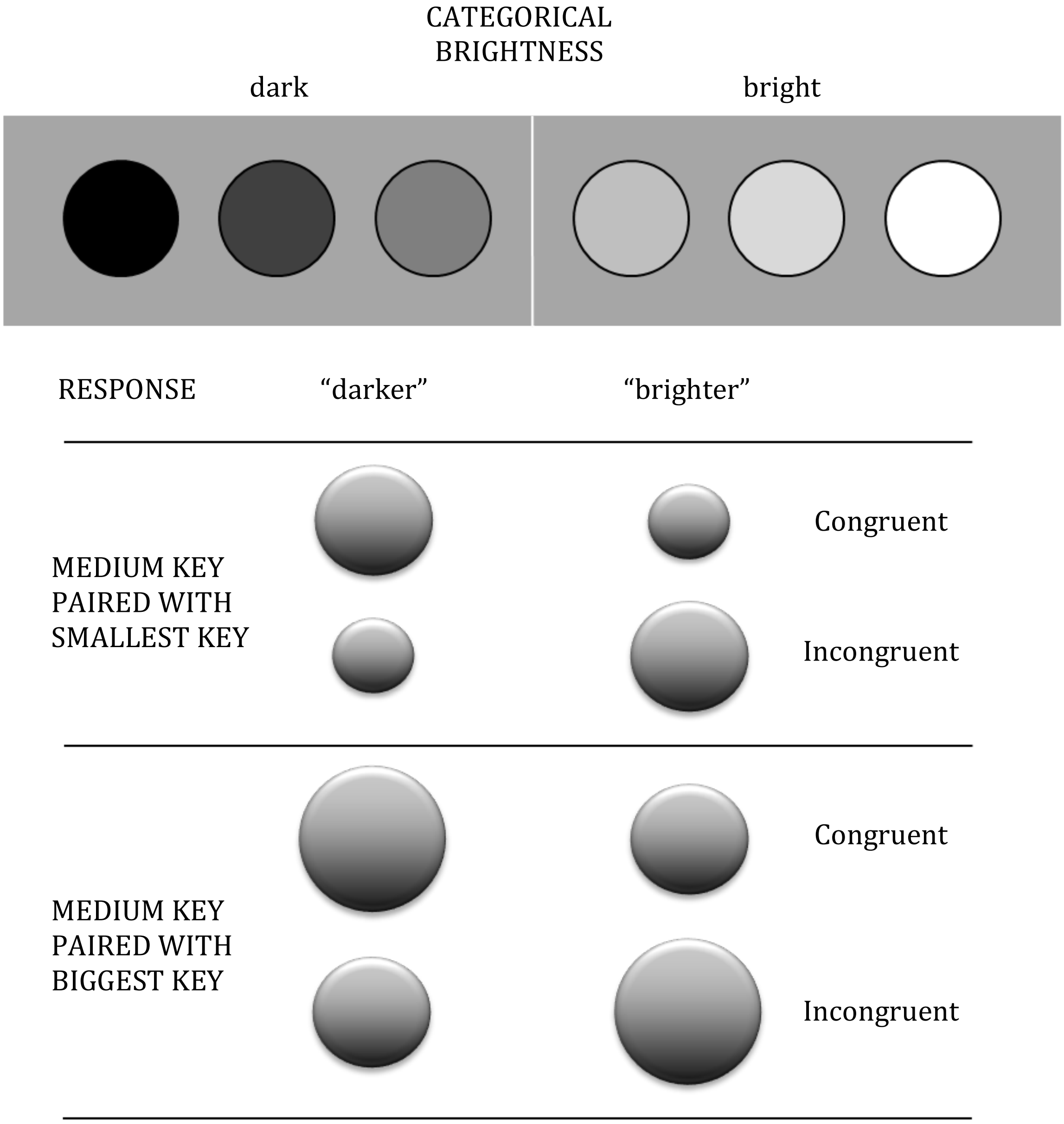

Figure 3. Schematic illustration of the two key pairings used in Experiment 2. In separate blocks of trials, the medium key was paired with either the smallest key, so that it was the bigger of the two keys being used by participants (top panel), or the biggest key, so that it was the smaller of the two keys being used by participants (bottom panel).

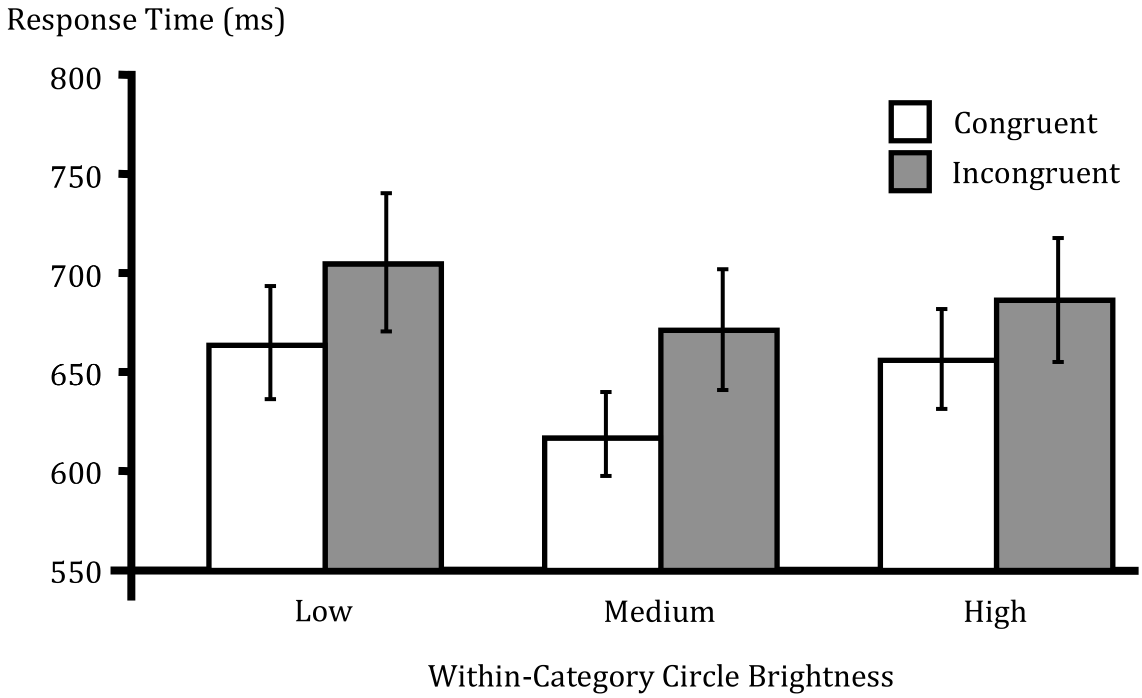

Figure 4. Mean correct response times for congruent and incongruent combinations of Circle Brightness Relative to Background and Size of Correct Key at each level of Within-Category Circle Brightness. Error bars show standard error of the mean.