Cross-Sensory Correspondences: Heaviness is Dark and Low-Pitched

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Author Note

This research was supported by an ESRC Research Studentship awarded to Gabrielle Scallon.

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Abstract

Everyday language reveals how stimuli encoded in one sensory feature domain can possess qualities normally associated with a different domain (e.g., higher pitch sounds are *bright*, *light in weight*, *sharp*, and *thin*). Such cross-sensory associations appear to reflect crosstalk among aligned (corresponding) feature dimensions, including brightness, heaviness, and sharpness. Evidence for heaviness being one such dimension is very limited, with heaviness appearing primarily as a verbal associate of other feature contrasts (e.g., darker objects and lower pitch sounds are heavier than their opposites). Given the presumed bi-directionality of the crosstalk between corresponding dimensions, heaviness should itself induce the cross-sensory associations observed elsewhere, including with brightness and pitch. Taking care to dissociate effects arising from the size and mass of an object this is confirmed. When hidden objects varying independently in size and mass are lifted, objects that feel heavier are judged to be darker and to make lower pitch sounds than objects feeling less heavy. These judgements track the changes in perceived heaviness induced by the size-weight illusion. The potential involvement of language, natural scene statistics, and Bayesian processes in correspondences, and the effects they induce, is considered.

Keywords: cross-sensory correspondences, heaviness-brightness correspondence, heaviness-pitch correspondence

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Cross-Sensory Correspondences

In everyday life we observe people commenting on the brightness, lightness in weight, and sharpness of a sound, the sharpness of a taste, and the darkness, heaviness, and thickness of a perfume. It seems that stimuli encoded in different sensory feature domains can, nevertheless, share the same perceptual qualities: Sounds can share the brightness of visual stimuli, and the sharpness and heaviness of objects seen and felt; tastes can share the sharpness of felt textures and shapes; and, odours can share the darkness, heaviness, and thickness of objects seen and felt.[1]

Brightness, heaviness, sharpness, and thickness are all feature dimensions, and evidence indicates that they are aligned with each other in a particular way, and that it is the relative positioning of their values on the dimensions that is common to stimuli encoded in different feature domains (see L. Walker & P. Walker, 2016). The resulting systematicity in the cross-sensory associations (i.e., progressively more extreme values on one dimension are linked to progressively more extreme values on the other dimension) is what the term cross-sensory *correspondence* is intended to capture. There are claims that, at the highest level, the feature dimensions are modality independent and conceptual in nature (e.g., it is the amodal concepts of elevation and size that are aligned, rather than specifically auditory pitch and visual size) (see Karwoski, Odbert, & Osgood, 1942; Martino & Marks, 1999; Melara & Marks, 1990; P. Walker & Smith, 1984; P. Walker, L. Walker, & Francis 2015).

Cross-Sensory Correspondences and Auditory Pitch

Asked to indicate the cross-sensory features possessed by simple sounds differing in pitch (typically pure tones), people judge higher pitch sounds to be, among other things, more active, brighter, faster, higher in space, lighter in weight, shallower, sharper (more angular/pointier), smaller, and thinner than lower pitch sounds (Boltz, 2011; Collier & Hubbard, 2004; Eitan & Timmers, 2010; Marks, 1978; Perrott, Musicant, & Schwethelm, 1980; Tarte, 1982; L. Walker, P. Walker, & Francis, 2012). And when young children indicate which of two bouncing balls they think is making a higher pitch impact sound, they point to the smaller or brighter of the two balls (Mondloch & Maurer, 2004). Furthermore, when adults draw music they are listening to, they draw lines and forms that are more angular (sharper), brighter, higher on the page, smaller, and thinner, the higher in pitch is the music (Karwoski, Odbert, & Osgood, 1942; Kussner & Leech-Wilkinson, 2013). Congruity effects in speeded classification confirm the same cross-sensory correspondences (e.g., Chiou & Rich, 2012; Evans & Treisman, 2010; Occelli, Spence, & Zampini, 2009; Ro, Hsu, Yasar, Elmore, & Beauchamp, 2009; P. Walker 2012a). For example, in a brightness classification task, people are faster to classify a visual stimulus as bright when it is accompanied by a higher pitch sound (a brighter sound) rather than a lower pitch sound (a darker sound) (Marks, 1987; Melara, 1989; Martino & Marks, 1999).

A Common Scheme for Cross-Sensory Correspondences

To the extent that the aligned dimensions are modality-independent and conceptual in nature, the same correspondences should emerge whichever sensory feature is used to probe them (e.g., visual stimuli contrasting in brightness, aromas contrasting in heaviness, or haptic objects and sounds contrasting in sharpness). The evidence, including from speeded classification tasks, indicates that this is the case (e.g., Collier & Hubbard, 2001; Martino & Marks, 2000; Occelli, Spence, & Zampini, 2009; Ro et. al., 2009; P. Walker, 2012a,b; P. Walker, Francis, & L. Walker, 2010). For example, when hidden objects varying in size are explored by touch alone, smaller objects are judged to be brighter, faster, higher in space, thinner, sharper, and to make higher pitch sounds compared to bigger objects (P. Walker & L.

Walker, 2012; L. Walker et al., 2012). It appears, therefore, that a single network of interconnected feature dimensions underpins all observed correspondences.

The Bi-Directionality of Correspondences

An important characteristic of cross-sensory correspondences follows from this conceptualisation, namely, that the crosstalk occurring between all the aligned dimensions is bi-directional (cf. Martino and Marks, 2001). Without this, the network of associations would risk being incoherent (see Walker, 2016, for discussion of this point). A growing body of evidence confirms the bi-directionality of correspondences (e.g., Ben-Artzi & Marks, 1995; Evans & Treisman, 2010; Melara & O'Brien, 1987; Patching & Quinlan, 2002). Regarding auditory pitch, for example, bigger visual stimuli, bigger haptic stimuli, darker visual stimuli, and more curved (less pointy) visual stimuli, have all been associated with lower pitch sounds than their opposites (e.g., L. Walker et al., 2012). Slower tempo musical sequences also have been associated with lower pitch sounds (Collier & Hubbard, 2001).

Heaviness as a Core Feature in Cross-Sensory Correspondences

Heaviness appears consistently as a feature implicated in cross-sensory correspondences. Not only are bigger visual objects (including tangible balls and geometric shapes) judged to be heavier than otherwise identical but smaller objects (L. Walker, P. Walker, & Francis, 2012; P. Walker & Smith, 1985), lower pitch sounds also are deemed to be heavier than higher pitch sounds (P. Walker & Smith, 1984; L. Walker, P. Walker, & Francis, 2012), as are curved geometric shapes compared to their size-matched pointy equivalents (L. Walker, P. Walker, & Francis, 2012). In addition, based on vision alone, darker coloured balls are deemed to be heavier than otherwise identical but brighter coloured balls (P. Walker, Francis, & L. Walker, 2010; P. Walker, 2012b).

In previous studies, heaviness has figured as a cross-sensory feature induced by a directly manipulated stimulus contrast, rather than as the basis for a stimulus contrast inducing cross-sensory feature associations. For example, when a contrast in object size (visual or tactile) has been created to reveal its cross-sensory feature associations, heaviness has aligned itself with bigger, just as darker and lower in pitch have aligned themselves with bigger (L. Walker, P. Walker, & Francis, 2012). It is not known, however, if objects contrasting in heaviness will reveal heavier to be aligned with bigger, darker, and lower in pitch.

Heaviness and Size

The cross-sensory association between heaviness and size echoes the strong natural co-variation of the two features (i.e., all else equal, bigger things tend to be heavier things). It is possible, therefore, that any apparent involvement of heaviness in cross-sensory correspondences is secondary to the involvement of size: Perhaps lower pitch sounds and curved shapes seem to be heavier only to the extent that they seem to be bigger. In which case, the involvement of heaviness in the core set of correspondences would be illusory.

There is evidence cautioning against dismissing heaviness in this way. Thus, when curved and pointy visual shapes are carefully matched for their judged size, and then rated for their cross-sensory features, curvedness aligns itself with heaviness despite the absence of a difference in perceived size (L. Walker, P. Walker, & Francis, 2012). Similarly, darker coloured objects are judged to be heavier than lighter coloured objects, even though the latter are more likely to be perceived to be bigger, rather than smaller, than the former (see Gundlach & Macoubray, 1931; Robinson, 1954; P. Walker, Francis, & L. Walker, 2010; Wallis, 1935). It remains a distinct possibility, therefore, that notwithstanding its strong association with size, heaviness functions as a cross-sensory feature dimension in its own right, with the potential to support bi-directional cross-sensory correspondences.

Mass, Weight, and Heaviness

The *mass* of an object is the principal physical attribute (loosely, amount of material) that gives an object the potential to feel heavy, whether or not this is experienced while gravitational forces are at play (e.g., whether an object is lifted or, instead, is pushed to one side when suspended from long wires). The *weight* of an object is the objective measure of mass that is revealed when weighing scales support the object against gravitational forces. *Heaviness* is a person's experience (perception) of an object's mass. Though this is normally experienced when the pull of gravity needs to be counteracted (as in lifting and carrying), it can also be experienced when gravity need not be counteracted, such as when pushing an object that is suspended on long wires.

The Present Study

That the perceived heaviness of an object is distinct from its weight is confirmed by the size-weight illusion: The smaller of two otherwise identical objects with the same weight feels to be the heavier of the two (e.g., Murray, Ellis, Bandomir & Ross, 1999; Buckingham, 2014). If cross-sensory correspondences emanate from perceptual attributes of stimuli, rather than directly from the encoding of their physical attributes, then it should be the perceived heaviness of an object, rather than its weight, that enters into correspondence with other feature dimensions: An object that is perceived to be relatively heavy should be judged to be more curved, darker, lower in pitch, slower, thicker, and to have lower spatial elevation, than an equivalent object that is perceived to less heavy, even if the objects are identical in weight. Rather than address this proposal by examining all of these correspondences, and because participants in the present study were to be asked to grasp hidden objects with their hands (thereby providing themselves with direct information about the shape, thickness, and spatial location of each object), initial focus was on the correspondences between heaviness and each of brightness and pitch.

Size and weight were manipulated independently in the creation of a set of nine solid cylindrical objects, with three values of weight being crossed with three values of size (see Figure 1). When the objects are lifted, therefore, their size, weight, and heaviness each has the potential to contribute to determining their cross-sensory features. There are several ways in which these features could combine to this end, and it is worth rehearsing the more obvious of these.

One possibility is that only the size of a lifted hidden object will determine its cross-sensory features. Assuming the perceived size of an object will not change when it is lifted, and will not change according to its weight, then it would be expected to induce the same cross-sensory features as observed in previous studies in which hidden objects were explored by touch but without being lifted. Because the objects were not lifted in these previous studies, their weight and heaviness could not contribute to determining their cross-sensory features, and it emerged that smaller objects were judged to be brighter and to make higher pitch sounds than bigger objects (L. Walker et al., 2012; P. Walker & L. Walker, 2012; P. Walker & Smith, 1985). But in these previous studies the objects were balls of different size, and it is uncertain if the same associations with size will be observed with other types of object, including the cylindrical objects created for the main study. Therefore, a preliminary study was undertaken to check if this was the case, with participants being asked to make judgements regarding a subset of three cylinders from the set of nine, one at each size. They were able to explore the objects by touch alone, but were not allowed to move or lift them.

A second possibility is that weight, but not perceived heaviness, will determine an object's cross-sensory features, with or without a separate contribution from the size of the object. Finally, a third possibility is that the perceived heaviness of an object, itself determined by both the size and weight of an object (as per the size-weight illusion), will determine its cross-sensory features, with or without a separate contribution from the size of the object. It was with this potential involvement of heaviness in mind that some participants in the main study were asked to provide judgements of the perceived heaviness of the cylindrical objects. These judgements could then replace values for the actual weights of the objects as an explanatory factor in the analyses, to see which is the better predictor of a lifted object's cross-sensory features.

Method

Materials

Nine solid cylindrical objects were created from thin-walled (approx. 1mm) aluminium tubing filled with evenly distributed fragments of lead mixed in builder's expanding foam. The ends of the cylinders were smoothed with a fine layer of epoxy resin, after which the cylinders were painted matt grey. Three values for cylinder size (i.e., diameters of 3, 4, and 5 cm, and heights matching these diameters) were crossed with three values for weight (i.e., 44, 107, and 190 gm) (i.e., for each size of object the same three weight versions were created). The weights of the cylinders were manipulated by varying the proportion of lead and builder's foam with which they were filled. The targeted values for weight were chosen on the basis that they should be a set of weights that objects at these various sizes could have when created from the same material (i.e., they reflect the natural co-variation of weight and size). The actual weights achieved were close approximations to the targeted values of 42, 101, and 196 gm, where these values correspond to a fixed density of 2 gm/cm^3 (see Figure 1).

Participants

One hundred and twelve students at Lancaster University completed the study after being approached in various social and learning spaces. All but 10 participants were right hand dominant by self-report, and none identified themselves as a synaesthete during post-experiment questioning. In the preliminary *no-lift* study (i.e., participants were not allowed to move or lift the objects), a group of 28 participants (2 males, mean age = 19.30 yrs) provided judgements of the heaviness, brightness, and pitch of three of the objects, one at each value for size (i.e., objects A, E, & I in Figure 1). In the main *lift* study (i.e., participants were required to lift the objects by hand), each of three additional groups of twenty-eight participants provided judgements of either their heaviness (8 males, mean age = 20.64 yrs), brightness (10 males, mean age = 20 yrs), or pitch (12 males, mean age = 20.86 yrs). Note that the *lift* condition, in contrast to the *no-lift* condition, involved different participants providing judgements about each of the three features.

Procedure

Pairs of objects were presented for participants to touch by placing them inside a black, wooden frame (height = 33 cm, width = 33 cm, depth = 33 cm) positioned on the table in front of them. A thick black drape hung over the front of the frame to prevent participants seeing the objects at any point during the study, including when they were exploring them by hand. The rating scales for heaviness, brightness, and pitch could be placed on top of the frame for participants to convey their judgements about each object. Each of these was a 9-point scale. For heaviness, it comprised a printed Likert scale with endpoints anchored with the labels *light* and *heavy*. For achromatic brightness, the scale comprised a sequence of 9 squares, ranging from white through to black, printed on a finely patterned olive green background. The values for achromatic brightness were taken from the scale available in the Munsell Book of Color (1976). Finally, for auditory pitch, a 9-point scale was marked out on the nine white keys running upward from middle C on a Casio SA-47H5 Mini Keys Keyboard. All three scales were positioned so that participants could easily use their non-dominant hand to indicate which point on the scale was appropriate for the object currently being explored with their dominant hand. They were asked to touch the relevant point and, in the case of the keyboard, to press the relevant key. The experimenter recorded the numerical value (1 – 9) linked to the participant's choice.

Participants in the preliminary *no-lift* study were presented with each possible pairing of the three different sized objects for exploration by touch alone, using the thumb and first two fingers of their preferred hand, with no requirement to maintain a precision-grip configuration with an object. They rated each object on all three features (heaviness, brightness, and pitch). The left-right placement of the paired objects was counterbalanced across participants, and the three possible orders in which the pairings could be presented were rotated across participants.

Participants in each of the three conditions in the *lift* study were presented with all 36 possible pairings of the nine objects to lift with the thumb and first two fingers of their preferred hand (i.e., with a precision grip). Fourteen random orderings for the 36 trials were determined in advance, with the constraint that the same object would not appear on successive trials. Each pair of objects was presented side-by-side in front of the participant (hidden from view behind the drape). The left-right placement of the objects in each of the 36 pairings was randomised, with the constraint that all nine objects appeared equally often on the left and right. Using the same fourteen random orderings, the left-right placement of the two objects in each pairing was reversed for the remaining participants in each of the three conditions. Participants were informed that they would be rating each of a small set of objects, with the objects being presented in pairs. They were to lift the objects in a pair individually and make their judgement for each one. For the heaviness judgements, they were asked to indicate how light or heavy the object felt. For the brightness judgements, they were asked to indicate how bright or dark in appearance they guessed the object was, while assuming the objects varied in their brightness. Finally, for the pitch judgements, participants were asked to imagine the object coming to life and making a sound, and to indicate how high or low in pitch the sound would be relative to the sounds made by all the other objects.

For participants in both the *no-lift* and *lift* studies, the numerical values assigned to the alternative feature values were equally likely to run in either of the two possible directions (e.g., high-low pitch being scaled as 1-9 or 9-1). In the *no-lift* study, in which the same participants rated the objects on all three scales, the direction of each scale was randomly determined, separately for each feature and each participant, with the restriction that the scales for the three features should align with each other equally often in each way possible. Varying and counterbalancing the directions of the numerical scales in this way offered protection against claims that participants in this condition selected cross-sensory features simply on the basis of them being assigned the same numerical scale value (e.g., when heaviness is assigned a rating of 2, the levels of pitch and brightness given this same numerical value also are selected). Because of the counterbalancing of scale direction, such a strategy of matching on the basis of the numerical values in the rating scales themselves would mitigate against getting evidence for any cross-sensory associations with heaviness. Prior to analysis, all judgements were standardised so that a rating of 9 marked the heaviest, darkest, and lowest-in-pitch ends of the scales.

Results

The effects of size alone on the judgements of brightness, pitch, and heaviness provided by participants in the *no-lift* condition were analysed first. This was intended to check that size, as instantiated in the current set of objects and in the absence of any direct information about weight, engaged the same cross-sensory feature associations observed in previous studies (i.e., smaller objects would be brighter and higher in pitch than bigger objects). Moving onto the *lift* condition, the effects of size and weight on judgements of the same features were analysed first (i.e., heaviness was not considered). Then, to determine if perceived heaviness is a better predictor of a lifted object's cross-sensory features than is weight, ratings of perceived heaviness replaced weight as an explanatory variable alongside size.

In all cases, the ratings on each scale were assumed to reflect a continuous variable (see Norman, 2010). For size and weight as explanatory variables, values 1 - 3 were used to indicate the three values for size (1 = small, 2 = medium, 3 = big) and weight (1 = light, 2 = medium, 3 = heavy). For perceived heaviness as an explanatory variable, the average heaviness ratings for the different objects, across all participants providing these ratings, were used. To take account of the repeated measures nature of the design, linear mixed effects analyses were undertaken using *R* (R Core Team, 2012) with the *lme4* package (Bates, Maechler & Bolker, 2014), and 95% confidence intervals were calculated using the *Wald* method with the *confint()* function.

Starting with a null model incorporating only a random effect of participants, additional comparison models were introduced to assess the significance of any contributions from size, size and weight, and then size and perceived heaviness. Likelihood ratio tests assessed the significance of including one or more of these fixed effects in a model. Alkaike Information Criterion (AIC) values provided a relative estimate of the amount of information not being captured by a model, balancing goodness of fit with the number of parameters the model contains. The AIC for alternative models of the same dataset were compared, with lower AIC values indicating a superior model. For all analyses of this kind reported below, visual inspection of residual Q-Q plots did not reveal any obvious departures from normality.

No-Lift: Object Size Alone

Figure 2 shows the mean ratings for judged brightness, pitch, and heaviness for each level of object size in the no-lift condition.

Brightness

For the brightness ratings, a likelihood ratio test confirmed that a model including size was preferred to the null model, $\chi^2(1) = 60.77$, $p < .001$, with AIC values of 751.4 and 692.7 for the null and comparison model, respectively. For each step increase in size, objects were judged darker by 1.50 points on the brightness scale, CI [1.16, 1.84].

Pitch

For the pitch ratings, a likelihood ratio test confirmed that a model including size was preferred to the null model, $\chi^2(1) = 79.90$, $p < .001$, with AIC values of 783.76 and 705.86 for the null and comparison model, respectively. For each step increase in size, objects were judged to be lower in pitch by 1.84 points on the pitch scale, CI [1.49, 2.19].

Heaviness

For the heaviness ratings, a likelihood ratio test confirmed that a model including size was preferred to the null model $\chi^2(1) = 138.82$, $p < .001$, with AIC values of 777.29 and 640.5 for the null and comparison model, respectively. For each step increase in size, objects were expected to be heavier by 2.21 points on the heaviness scale, CI [1.91, 2.50].

In summary, the effects of size on judgements of brightness, pitch, and heaviness confirm previous observations that increasing size is associated with increasing darkness, lowering of pitch, and increasing heaviness (L. Walker et al., 2012; P. Walker & Smith, 1985; P. Walker & L. Walker, 2012).

Lift: Object Size, Weight and Heaviness

Brightness

Figure 3 shows the mean ratings for judged brightness from the lift condition for each level of object size and object weight. A likelihood ratio test confirmed that a model including size was preferred to the null model, $\chi^2(1) = 34.647$, $p < .001$, with AIC values of 8616.4 and 8583.7 for the null and comparison model, respectively. Adding weight to the model significantly and considerably increased its explanatory power, $\chi^2(1) = 397.74$, $p < .001$, yielding a new AIC value of 8188.0. Estimates from the comparison model that included size and weight reveal how with each step increase in size objects were judged to be brighter (rather than the more usual darker) by 0.32 points on the brightness scale, CI [0.42,0.23]. With each step increase in weight they were judged to be darker (as expected) by 1.04 points on the brightness scale, CI [0.94, 1.14]. Finally, a likelihood ratio test confirmed that removing size from this comparison model resulted in a significant reduction in its explanatory power, $\chi^2(1) = 42.24$, $p < .001$, with an AIC of 8228.2, confirming that size continued to be influential when weight was included in the model.

Pitch

Figure 4 shows the mean ratings for judged pitch from the lift condition for each level of object size and object weight. A model including size was preferred to the null model, $\chi^2(1) = 16.76$, $p < .001$, with an AIC value of 9331.0 and 9316.2 for the null and comparison model, respectively. Adding weight to the model significantly and considerably increased its explanatory power, $\chi^2(1) = 722.54$, $p < .001$, yielding a new AIC value of 8595.7. Estimates from the comparison model that included both size and weight reveal how with each step increase in size objects were judged to be higher in pitch, rather than the usual lower in pitch, by 0.27 points on the pitch scale, CI [0.16, 0.38]. With each step increase in weight they were judged to be lower in pitch (as expected) by 1.62 points on the pitch scale, CI [1.51, 1.73]. Finally, a likelihood ratio test confirmed that removing size from this comparison model resulted in a significant reduction in its explanatory power, $\chi^2(1) = 24.06$, $p < .001$, with an AIC of 8617.7, confirming that size continued to be influential when weight was included in the model.

Heaviness

Figure 5 shows the mean ratings for judged heaviness from the lift condition for each level of object size and object weight. A model including size was preferred to the null model, $\chi^2(1) = 168.71$, $p <.001$, with AIC values of 9535.4 and 9368.7 for the null and comparison model, respectively. Adding weight to the model significantly increased its explanatory power, $\chi^2(1) = 2098.4$, $p <.001$, yielding a new AIC value of 7272.3. Estimates from the comparison model that included size and weight revealed how with each step increase in size objects were judged to reduce, rather than increase, in perceived heaviness by 0.885 points on the heaviness scale, CI [0.81, 0.96]. With each step increase in weight their perceived heaviness was judged to increase by 2.40 points on the heaviness scale, CI [2.32, 2.48]. Finally, a likelihood ratio test confirmed that removing size from this comparison model resulted in a significant and considerable reduction in its explanatory power, $\chi^2(1) = 450.76$, $p <.001$, with an AIC value of 7721.1, confirming that size continued to be influential when weight was included in the model.

Interim Summary. Though increases in weight had the predicted effects on judgements of an object's brightness and pitch, increases in size had effects that were the reverse of what was observed in the no-lift condition, and the reverse of what would be expected on the basis of cross-sensory correspondences involving size observed elsewhere. Thus, increasing the size of an object induced participants to think of it as being brighter rather than darker, of creating a higher pitch sound rather than a lower pitch sound, and of being lighter in weight rather than heavier. The reverse effects of size on brightness and pitch could be a consequence of the influence of size on perceived heaviness, with judgements of brightness and pitch being more strongly determined, if not solely determined, by the heaviness of an object rather than by its size. If solely determined by heaviness, then size would influence judgements of the brightness and pitch of an object only indirectly through its contribution to determining the perceived heaviness of the object. In which case, replacing actual weight with the average ratings for perceived heaviness should confirm the latter as a better predictor of judged brightness and pitch than the former. At the same time, it might reveal size to have either no separate influence on these cross-sensory features, or to have the same influence observed in the no-lift condition.

Replacing Weight with Judged Heaviness

The mean heaviness rating for each object across all participants providing them replaced their weight as an independent variable in a repeat of the above analyses of the brightness and pitch ratings.

Brightness

A model including heaviness was preferred to the null model, χ^2 (1) = 425.26, *p* < .001, with AIC values of 8616.4 and 8193.1 for the null and comparison model, respectively. Adding size to the model did not enhance its explanatory power, χ^2(1) = 1.0537, *p* = 0.305, consistent both with the confidence interval for the estimated effect of size straddling zero, CI [-0.049, 0.16], and with an unchanged AIC value (which dropped only slightly from 8193.1 to 8188.0 by adding size to the model). Estimates linked to the comparison model that incorporated heaviness alone reveal how with every point increase on the heaviness scale, objects were now judged to be darker by 0.427 points on the brightness scale, CI [0.38, 0.46].

Pitch

A model including heaviness was preferred to the null model, χ^2 (1) = 719.01, *p* < .001, with AIC values of 9331.0 and 8193.1 for the null and comparison model, respectively. Adding size to the model did enhance its explanatory power, χ^2(1) = 31.187, *p*<.001, yielding a new AIC value of 8584.8. Estimates from the comparison model that included both size and heaviness reveal how for every step increase in size the objects were now judged to be lower in pitch by 0.327 points on the pitch scale, CI [0.21, 0.44], which is as expected on the basis of the results from the no-lift condition and correspondences more generally. Finally, with every point increase in perceived heaviness the objects were judged to be lower in pitch by .675 points on this scale, CI [0.63, 0.72].

Discussion

Results from the no-lift procedure, in which three hidden objects varying in size were explored by touch alone (i.e., the objects were not moved or lifted), agree with previous observations concerning cross-sensory correspondences involving size, whether haptic size (P. Walker & Smith, 1985; P. Walker & L. Walker, 2012) or size more generally (L. Walker et al., 2012): Smaller aligned itself with brighter and higher in pitch.

With the lift procedure, in which all nine hidden objects were lifted by hand, the independent manipulation of size and weight allowed a separate contribution from perceived heaviness to cross-sensory correspondences to be assessed. The results confirm the predicted contribution of heaviness, and in so doing show for the first time how its cross-sensory feature associations are functionally bi-directional. Thus, mirroring previous demonstrations that visually darker stimuli and lower pitch sounds are judged to be heavier than their opposites (e.g., L. Walker, P. Walker, & Francis, 2012; P. Walker, Francis, L. Walker, 2010; P. Walker & Smith, 1984), increasing the heaviness of objects induced people to judge them to be darker and to make lower pitch sounds. Furthermore, under the conditions of the present study, heaviness had a stronger influence on judgements of brightness and pitch than did size, confirming that its influence is not mediated solely through its natural co-occurrence with size (i.e., the effects of variations in heaviness do not arise solely from the variations in size with which they normally co-occur).

When size was considered alongside actual weight as a predictor variable, rather than alongside perceived heaviness, it did influence judgements of brightness and pitch despite the stronger influence of weight. However, the direction of its alignment with these two features was the reverse of that observed without lifting, and the reverse of what would be expected on the basis of the correspondences observed elsewhere: Brighter and higher in pitch were both associated with *increasing* size, rather than with *decreasing* size. But size also reversed its natural alignment with the perceived heaviness it induced, with *reductions* in size inducing *increases* in heaviness, as per the size-weight illusion. It is proposed that this early interaction between size and weight, that determines the perceived heaviness of an object, is responsible for the reversal of the usual associations between size and each of brightness and pitch. On this account, most, if not all, of the influence of size on a lifted object's cross-sensory features is mediated indirectly through its contribution to determining the perceived heaviness of the object, with the perceived heaviness of the object then being largely responsible for determining its brightness and pitch (see Figure 6 for a graphic account of the main findings).

This proposed explanation was tested by replacing actual weight with perceived heaviness as a predictor of brightness and pitch, alongside size. Unsurprisingly, perceived heaviness proved to have the same general effects as actual weight on judgements of brightness and pitch (i.e., heavier was aligned with darker and lower in pitch). Of most importance, however, size no longer had the reverse alignment with the levels of brightness and pitch it induced. With regard to brightness, size ceased to have a significant effect, being completely overshadowed by heaviness. With regard to pitch, the effect of size, though modest in strength, was now similar in nature to its effect in the no-lift condition, with bigger once again being aligned with lower in pitch. The relatively modest influence of size on brightness and pitch reveals how heaviness can overshadow size in determining a lifted object's cross-sensory features.

Observing judgements of brightness and pitch track the variations in perceived heaviness resulting from the size-weight illusion, rather than track weight itself, confirms a perceptual basis for cross-sensory correspondences. That is, it is perceived heaviness, rather than weight per se, that engages with the conceptual dimension of heaviness, that in turn engages in crosstalk with the other dimensions with which it is aligned.

The bi-directionality of the correspondence between heaviness and each of brightness and pitch demonstrated here has theoretical implications going beyond reinforcing the principle that all correspondences are bi-directional. Satisfying this principle ensures there is sufficient coherence in the network of cross-sensory correspondences to guarantee transitivity among them (e.g., *If brighter is higher, and higher is smaller, then brighter will be smaller*).[2] Figure 7 illustrates the significance of bi-directionality in this regard, and how, without bi-directionality, and the transitivity that follows, contradictory feature values are likely to be induced (see P. Walker, 2016, for a discussion of this in the context of music).

Where Do Cross-Sensory Correspondences Originate?

Discussion thus far has simply accepted that cross-sensory correspondences exist. A fuller appreciation of the wider implications of the present and related findings requires some consideration of the origin(s) of cross-sensory correspondences. Why are feature dimensions aligned, and why are they aligned in the way they are (e.g., with higher pitch and brighter corresponding with lighter in weight, rather than with heavier)? Two strong candidates are that correspondences originate in language and/or in natural feature co-occurrences (scene statistics).

Correspondences in Language

At least some cross-sensory correspondences are represented as verbal associations in language, and it could be through exposure to such associations that people come to appreciate correspondences, with top-down processes ensuring they also become established as perceptual associations.

Very clear examples of this, from English, involve the word *light* being used to refer both to a brighter colour and to less weight, and the words *high* and *low* being used to refer both to spatial elevation and auditory pitch. In addition, in Western musical notation individual notes that are slightly *higher* in pitch are referred to as being *sharp.* Indeed, English dictionaries reveal that *high*-pitched sounds are *bright, sharp* and *thin* sounds, *sharp* bends are *quick* bends, *dim* objects in memory are *blurred* (i.e., not *sharp*), and a *thick* head is one that feels *dull* and *heavy*. Such definitions could explain why Google's Ngram Viewer reveals that corresponding polar adjectives tend to co-occur in English text more frequently than non-corresponding adjectives (e.g., the text string *dark and thick* appears more frequently than either *dark and thin* or *bright and thick*).[3] Though the correspondence between heaviness and auditory pitch, investigated in the present study, is not vulnerable in this way to an explanation based on language, at least with regard to English, the correspondence between lightness in weight and lightness in colour is vulnerable. However, at least three lines of evidence indicate that, in general, peoples' appreciation of cross-sensory correspondences is not contingent on their being represented as verbal associations in language.

First, many species of animals appreciate the systematic association between, for example, auditory pitch and size: When they find themselves competing for food, or a mate, they lower the pitch of their vocalizations at the same time as making themselves appear bigger visually (e.g., through piloerection), with both manoeuvres being designed to give the impression they are stronger than they would otherwise appear to be (Fitch, & Hauser, 2002; Morton, 1994; Ohala, 1994). Similarly, chimpanzees performing a speeded brightness classification task respond more easily when the pitch of a concurrent task-irrelevant sound is in correspondence with the brightness of the visual stimulus they are classifying (e.g., when a brighter stimulus is accompanied by a higher pitch sound) (Ludwig, Adachi, & Matsuzawa, 2011).

Second, some prominent correspondences do not have the same verbal labels being applied to corresponding feature values. Examples include the correspondence between brightness and heaviness for speakers of German (see Wright, 1962) (where light in brightness is labeled *hell*, and light in weight is labeled *leicht*), and the correspondence between auditory pitch and visuo-spatial elevation for people of the Kreung Hill tribe in Cambodia (for whom contrasting values of pitch are labeled *tight* and *loose*) (see Parkinson, Kohler, Sievers, & Wheatley, 2012). This is also the case when speakers of English, and of other languages adopting *high* and *low* as the labels for contrasting values of auditory pitch, reveal their sensitivity to the correspondence between pitch and visual surface brightness (e.g., Martino & Marks, 1999), visual pointiness (e.g., P. Walker, 2012a), visual size (e.g., Evans & Treisman, 2010), and visual thinness (e.g., Dolscheid, Hunnius, Casasanto, & Majid, 2013). It is also the case when speakers of English reveal their sensitivity to the correspondence between auditory pitch and heaviness, as they did in the present study.

Third, pre-lingual infants are sensitive to cross-sensory correspondences. Indeed, on one account, it is this sensitivity that allows sound symbolism to help bootstrap their acquisition of language (e.g., Imai & Kita, 2014), the clear implication being that correspondences are in place before language is acquired. Evidence that 14-month-olds learn words more easily when their acoustic features share cross-sensory features with the concepts the words name supports these claims (see Imai et al., 2015). In addition, 10-month-olds appreciate the correspondence between auditory pitch and each of visual brightness and visual size (Haryu & Kajikawa, 2012), while 7- to 12-month-olds appreciate the correspondence between auditory pitch and visuospatial elevation (Jeschonek, Pauen, & Babosci, 2012). An essential role for language in giving rise to cross-sensory correspondences seems especially unlikely with evidence that 3- and 4-month-olds are sensitive to the correspondences between auditory pitch and each of visuospatial elevation

(Dolscheid et al., 2014; Walker et al., 2010), visual pointiness (Walker et al., 2010), visual thinness (Dolscheid et al., 2014) and visual size (Pena, Mehler, & Nespor, 2012).

It now seems clear, therefore, that long before they get immersed in the language of their culture, young infants are sensitive to at least some cross-sensory correspondences. This resonates with the point made by Dolscheid et al. (2013), namely, that all correspondences are in place before a child is introduced to relevant aspects of the language of their culture, and so are in place without influence from them. Thereafter, however, language can amplify the salience, and influence, of some correspondences over others (see Dolscheid et. al., 2013).

Natural Feature Co-occurrences

Whatever support there might be for the language hypothesis, it begs a question as to why cross-domain feature associations should be present in language at all and, more specifically, why the same correspondences should be in evidence across languages themselves having distinct origins. An alternative approach, that can accommodate this observation, begins by acknowledging that at least some cross-sensory correspondences exist as natural feature co-occurrences (i.e., within natural scene statistics), and it could be through exposure to these, rather than exposure to language, that a child comes to appreciate correspondences. The co-occurrences between size, heaviness, and auditory pitch, that are especially pertinent to the present study, are cases in point. Thus, bigger/heavier animals make lower pitch vocalizations (Bee, Peril & Owen, 2000; Harrington, 1987), and bigger/heavier objects make lower pitch impact sounds when they collide with other objects (Grassi, 2005). Other examples include the co-occurrence between thinness and pitch (e.g., thinner objects, such as guitar strings, resonate at higher frequencies), and the co-occurrence between visuospatial elevation and pitch (e.g., higher pitch sounds tend to originate from higher spatial locations in the world, see Parise, Knorre & Ernst, 2014). In general, however, it remains unclear if all known cross-sensory correspondences have matching natural feature co-occurrences. For example, it is not easy to identify co-occurrences able to support the correspondences between surface brightness and auditory pitch, or surface brightness and heaviness (see P. Walker, Francis & L. Walker, 2010, for discussion of the latter). Clearly, if it is confirmed that some correspondences, such as that between surface brightness and heaviness, are not supported by natural feature co-occurrences, then these correspondences could not originate from the statistical learning of such co-occurrences.

Given that the learning of natural scene statistics is a key component of the Bayesian approach to perception, the approach may not be able to explain those cross-sensory correspondences for which there is no evidence for matching feature co-occurrences. At the time of writing, this includes the correspondence between heaviness and brightness. But even where such evidence exists, as for the correspondence between size and weight, the Bayesian approach might still fail to explain perceptual aspects of the correspondence, including any correspondence-induced illusions of heaviness (e.g., Ernst, 2009). The reason is that the level of perceived heaviness resulting from such a correspondence-induced illusion appears not to be a compromise between the weight indicated by sensory-motor information and the weight indicated by knowledge-based expectations learned from experiencing real-world co-occurrences. Instead, the illusory level of heaviness lies outside the range set by these two values (Brayanov & Smith, 2010). In the case of the size-weight illusion, prior experience suggests that the smaller of the two otherwise identical objects will feel lighter in weight than the bigger object, but the former is actually perceived to be heavier. The Bayesian approach, in contrast, predicts that the smaller object should be perceived to be less heavy, albeit to a lesser extent than prior experience alone would predict. The same challenge to the Bayesian approach is presented by the brightness-weight illusion, where the brighter of two otherwise identical objects, though expected to be lighter in weight on the basis of the brightness-weight correspondence, actually feels heavier than the darker object when they are lifted (P. Walker, Frances & L. Walker, 2015).

Given that, in the context of the correspondence-induced size-weight illusion, estimates of weight used for motor control during the lifting of objects do conform to Bayesian predictions, and need not mirror any concurrent illusions of perceived heaviness, it is possible that perceptual aspects of correspondences are dissociable from the processes underpinning the control of action (see Brayanov & Smith, 2010).

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Footnotes

1. Adopting the term 'cross-sensory correspondences', as opposed to 'cross-modality correspondences', is intended to allow for correspondences emanating from different types of feature encoded within the same modality. In the case of vision, for example, this might involve the separate feature encoding channels dealing with the early processing of visual form, brightness, movement, and size (see Walker, 2012a, for evidence of a correspondence based on visual brightness and visual pointiness). Evidence for separate sensory feature domains of this kind comes from the neurophysiological and psychological research underpinning Treisman's feature integration theory of attention (see Humphreys, 2016, for a review).

2. *Transitivity of implication* in logic refers to a rule governing the relationships linking the different material properties of things (also known as material conditional). In general, the logic of material implication is: *If A implies B, and B implies C, then A implies C.* To indicate its relevance to correspondences, the same logic can be exemplified as: *If heaviness is dark, and dark is low-pitch, then heaviness will be low-pitched.* P. Walker and L. Walker (2012) assumed, as had others (e.g., Hornbostel, 1931), that cross-sensory correspondences will display this type of transitivity, on which basis they predicted, and then confirmed, the existence of a correspondence between size and brightness. They reasoned that it was already known that higher pitch sounds are bi-directionally associated with both smaller and brighter things, as compared with lower pitch sounds. Though there was very little evidence available for a correspondence between size and brightness (though see P. Walker & Smith, 1985), they predicted one on the basis of transitivity, reasoning that: *If brighter is higher, and higher is smaller, then brighter will be smaller.*

3. There are, nevertheless, a few exceptions to this generalization that are troublesome for the language hypothesis, including the more frequent appearance of *light and dark* compared to

either *light and bright* or *heavy and dark,* and the more frequent appearance of *thick and fast* compared to either *thick and slow* or *thin and fast*.

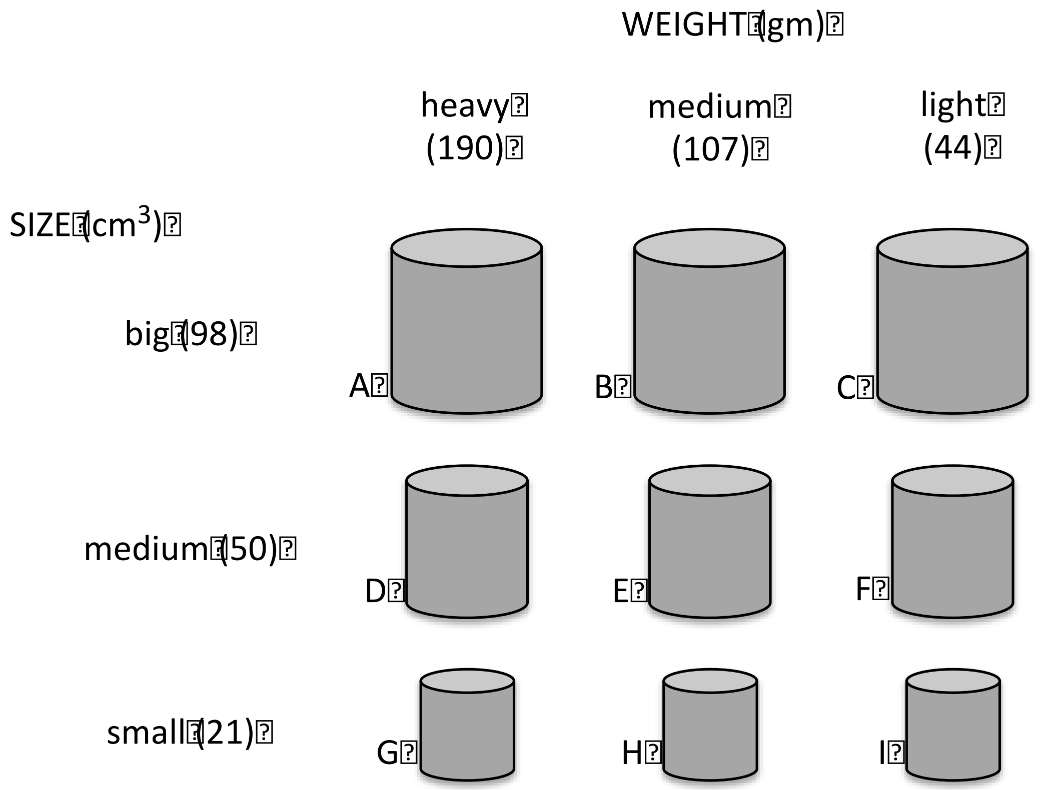


Figure 1. Illustrating the size and weight of each object in the set of nine objects created by crossing weight and size. The objects are labelled in the figure to facilitate discussion here, but were not labelled in the experiment. The three alternative values for weight were chosen on the basis that they are a set of values that could arise when objects at the three different sizes are made from the same material (i.e., the same density). Therefore, objects A, E, and I are very close to forming a natural set of objects whose weights confirm that they are formed from the same material.

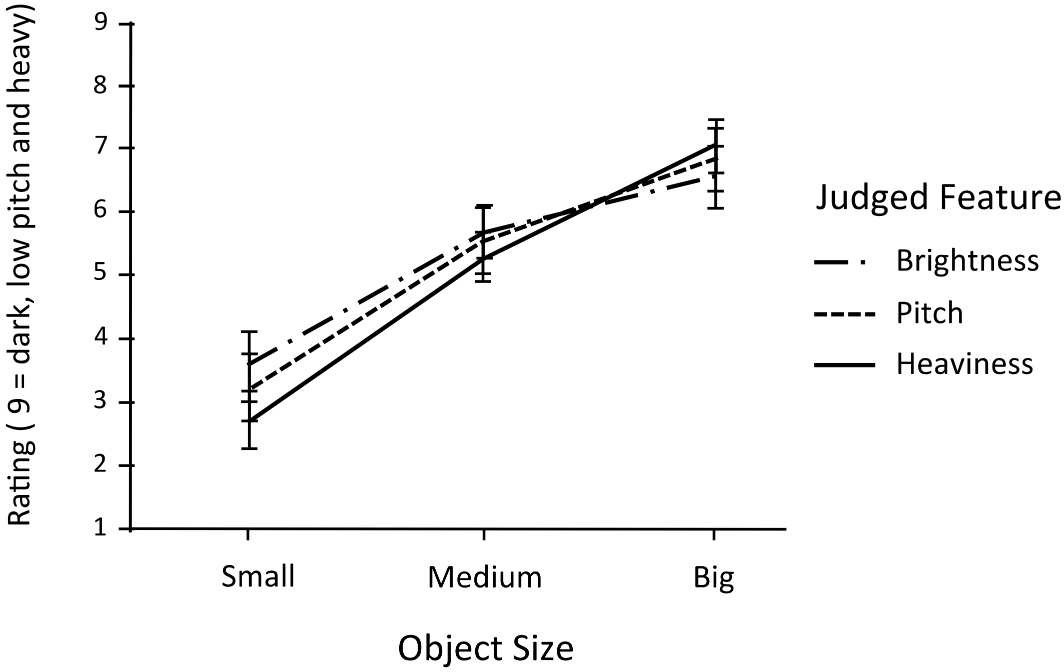


Figure 2. Mean brightness, pitch, and heaviness ratings for each size of object in the no-lift condition (along with the 95% confidence interval for each mean).

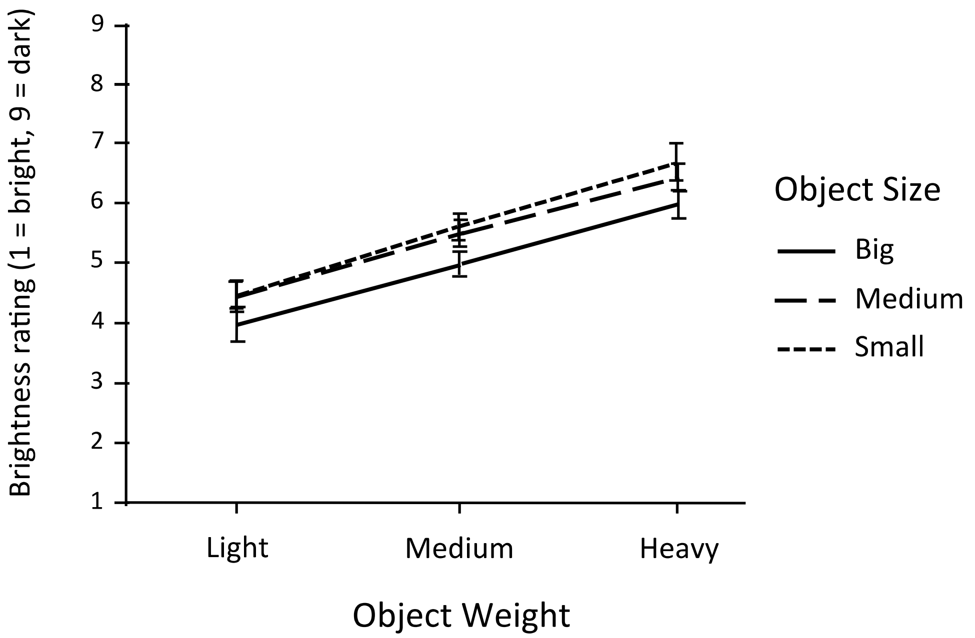


Figure 3. Mean brightness ratings according to the weight and size of a lifted object (along with the 95% confidence interval for each mean).

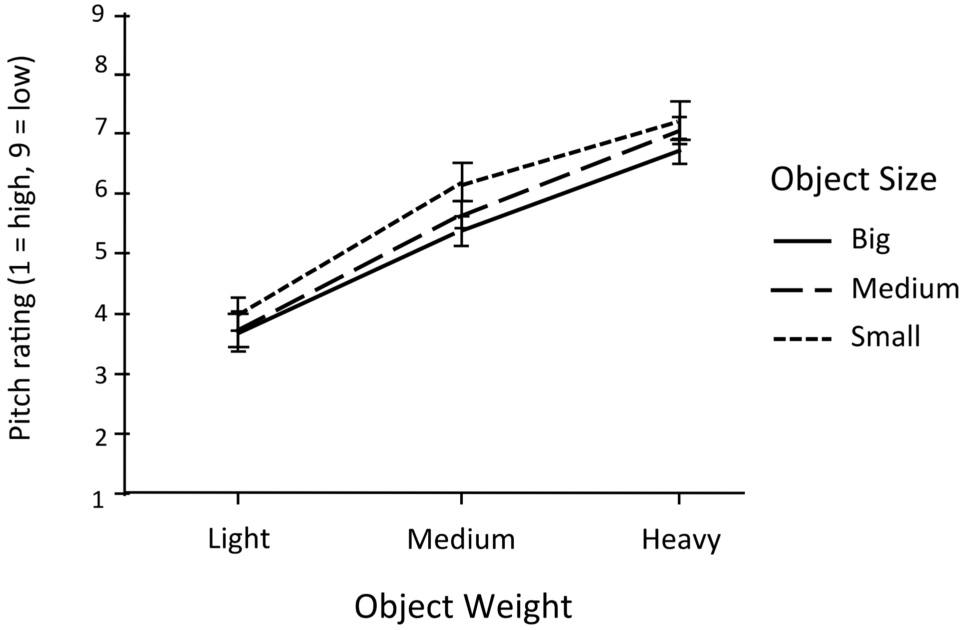


Figure 4. Mean pitch ratings according to the weight and size of a lifted object (along with the 95% confidence interval for each mean).

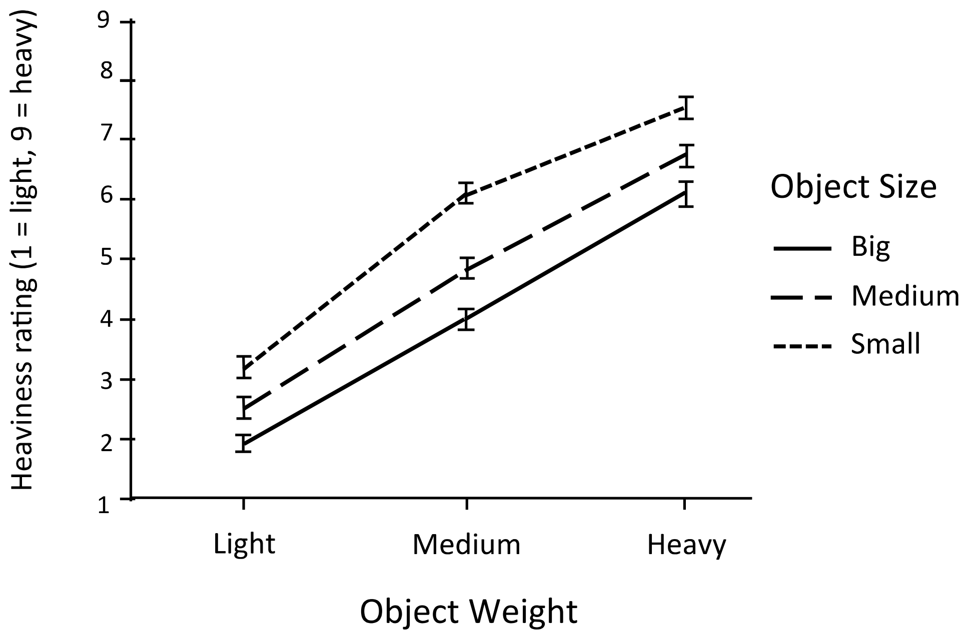
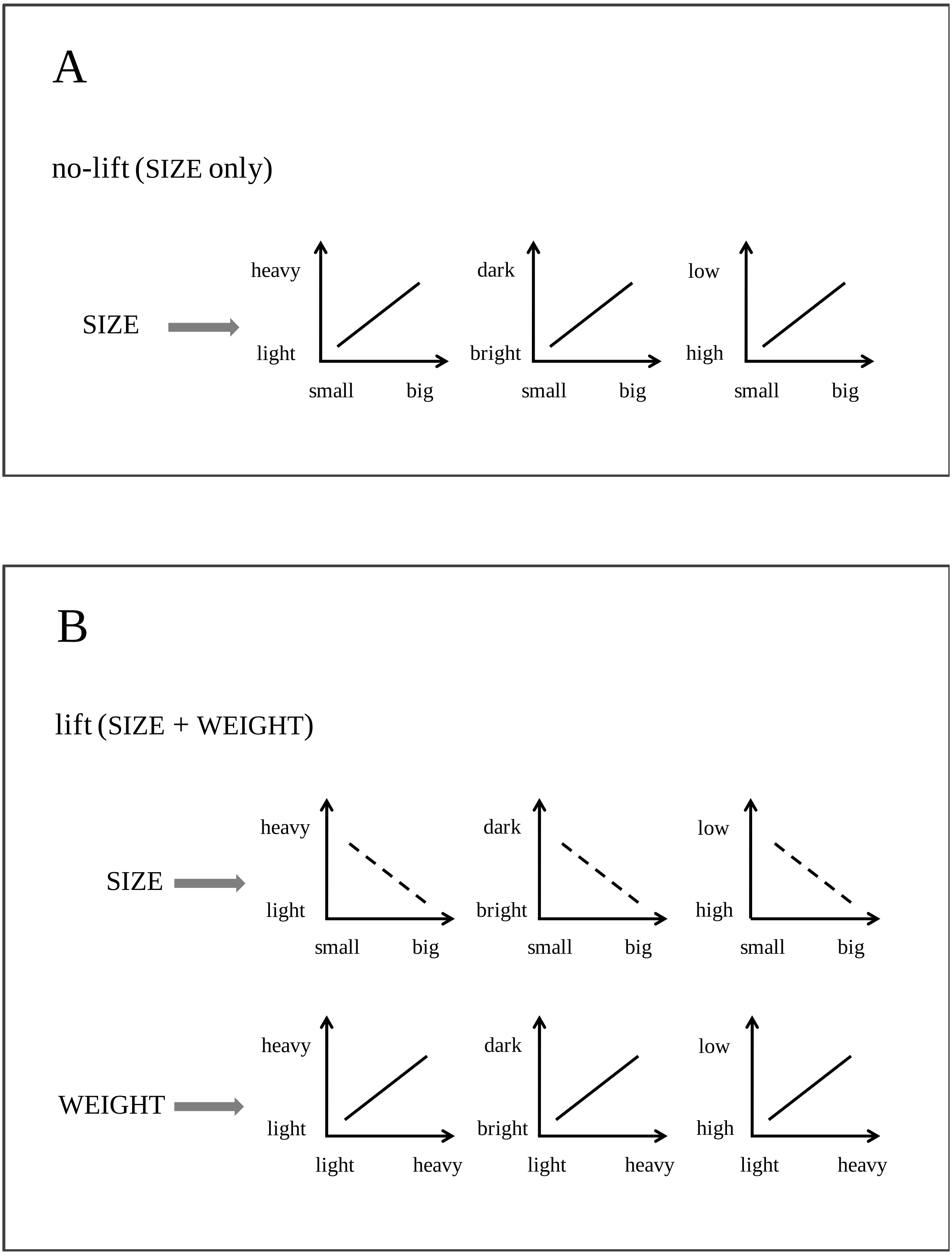


Figure 5. Mean heaviness ratings according to the weight and size of a lifted object (along with the 95% confidence interval for each mean).


A
no-lift (SIZE only)
SIZE
heavy
light
small
big
dark
bright
small
big
low
high
small
big
B
lift (SIZE + WEIGHT)
SIZE
heavy
light
small
big
dark
bright
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big
WEIGHT
heavy
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heavy
low
high
light
heavy

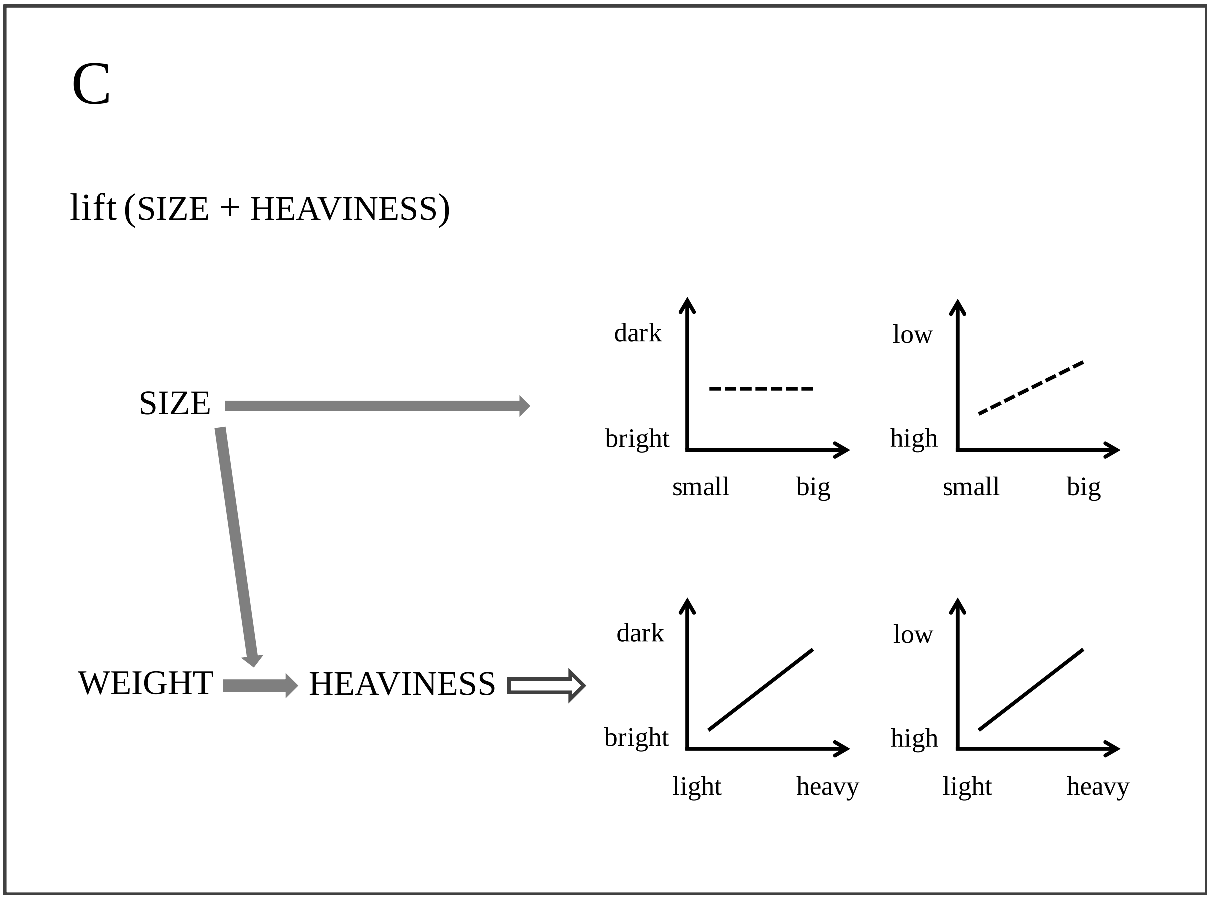
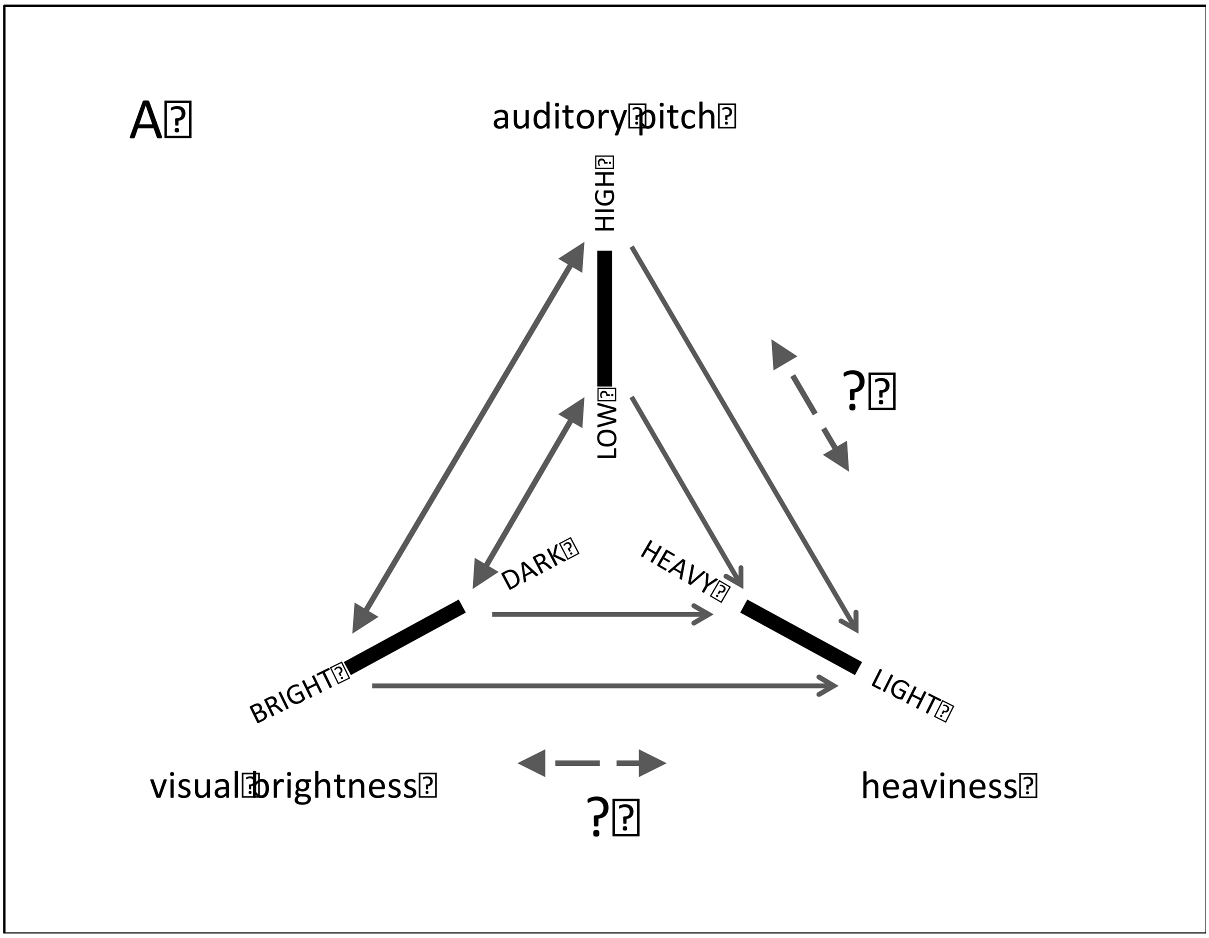
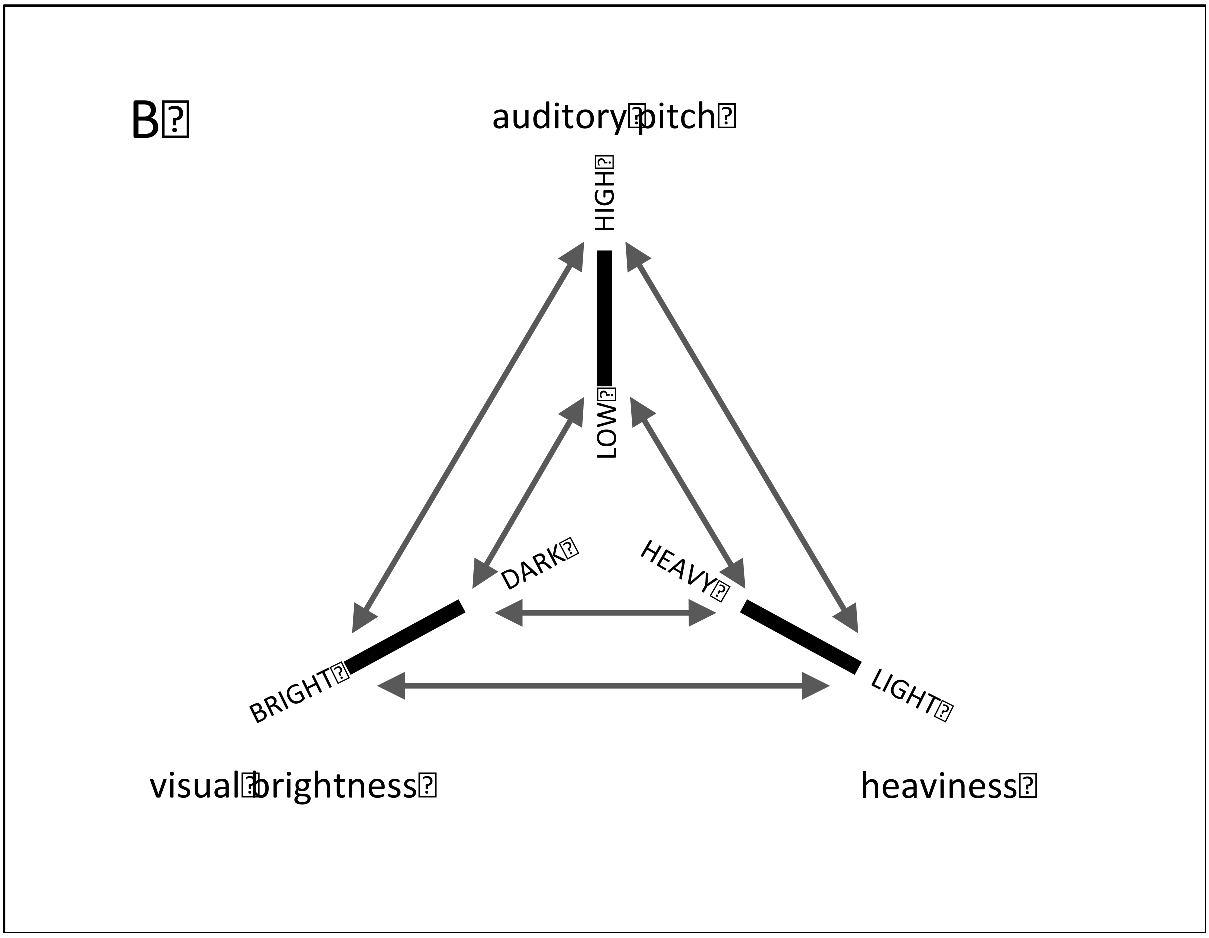
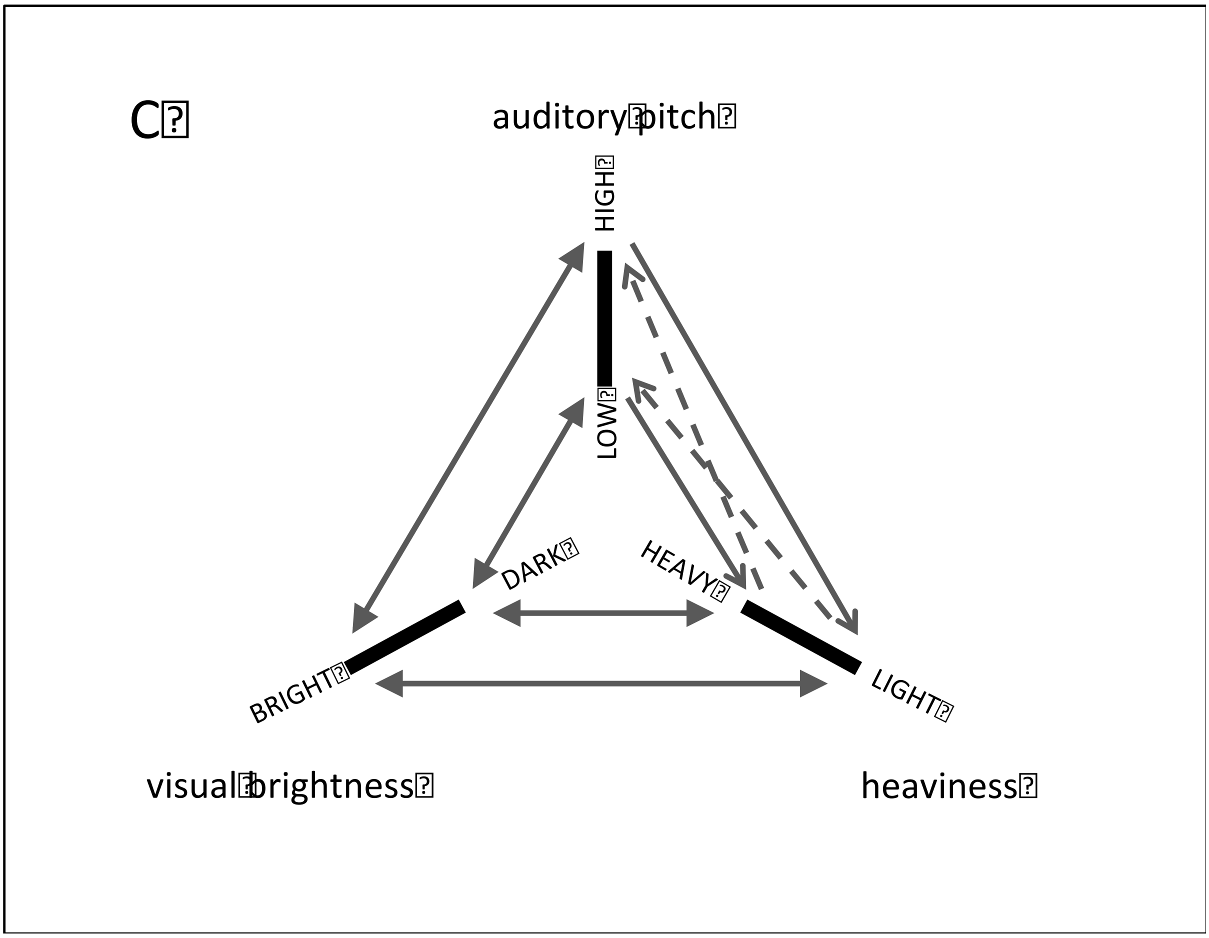


Figure 6. Illustrating the main findings. A. When objects are explored without lifting, so that information about their size but not their weight is available, judgements of heaviness, brightness, and pitch show relationships with size that agree with those observed in cross-sensory correspondences (i.e., bigger is heavier, darker, and lower in pitch). B. When objects are explored by by lifting, so that information about both size and weight is available, judgements of brightness and pitch confirm relationships with heaviness that are in line with those observed elsewhere (i.e., heavier being darker and lower in pitch). However, judgements of both brightness and pitch reveal contrary relationships with size, with bigger being brighter and higher in pitch. It is proposed that this reversal reflects the dependency of these judgements on perceived heaviness, with this also showing a contrary relationship with size, whereas bigger is less heavy

rather than more heavy. C. This proposal receives support when mean values for the perceived heaviness of the objects replace actual weight as a predictor variable. Heaviness now dominates size in determining the brightness and pitch of the objects, completely overshadowing it in relation to brightness (so that brightness has no relationship with size) and partially overshadowing it in relation to pitch. The relationship of pitch to size is now as it is without lifting, and is again in agreement with how the two feature dimensions align in correspondences.


A
auditory pitch
HIGH
LOW
DARK
HEAVY
BRIGHT
LIGHT
?
visual brightness
?
heaviness


B
auditory pitch
HIGH
LOW
DARK
HEAVY
BRIGHT
LIGHT
visual brightness
heaviness


C
auditory pitch
HIGH
LOW
DARK
HEAVY
BRIGHT
LIGHT
visual brightness
heaviness

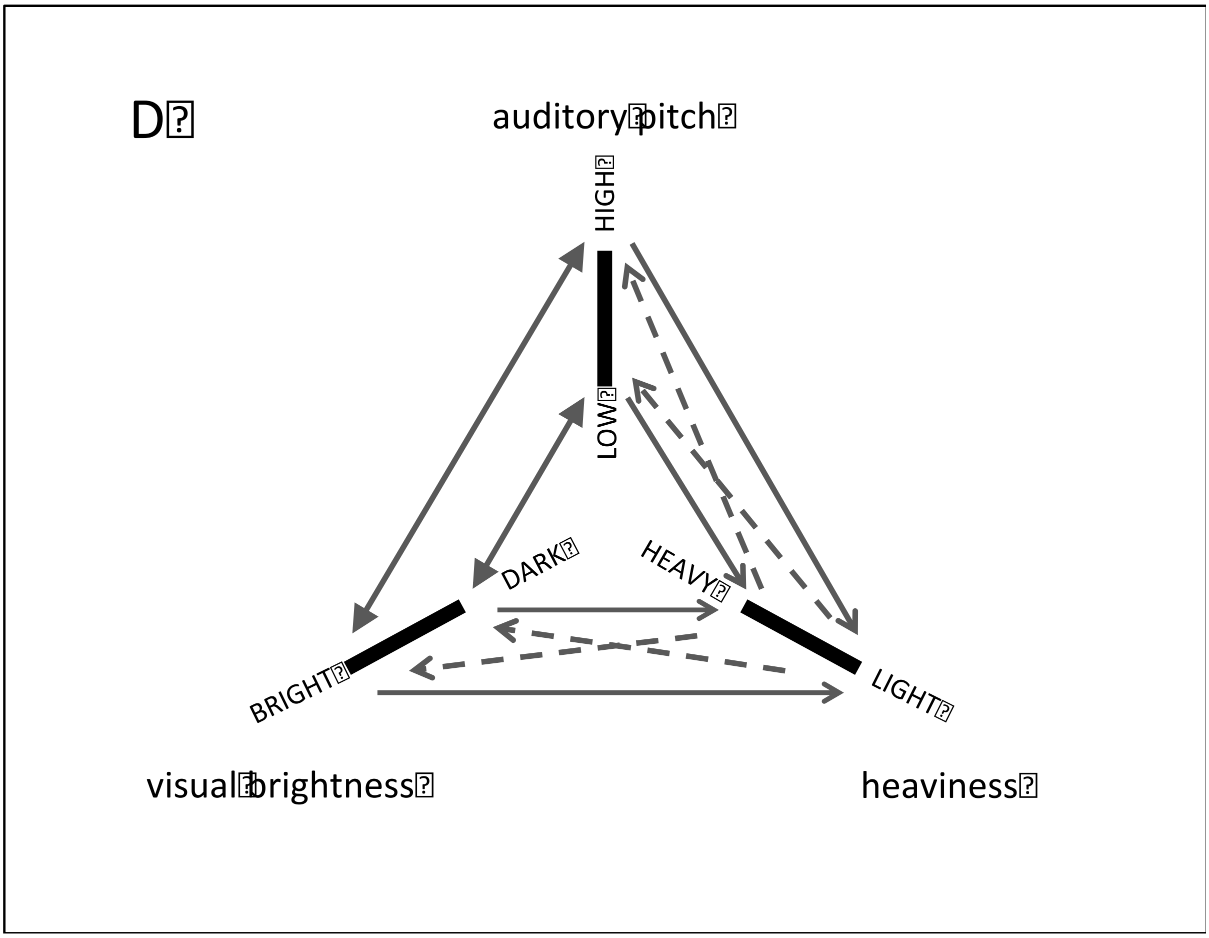

D
auditory pitch
HIGH
LOW
DARK
HEAVY
BRIGHT
LIGHT
visual brightness
heaviness

Figure 7. The significance of bi-directionality for the transitivity of cross-sensory associations is illustrated with reference to the three conceptual features investigated in the present study. A. Previous studies confirm that the cross-sensory association between visual brightness and auditory pitch is functionally bi-directional. They also demonstrate that each of pitch and brightness has heaviness as a cross-sensory feature, with lower pitch and darker aligning themselves with heavy. What remained to be determined was whether the cross-sensory associations between heaviness and each of pitch and brightness also are bi-directional, that is, whether heavy induces notions of lower pitch and darker. B. Results from the present study confirm the functional bi-directionality of the cross-sensory association between heaviness and each of auditory pitch and visual brightness. Assuming it is a single, generic notion of heaviness that relates to both auditory pitch and visual brightness, the bi-directionality of the correspondences ensures transitivity among them. For example, whether one goes from heaviness to auditory pitch directly (e.g., *If light in weight, then high in pitch*), or does so only indirectly via visual brightness, the same relative level of auditory pitch is induced (e.g., *If light in weight is visually bright, and visually bright is high in pitch, then light in weight will be high in pitch*). C. Transitivity among the correspondences would not have emerged if either the heaviness-pitch association, or the heaviness-brightness association, had failed to be functionally bidirectional. Illustrated in C is a lack of functional bi-directionality for the heaviness-pitch association. The absence of transitivity that then follows is apparent from the fact that whereas the direct link between heaviness and pitch ensures that lighter in weight induces notions of lower in pitch, the indirect link via brightness ensures that lightness in weight induces contradictory notions of higher in pitch. Without bi-directionality, there is also the more local problem that lightness in weight induces notions of lower pitch, which then immediately feeds back to induce notions of relative heaviness, thus contradicting the original notion of lightness in weight. D. The same

problem of feedback serving to contradict an original feature value would emerge if neither the heaviness-pitch nor the heaviness-brightness association had proven to be functionally bi-directional. Then, for example, lightness in weight would induce notions of relative darkness, which would then induce notions of being lower in pitch, which would finally induce notions of heavy in weight, thereby contradicting the original notion of lightness in weight.