Journal of Experimental Psychology: Human Perception and Performance

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Online First Publication, August 17, 2015. http://dx.doi.org/10.1037/xhp0000120

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0096-1523/15/$12.00 http://dx.doi.org/10.1037/xhp0000120

Grasping the Sound: Auditory Pitch Influences Size Processing in Motor Planning

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Growing evidence shows that individuals consistently match auditory pitch with visual size. For instance, high-pitched sounds are perceptually associated with smaller visual stimuli, whereas low-pitched sounds with larger ones. The present study explores whether this crossmodal correspondence, reported so far for perceptual processing, also modulates motor planning. To address this issue, we carried out a series of kinematic experiments to verify whether actions implying size processing are affected by auditory pitch. Experiment 1 showed that grasping movements toward small/large objects were initiated faster in response to high/low pitches, respectively, thus extending previous findings in the literature to more complex motor behavior. Importantly, auditory pitch influenced the relative scaling of the hand preshaping, with high pitches associated with smaller grip aperture compared with low pitches. Notably, no effect of auditory pitch was found in case of pointing movements (no grasp implied, Experiment 2), as well as when auditory pitch was irrelevant to the programming of the grip aperture, that is, in case of grasping an object of uniform size (Experiment 3). Finally, auditory pitch influenced also symbolic manual gestures expressing "small" and "large" concepts (Experiment 4). In sum, our results are novel in revealing the impact of auditory pitch on motor planning when size processing is required, and shed light on the role of auditory information in driving actions.

Keywords: motor system, auditory pitch, size processing, pitch-size correspondence, crossmodal correspondence

Supplemental materials: http://dx.doi.org/10.1037/xhp0000120.supp

In everyday life, humans show a tendency to spontaneously match attributes and dimensions of experience across different sensory modalities, a phenomenon known as crossmodal correspondence (see Spence, 2011, for a discussion). During the last years, several studies focused on correspondences occurring between audition and vision (see Marks, 2004, for a review; see also Parise & Spence, 2013) and, in particular, between auditory pitch and visual size. These studies show that the task-irrelevant frequency of a sound can influence visual size estimation, with responses being facilitated when high-pitched sounds are presented in correspondence with smaller stimuli and low-pitched sounds with larger ones (Evans & Treisman, 2010; Gallace & Spence, 2006; Parise & Spence, 2008, 2009, 2012; Walker & Smith, 1985).

Robust evidence supports the hypothesis that pitch-size correspondence is grounded in the statistics of the external world. Specifically, in nature a correlation exists between the size of an object and its relative resonant frequency: the lower the frequency of the sound, the larger the object that is generating the sound (Coward & Stevens, 2004; Grassi, 2005; Grassi, Pastore, & Lemaitre, 2013). A widely acknowledged account of crossmodal correspondence suggests that humans would refer to the natural mapping between auditory pitch and visual size when processing and integrating new audiovisual information (Ernst, 2007; see for a discussion Spence, 2011). Accordingly, when hearing a high-/low-pitched sound, an individual would expect a small/large-size object to have produced it (Grassi, 2005; Grassi et al., 2013; see Parise & Spence, 2013). Critically, although vision and audition

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This research was supported by the grant "Fondi di Ricerca" from Progetto Cariplo to Luca Rinaldi and Carlotta Lega. We especially thank Simone Riva for his technical assistance.

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are known to play a critical role in the planning and control of action (Goodale & Humphrey, 1998; Sedda, Monaco, Bottini, & Goodale, 2011), pitch-size correspondence has been so far documented only for perceptual processing. It is therefore possible that the motor system might be as well affected by pitch-size correspondence. Indeed, humans can estimate the size of objects dropped on a surface by the frequency of the sound they produce (Grassi, 2005; Grassi et al., 2013). In turn, the frequency of this sound can be informative for the planning of a subsequent reach-to-grasp movement (see Sedda et al., 2011).

According to "A Theory Of Magnitude" (ATOM), magnitude-related information would be processed by a generalized system located in the inferior parietal cortex (Bueti & Walsh, 2009; Walsh, 2003). In this view, prothetic dimensions (i.e., concerned with quantitative variation; Stevens, 1957), such as quantity, space, and time, all share a magnitude code. These dimensions would mutually operate on similar magnitude representations, because of the need to learn about the environment for acting on it (Walsh, 2003). Accordingly, increasing evidence has shown that symbolic number processing influences action planning (Andres, Davare, Pesenti, Olivier, & Seron, 2004; Lindemann, Abolafia, Girardi, & Bekkering, 2007). More recently, however, some authors have proposed an even broader scope of ATOM to include metathetic (i.e., concerned with qualitative variation, Stevens, 1957) dimensions as well, such as auditory pitch (see Bottini & Casasanto, 2013, for a discussion). Indeed, auditory pitch has been found to be consistently associated not only with size, but also with space (see Spence, 2011, for a review). For instance, in the vertical plane, individuals associate high pitches with high positions in space (Chiou & Rich, 2012; Pratt, 1930; Rusconi, Kwan, Giordano, Umiltà, & Butterworth, 2006). Likewise, auditory pitch is also represented along an horizontal spatial dimension, with high tones preferentially mapped to rightward spatial positions, while low tones to leftward positions (e.g., Lega, Cattaneo, Merabet, Vecchi, & Cucchi, 2014; Lidji, Kolinsky, Lochy, & Morais, 2007; Rusconi et al., 2006; but see also Trimarchi & Luzzatti, 2011). Nevertheless, no study has so far explored if auditory pitch influences size processing in action planning.

On these grounds, in four different experiments, we investigate whether pitch-size correspondence modulates motor planning. In the first experiment, participants were required to reach, grasp, and lift either the smaller or the larger section of a target object, depending on the auditory pitch of musical tones. In the second experiment, participants had to merely point to a specific section of the target object, an action requiring no size processing. In the third experiment, participants were required to reach, grasp, and lift an object of uniform size (i.e., either small or large), so that now auditory pitch was irrelevant to the programming of the grip aperture. Finally, we evaluated whether auditory pitch influences manual gestures conveying abstract concepts; to this end, participants were required to perform symbolic gestures expressing "small" and "large."

In particular, we expect that if participants exploit the audiovisual natural mapping to integrate current multisensory information for action, they should be facilitated in selecting the appropriate motor response when the information is congruent. This should be reflected, for instance, by faster reach-to-grasp movements toward a small object when the action is primed by a (congruent) high-pitched sound, compared with when it is primed by a (incongruent) low-pitched sound. This natural pitch-size correspondence would, therefore, facilitate action when crossmodal information is congruent, even if the auditory stimulus and the visual object are not part of the same event. Thus, this may happen regardless of whether the auditory information is perceived as originating from the object (see Sedda et al., 2011) or not, as in the present study, since learnt statistical properties of the environment would facilitate (i.e., faster reaction times, RTs) integration of congruent multisensory information. In fact, humans judge the size of a visual stimulus more rapidly when the frequency of a simultaneous irrelevant sound is congruent (i.e., high pitch tone with a small visual stimulus; Gallace & Spence, 2006). Hence, prior experience with the acoustic resonance properties of stimuli varying in size can influence current integration of multisensory information, even when visual and auditory stimuli are not apparently related (Gallace & Spence, 2006; Grassi, 2005). Similarly, we also reasoned that auditory pitch should be capable of influencing movement scaling, with higher pitches associated to relatively smaller grip apertures, and lower pitches to larger grip apertures. More specifically, whenever hearing a high/low-pitched sound, participants should expect a small/large object to be associated with it. This possibility should, in turn, affect grip scaling, by modulating the contribution of visual information (i.e., the real object size) in motor planning.

Experiment 1

Experiment 1 investigated whether auditory pitch influences initiation times and kinematic parameters of grasping movement. Participants had to judge the pitch, that is, high versus low, of auditory stimuli, by means of two different reach-to-grasp movements toward the smaller versus the larger section of a target object. Half of the participants performed the task with a wooden object consisting of two cylindrical sections, a larger section at the bottom and a thinner section on top of it (standard orientation). The other half of participants performed the same task with the object tilted upside-down, that is, with the thinner section at the bottom and the larger one at the top of it (tilted orientation). This manipulation was introduced in light of prior evidence showing that auditory pitch is mentally represented in a spatial format, with high pitches consistently associated with higher spatial positions than low pitches (Chiou & Rich, 2012; Pratt, 1930; Rusconi et al., 2006).

Grasping an object relies on estimates of various object proprieties, such as size and shape (Jeannerod, Arbib, Rizzolatti, & Sakata, 1995). Accordingly, we hypothesized that if pitch is associated to object size, small grips should be initiated faster in response to high tones, whereas large grips should be initiated faster in response to low tones, for both object orientations. This pattern should therefore extend previous compatibility effects between auditory pitch and size to more complex motor planning. Conversely, if actions are influenced by pitch-space associations along the vertical dimension, we should expect movements toward the higher part of the target object to be initiated faster in response to high pitches and vice versa for low pitches. Importantly, we also explored whether auditory pitch might affect kinematic parameters. More specifically, if auditory pitch plays a critical role in size processing, we hypothesized that it might influence the relative scaling of the hand preshaping, with high tones associated to smaller grip aperture.

Participants

Participants included 28 students, randomly assigned to 2 groups. A first group of participants (N = 14, M age = 29 years, SD = 2.1; 5 females) performed the experiment with the object in the standard orientation, while a second group (N = 14, M age = 26.6 years, SD = 3.7; 7 females) completed the experiment with the object tilted upside-down. Handedness was assessed by means of the Edinburgh Inventory (Oldfield, 1971). All participants were classified as right-handers. All participants expressed written informed consent to participate in the study. The study protocol was approved by the ethics board of the University of Milano-Bicocca.

Apparatus and Stimuli

Participants sat in front of a table on which they rested their right hand with the thumb and index finger in pinch position, in front of the body, centered relative to body midline (starting position; see Figure 1). A first group of participants performed the task with a wooden object consisting of two cylindrical sections, a larger section (diameter: 5 cm; height: 5 cm) at the bottom and a thinner section (diameter: 1 cm; height: 5 cm) on top of it. The object was placed in front of the participant, 21 cm distant from the starting position. The starting position was represented by a blue sticker placed on the table. Participants were explicitly instructed to move back to the sticker at the end of the required movement. A second group performed the task with the object tilted upside-down. Because the thinner section was placed on the table surface, making the whole object unstable, a squared base (side: 2.5 cm; height: 0.5 cm) was fastened below the object in the tilted orientation. This was done to prevent participants to have to handle an unstable object, which could have altered their motor performance.

The auditory stimuli consisted of a piano low-pitched tone (C1, Hz = 32.7), a piano high-pitched tone (C6, Hz = 1046.5), and a white noise, that were all normalized in loudness at 0 db, by means of the software Audacity (http://audacity.sourceforge.net/). In particular, we adopted the peak normalization procedure, wherein the gain is changed to bring the highest signal peak to a given level (in our case 0 db, the loudest level allowed). Although all the sounds used were normalized at 0 db, auditory stimuli may differ in terms of perceived loudness. To control for this possible confound, 8 participants of Experiment 1 performed a control experiment, in which they were required to match in loudness the auditory stimuli. Participants were first presented with the white noise to be used as standard, and subsequently, they had to adjust a target stimulus (i.e., the high- or low-pitched tone) till it matched the loudness of the standard (see for a similar method, Parise, Knorre, & Ernst, 2014). Varying systematically loudness levels of the

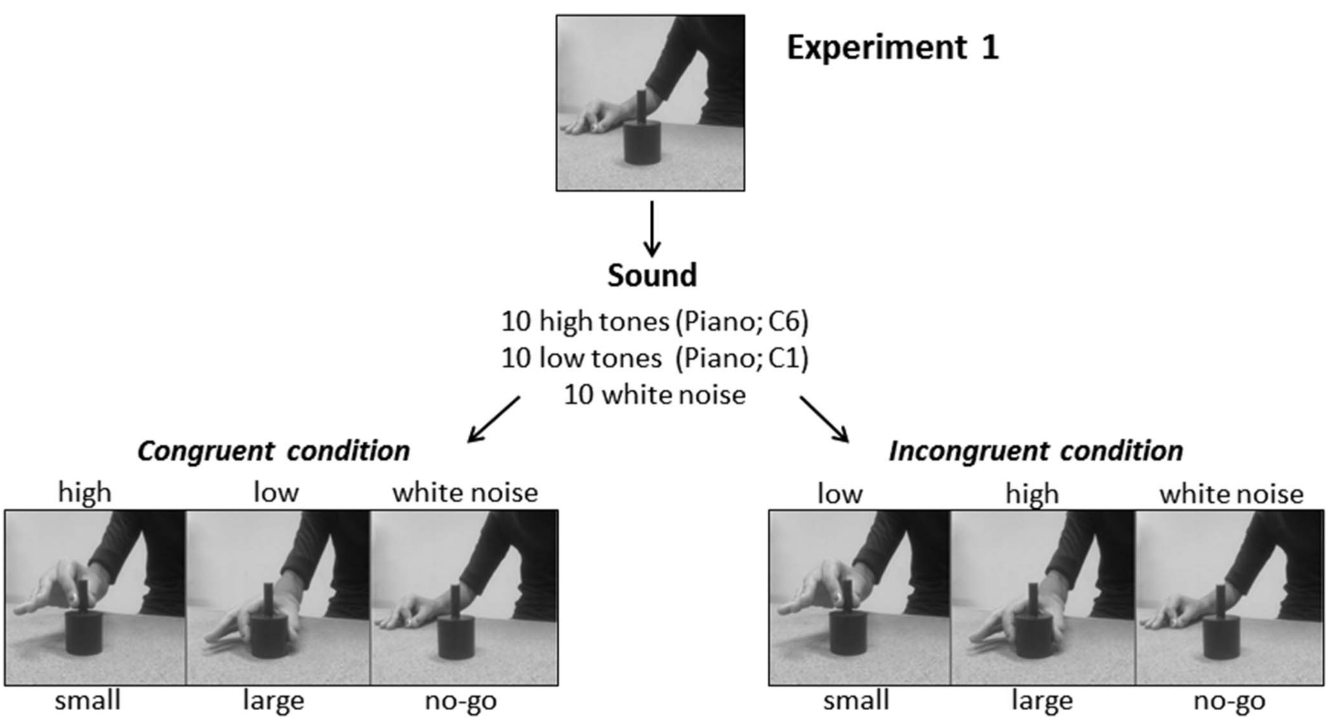

Figure 1. Apparatus and procedure of Experiment 1 with the standard object orientation. Each trial started with a sound (high tone, low tone, or white noise) presented for 1,500 ms via headphones. Upon sound presentation, participants had to perform a precision grip movement toward the object (*go*-trials) or refrain from moving (*no-go* condition). In *go*-trials, participants were required to grasp the object by its smaller versus larger section depending on the auditory pitch (congruent condition: high pitch = small section and low pitch = large section vs. incongruent condition: low pitch = small section and high pitch = large section). A second group of participants performed the same go/no-go task with the object tilted upside-down.

standard and of targets, a total of 36 trials, was presented. Results showed no differences between the high and the low tones, hence indicating that the sounds were perceived as equal in terms of loudness. The details of this control experiment can be found online in the supplemental material.

Procedure

Participants performed a go/no-go grasping task. Each trial started with the presentation of an auditory stimulus, lasting for 1,500 ms, delivered through headphones (Sennheiser HD 280 Pro headphone). As fast as possible after the onset of the sound, participants had to perform a precision grip movement or no movement at all, depending on the sound perceived (see Figure 1). In particular, for both the object orientations, in "go" trials participants had to reach, grasp, and lift the object from its larger section when hearing a low tone and from its thinner section when hearing a high tone, or vice versa depending on the experimental block. In turn, the white noise always signaled that no movement had to be performed ("no go" trials). In "go" trials, after completion of the movement, participants had to place their right hand back to the starting position. After 5 s from the presentation of the sound, the next trial began. To avoid artifacts induced by linguistic correspondence (see Dolscheid, Shayan, Majid, & Casasanto, 2013), words referring to size (e.g., small or large) or to space (e.g., high or low) were not used for the instruction in any of the experiments.

Participants took part in two experimental blocks of 30 trials each (10 presentations for each auditory stimulus—low tone, high tone, and white noise—in a pseudorandomized order), one with the high tone assigned to grasping the object from its smaller section and the low tone assigned to grasping the object from its larger section (congruent condition), and one with the reversed assignment (incongruent condition). The order of blocks was counterbalanced across participants.

Data Acquisition and Analysis

A 3D-optoelectronic motion analyzer (SMART system, sampling rate of 120 Hz, spatial resolution $\approx$ 0.3 mm) recorded the 3D spatial position of three passive reflective markers fixed respectively on the tip of the right thumb (marker 1), on the tip of the right index finger (marker 2), and on the styloid process of the ulna (marker 3) of the participant.

Marker 3 was used to compute the RT, defined as the time elapsed between the onset of the sound and the onset of the reaching movement. The beginning of the reach was measured as the first frame during which the displacement of the wrist marker along any Cartesian body axis increased more than 0.3 mm, with respect to the previous frame. The detection of movement onset was performed automatically via software and, for each movement, was visually checked and manually corrected when necessary. Markers 1 and 2 were used to compute the maximum grip aperture (MGA), defined as the maximum distance between marker 1 and 2 between reach onset and offset.

Data were analyzed offline for each trial and then averaged across trials for each experimental condition and participant, with a custom software written in MATLAB version 7.7 (R2008b). All variables showed normal distribution, as confirmed by the Kolmogorov–Smirnov test (all p values $> .05$). A repeated measures analysis of variance (ANOVA) with auditory pitch (high, low) and object section (small, large), as within-subjects variables and with object orientation (standard, tilted) as between-subjects factor, was performed on each variable. For the RTs analysis, the presence of a congruency effect between auditory pitch and object section was tested by the interaction in the ANOVA.

Results and Discussion

Incorrect motor responses were excluded from the analysis, resulting in the removal of 1.7% of the trials.

Figure 2A reports the RT data. A repeated measures ANOVA on mean RTs with auditory pitch (high, low) and object section (small, large) as within-subjects variables and with object orientation (standard, tilted) as between-subjects factor, revealed no significant main effects for either auditory pitch, $F(1, 26) < 1$, $p = .51$, or object orientation, $F(1, 26) < 1$, $p = .49$. A significant main effect of object section was found, $F(1, 26) = 6.08$, $p < .05$, $\eta_p^2 = .19$, power $= .66$, indicating faster initiation of movements directed to the small section compared with the large section of the target object. Importantly, the interaction auditory pitch *by* object section was significant, $F(1, 26) = 56.89$, $p < .001$, $\eta_p^2 = .69$, power $= 1$ (Figure 2A). Post hoc analysis showed that movements toward the small section of the target object were initiated faster in response to high pitches than to low pitches, $p < .001$, whereas movements toward the large section were initiated faster in response to low pitches than to high ones, $p < .001$, thus indicating the presence of a congruency effect. Finally, the interaction auditory pitch by object section by object orientation was significant, $F(1, 26) = 4.88$, $p < .05$, $\eta_p^2 = .16$, power $= 1$. Post hoc analysis indicated that for both object orientations, the congruency effect was significant, all p values $< .001$, although maximized in the standard orientation. Neither the interaction object section by object orientation, $F(1, 26) < 1$, $p = .35$, nor the interaction auditory pitch by object orientation reached significance, $F(1, 26) < 1$, $p = .81$.

The grand-averaged profiles of grip aperture in different conditions are shown in Figure 3. The ANOVA on mean MGA revealed a main effect of object section, $F(1, 26)$ 1974, $p < .001$, $\eta_p^2 = .99$, power $= 1$, with a larger MGA for grasping the large section of the target object than the small one. Importantly, the main effect of auditory pitch was also significant, $F(1, 26) = 23.42$, $p < .001$, $\eta_p^2 = .47$, power $= .99$ (Figure 2B), indicating that pitch influenced the relative scaling of the hand preshaping, with high pitches being associated with smaller grip aperture compared with lower ones. Conversely, the main effect of object orientation was not significant, $F(1, 26) < 1$, $p = .45$. Neither the interaction object section by object orientation, $F(1, 26) = 2.88$, $p = .1$, nor the interaction auditory pitch by object section reached significance, $F(1, 26) < 1$, $p = .46$. The interaction auditory pitch by object orientation showed a trend toward significance, $F(1, 26) = 3.76$, $p = .063$, $\eta_p^2 = .13$, power $= .46$. Post hoc analysis showed that high pitches were always associated with smaller grip aperture compared with lower ones, although this effect was maximized in the tilted orientation, $p < .001$ vs. standard orientation, $p < .05$.

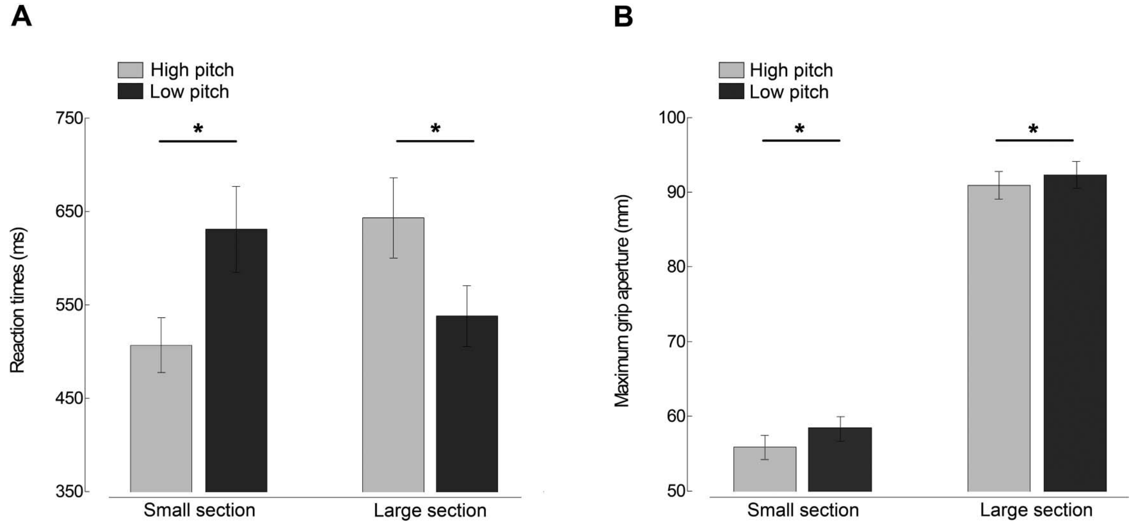

Figure 2. Results of Experiment 1. Movements toward the small section of the target object were initiated faster in response to high pitches, whereas movements toward the large section were initiated faster in response to low pitches (panel A). Pitch influenced the relative scaling of the hand preshaping, with high pitches associated with a smaller grip aperture, compared with low pitches, irrespective of the object section to be reached (panel B). Error bars indicate ±1 standard error of the mean.

Finally, the interaction auditory pitch by object section by object orientation was not significant, $F(1, 26) < 1$, $p = .91$.

Overall, the results of Experiment 1 support the hypothesis of an influence of auditory pitch on grasping movements in the context of size processing. Indeed, the observed effect of auditory pitch on initiation times is in agreement with the stimulus-response compatibility effect so far reported in pitch-size perceptual processing (Gallace & Spence, 2006). The present results show for the first time that this compatibility effect extends to more complex motor processing. More critically, grasping kinematic was also influenced by auditory pitch. In fact, auditory pitch modulated the grip aperture independently from the object size and prior to any interaction with it. This means that auditory pitch was per se informative about size in motor planning. Notably, this compatibility effect was mainly driven by the pitch-size association, because object orientation did not impact on the reported tendency (although at a descriptive level, the congruency effect was more accentuated with the object in the standard orientation than in the reversed orientation).

Experiment 2

The results from Experiment 1 provide evidence for an influence of auditory pitch on actions requiring size processing. However, the facilitation in movement initiation could be driven by a crossmodal association at a visual level, rather than by the size processing required when grasping a tool. Accordingly, Experiment 2 explored whether the effects of auditory pitch were exclusively determined by the visual object size or whether grip preparation was a necessary context for these effects to manifest. To address this possibility, in Experiment 2, we required participants to point to the object sections, thus reaching the object without grasping it. Indeed, grasping requires the translation of the object size into an appropriate grip aperture, and this size processing might be critical for observing the reported effects (see Lindemann et al., 2007). Consequently, if pitch influences actions only when size processing is required, we should expect no effect of auditory pitch when merely pointing to the target object. Contrarily, if the effects found in the previous experiments reflect a perceptual crossmodal correspondence between auditory pitch and visual size, movement initiation times should be affected by the frequency of the sound.

Participants

A new group of 13 right-handed students ($M = 28.2$ years, $SD = 6.1$; 12 females) took part in Experiment 2.

Stimuli and Procedure

We used the same apparatus as in Experiment 1. Participants performed the same go/no-go task of Experiment 1. However, this time participants were required to perform a pointing movement toward the target without reaching it (i.e., stopping at a distance of about 1 cm). Specifically, participants had to point their right index finger to either the small or to the large section of the target object, depending on the auditory pitch.

Data Acquisition and Analysis

Two passive reflective markers were fixed on the styloid process of the ulna (marker 1) and on the tip of the right index finger (marker 2). Marker 2 was used to compute the RT, defined as the time elapsed between the onset of the sound and the onset of the pointing movement. All variables showed normal distribution, as confirmed by the Kolmogorov–Smirnov test, all p values $> .05$. A two-way repeated measures ANOVA on auditory pitch (high, low) and object section (small, large), as within-subjects variables, was

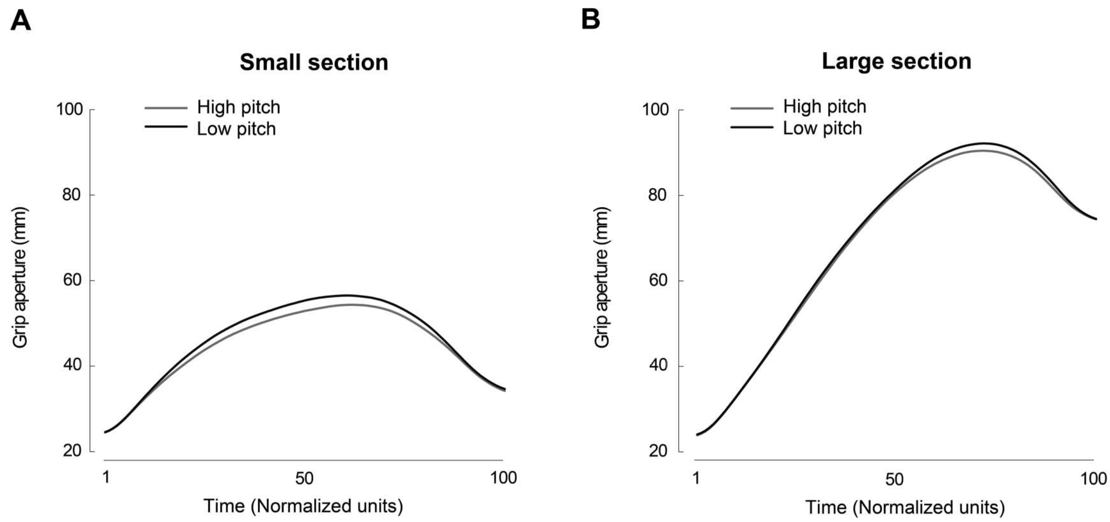

Figure 3. Grand-average of grip apertures profiles of Experiment 1. The time dimension was normalized to 100 units. Black and gray lines represent the grip aperture averages for the high and low auditory pitch, respectively. Grip apertures toward the small section of the target object (panel A). Grip apertures toward the large section of the target object (panel B).

performed on RT. For the RTs analysis, the presence of a congruency effect between auditory pitch and object section was tested by the interaction in the ANOVA.

Results and Discussion

Incorrect motor responses were excluded from the analysis, resulting in the removal of 1.7% of the trials.

A two-way repeated measures ANOVA on mean RTs with auditory pitch (high, low) and object section (small, large) as factors, revealed no significant effects for either auditory pitch, $F(1, 12) = 1.8$, $p = .20$, object section, $F(1, 12) < 1$, $p = .44$, or for their interaction, $F(1, 12) < 1$, $p = .54$ (see Figure 4).

In short, no compatibility effect was found when merely pointing to the object, indicating that auditory pitch only influences motor control of actions requiring size processing.

Experiment 3

Experiment 1 revealed that reach-to-grasp movement initiation was affected by the compatibility between the size of the object sections to be grasped and the auditory pitch. However, in Experiment 1, pitch modulated grip aperture irrespective of the size of the object (i.e., there was no interaction between pitch and size). Therefore, from Experiment 1, it is not clear whether size processing is necessary to modulate grip aperture. Indeed, it may be possible that pitch alone is sufficient to systematically alter grip aperture. In order to verify whether size processing is a precondition for pitch to modulate grip aperture, we carried out an additional experiment based on a paradigm similar to Experiment 1, but in which the object was kept constant in size. In Experiment 3, we tested whether the effects of pitch on maximum grip aperture might arise even when auditory pitch is irrelevant to the programming of the grip aperture.

Participants

Fourteen right-handed students ($M = 26.3$ years, $SD = 3.3$; 11 females) took part in Experiment 3. None of them had participated in Experiments 1 and 2.

Stimuli and Procedure

We used the same apparatus and task of Experiment 1. However, two new objects were used, both consisting of a unique piece (and not made of different sections): a small object and a large

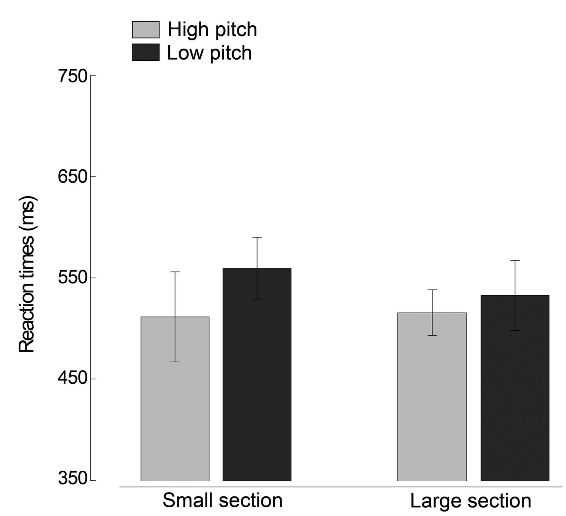

Figure 4. Results of Experiment 2. RTs for pointing movements toward the object were not affected by either auditory pitch or by the target section of the object (small vs. large). Error bars indicate ±1 standard error of the mean.

object. The small object and the large objects corresponded in shape and size to the small and large sections, respectively, of the composite object used in Experiment 1. In one block, participants were only presented with the large object, in another block only with the small object. The order of blocks was counterbalanced across subjects.

Data Acquisition and Analysis

Data acquisition and analysis were identical to Experiment 1. All variables showed normal distribution, as confirmed by the Kolmogorov–Smirnov test, all p values $> .05$. A two-way repeated measures ANOVA with auditory pitch (high, low) and object size (small, large), as within-subjects variables, was performed on each variable. For the RTs analysis, the presence of a congruency effect between auditory pitch and object size was tested by the interaction in the ANOVA.

Results and Discussion

Incorrect motor responses were excluded from the analysis, resulting in the removal of 0.9% of the trials.

The analysis on mean RTs revealed no significant effects of either auditory pitch, $F(1, 13) < 1$, $p = .62$, object size, $F(1, 13) < 1$, $p = .77$, or their interaction, $F(1, 13) = 2.2$, $p = .16$ (Figure 5A).

The same ANOVA on mean MGA revealed that the main effect of object size was significant, $F(1, 13) = 668.5$, $p < .001$, $\eta_p^2 = .98$, power = 1, with a larger MGA for grasping the large object than the small one. Neither auditory pitch, $F(1, 13) = 1.43$, $p = .25$, nor the interaction pitch by object size, $F(1, 13) < 1$, $p = .54$, were significant (Figure 5B).

Results of Experiment 3 indicate that auditory pitch does not affect grasping movements when it does not convey information about the type of grasping to be performed.

Experiment 4

In Experiment 4, we extended the investigation of the pitch-size associations to symbolic manual gestures. We reasoned that auditory pitch might not only interact with object-directed grasping, but also with communicative actions conveying size. Indeed, in many everyday life situations, individuals refer to size by spontaneously gesturing about quantity (Winter, Perlman, & Matlock, 2013). More specifically, speakers' metaphorical conceptualizations of size are often translated in gesture: when emphasizing that a certain quantity is a large quantity, speakers might move their arms away from their body, thus increasing the space between hands; contrarily, speakers might move their arms close to each other, to emphasize a small quantity (Winter et al., 2013). Similar gestures are also exploited in the American Sign Language to express size-related concepts. Thus, in Experiment 4, we explored whether auditory pitch might influence manual gestures conveying abstract concepts about size. Consequently, we required participants to perform manual gestures, adapted from American Sign Language, expressing small and large concepts.

Participants

A new group of 13 right-handed students (M = 28.3 years, SD = 2.6; 8 females) took part in Experiment 4.

Stimuli and Procedure

Participants were comfortably seated and were blindfolded throughout the experiment in order to avoid any motor adjustment based on visual feedback of the hands. The same auditory stimuli of Experiment 1 were used.

Participants performed a go/no-go task similar to Experiment 1. In Experiment 4, they were required to keep their arms attached to the trunk with their elbows at 90° angle and their hands open and

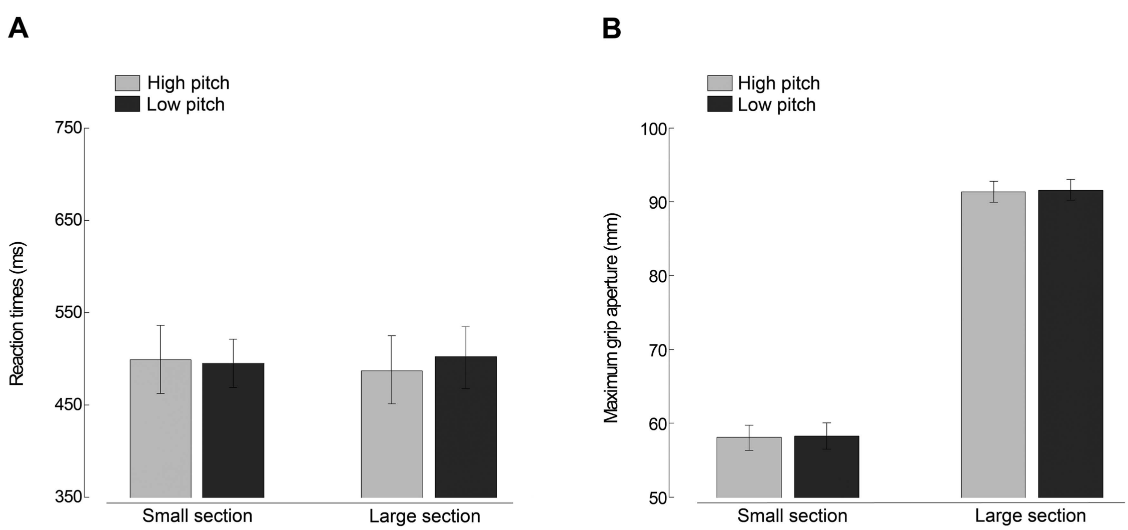

Figure 5. Results of Experiment 3, in which two different sized objects were presented in two separated blocks. RTs for reaching movements toward the target object were not affected by either auditory pitch (high vs. low) or by object size (small vs. large; panel A). Auditory pitch did not influence the relative scaling of the hand preshaping, either when grasping the small or the large object (panel B). Error bars indicate ±1 standard error of the mean.

parallel out in front of the body (i.e., starting position; see Figure 6). Participants were then required to move their hands away (large gesture) or close (small gesture) to each other, depending on the auditory pitch, avoiding rotation of the hands and without touching the palms (see Figure 6). At the beginning of the experiment, participants practiced the required actions. Participants took part in two experimental blocks, one with the high tone assigned to the small gesture and the low tone assigned to the large gesture (congruent condition), and one with the reversed assignment (incongruent condition). The order of blocks was counterbalanced across participants.

Data Acquisition and Analysis

Four passive reflective markers were fixed respectively on the right (marker 1) and on the left (marker 2) styloid process of the ulna and on the right (marker 3) and on the left (marker 4) tip of the index finger. Markers 1 and 2 were used to compute the RT, defined as the time elapsed between the onset of the sound and the onset of the hands movement. As in the previous experiments, the beginning of the movement was measured as the first frame during which the distance along any Cartesian body axis between marker 1 and 2 increased (large gesture) or decreased (small gesture) more than 0.3 mm, with respect to the previous frame. The detection of movement onset was performed automatically via software and for each movement was visually checked and manually corrected when necessary.

Markers 1 and 2 were used to compute hands aperture (HA). For the large gesture, HA was defined as the maximum distance between hands. Specifically, we subtracted, in each trial, the final hands aperture from the initial hands aperture, and we considered the maximum value during the hands movement. Conversely, for the small gesture, HA was defined as the minimum distance between hands. In this case, we subtracted the initial hands aperture from the final hands aperture, and we considered the minimum value during hands movement.

All variables showed normal distribution, as confirmed by the Kolmogorov–Smirnov test, all p values $> .05$. A two-way repeated measures ANOVA on auditory pitch (high, low) and type of gesture (small, large), as within-subjects variables, was performed on each variable. For the RTs analysis, the presence of a congruency effect between auditory pitch and type of gesture was tested by the interaction in the ANOVA.

Results and Discussion

Incorrect motor responses were excluded from the analysis, resulting in the removal of 2% of the trials.

A two-way repeated measures ANOVA was carried out on mean RTs with auditory pitch (high, low) and type of gesture (small, large) as within-subjects factors. The analysis revealed no significant main effects for auditory pitch, $F(1, 12) = 1.1$, $p = .33$, or gesture, $F(1, 12) = 2.62$, $p = .13$. The interaction auditory pitch *by* type of gesture was significant, $F(1, 12) = 5.71$, $p < .05$, $\eta_p^2 = .32$, power = .59 (Figure 7A). In particular, small gestures were initiated faster in response to high pitches than to low pitches, $p < .05$, whereas large gestures were initiated faster in response to low pitches than to high pitches, $p < .05$, thus indicating the presence of a congruency effect.

The same ANOVA on mean HA revealed a trend for auditory pitch, $F(1, 12) = 4.16$, $p = .06$, $\eta_p^2 = .26$, power = .47 (Figure 7B), indicating that high pitches tended to be associated with smaller HA than low pitches. Furthermore, the main effect of type of gesture was significant, $F(1, 12) = 37.7$, $p < .001$, $\eta_p^2 = .76$, power = 1, indicating larger HA for larger gestures than smaller

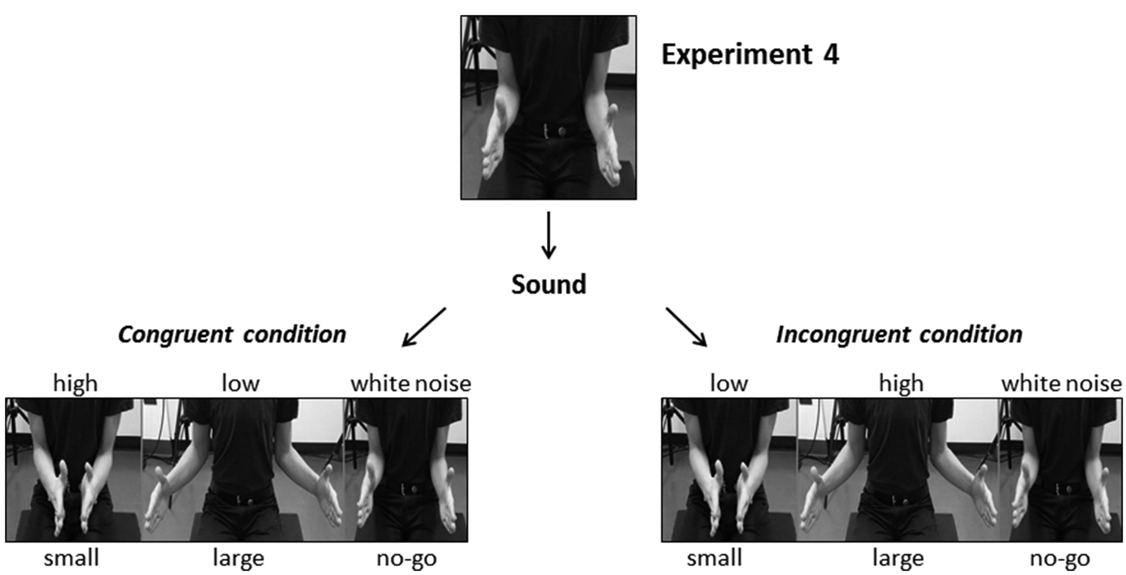

Figure 6. Procedure of Experiment 4. Similarly to Experiment 1, participants had to act in response to the auditory pitch of auditory stimuli. When the sound was presented, participants had to move their hands close to each other (small gesture) or away from each other (large gesture). The movement depended on the auditory pitch of the sound (congruent condition: high pitch = small and low pitch = large vs. incongruent condition: low pitch = small and high pitch = large).

gestures. The interaction pitch by gesture was not significant, $F(1, 12) < 1$, $p = .48$.

These results, therefore, partially extend the previous finding to manual gestures conveying symbolic size information.

General Discussion

In four kinematic experiments, we investigated the effects of auditory pitch on motor planning by requiring participants to perform different manual actions primed by sounds. We found that pitch influenced the execution of manual actions when they implied size processing.

First, movement initiation times revealed that pitch-size compatibility effect, so far reported for perceptual processing (see Marks, 2004, for a review), holds for motor processing too. In particular, actions directed to small objects were facilitated by the presentation of high-pitched tones, while actions directed to larger objects were facilitated by low-pitched tones (Experiment 1). This pattern of results extends previous findings in the literature (e.g., Gallace et al., 2006) to more complex motor behavior. Pointing movements were not affected by auditory pitch (Experiment 2), likely because in this case, the size of the target was irrelevant for the purpose of the action. Moreover, no effect on initiation times was found when auditory pitch was irrelevant to the programming of the grip aperture (Experiment 3). Finally, a pitch-size compatibility effect was also found for manual gestures expressing small and large concepts, where actions were not aimed at grasping an object (Experiment 4).

Second, and more importantly, we found that auditory pitch influenced the size of the hand preshaping. In fact, high pitches prompted smaller grip aperture, while low pitches prompted larger grip aperture (Experiment 1). Yet, this effect emerged only when auditory pitch was relevant to the task, that is, when it conveyed information about the type of grasping to be performed (Experiment 3). Overall, these results suggest that, when size processing is necessary, auditory pitch per se is informative about size in motor planning, and this influence can be seen both in the context of interacting with a real object and when referring to abstract concepts.

The present study contributes to the current debate concerning how humans process magnitude-related information (Bueti & Walsh, 2009). According to the ATOM theory (Walsh, 2003), space, time, and quantity (i.e., prothetic dimensions) would mutually operate on similar magnitude representations. The development of such representations would be regulated by a continuous interaction with the surrounding environment, so that magnitude processing would be tightly linked with motor reaching, grasping, and object manipulation (Bueti & Walsh, 2009). In line with this, compelling evidence suggests that action planning and symbolic number processing share a cognitive representation of magnitude (Andres et al., 2004; Lindemann et al., 2007). In particular, Lindemann et al. (2007) investigated the effect of numerical processing on the planning and control of reach-to-grasp movements, reporting that small grip movements were initiated faster in response to small numbers, while large grip movements were initiated faster in response to large numbers. Moreover, grip aperture was influenced by number magnitude, with a larger maximum grip aperture in response to larger numbers (Lindemann et al., 2007). However, according to a more comprehensive view of ATOM, metathetic dimensions concerned with qualitative variations, such as auditory pitch, should be included as well, because they are also associated with space and quantity (see Bottini & Casasanto, 2013, for a discussion). In the present study, both initiation times and grip aperture revealed that the influence of auditory pitch on size processing is not limited to perception, but rather it extends to actions. Consequently, the present study shows that auditory pitch processing and action planning share a cognitive representation of magnitude.

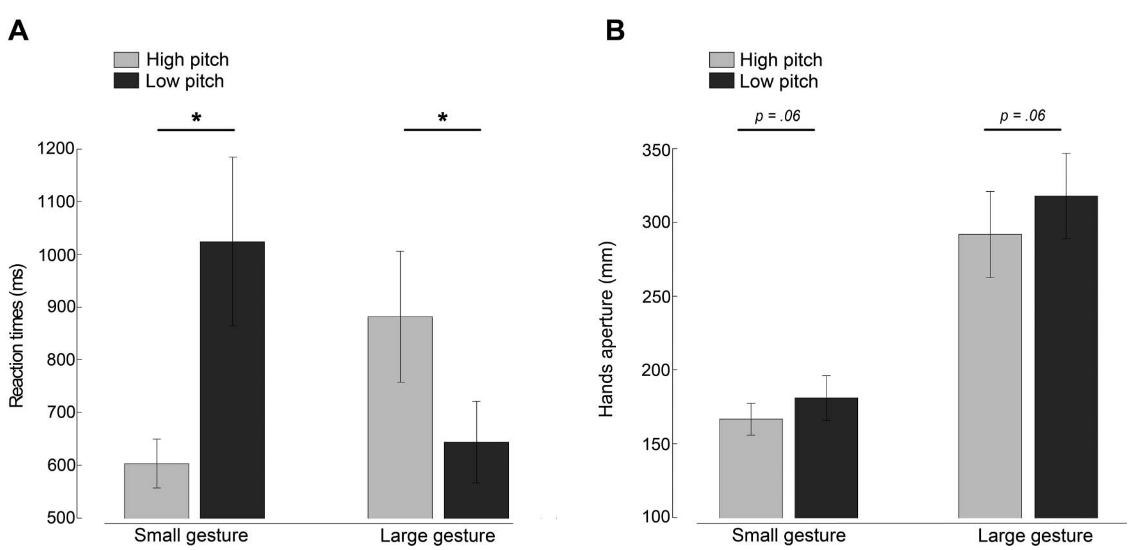

Figure 7. Results of Experiment 4. RTs were faster for small gestures that had to be performed in response to high pitches, and for large gestures that had to be performed in response to low pitches (panel A). Analysis of the hands aperture showed a statistically nonsignificant trend, with high pitches associated with a smaller hands aperture, compared with low pitches, suggesting that manual gestures expressing symbolic size information were affected by auditory pitch (panel B). Error bars indicate ±1 standard error of the mean.

Taken together, our findings extend prior literature on pitch-size correspondence (see Spence, 2011, for a review). In nature, object resonant frequency is related to object size and experiencing such correspondence is known to bias, through repetition, our perception of the surrounding world (see Parise et al., 2014, for a statistical account of pitch-space association). For instance, if we are listening to a high-frequency sound, we expect the sound to be generated by a small object (Grassi et al., 2013). Given the tight link between perception and action, pitch-size natural correspondence might also bias our actions in the environment. The present study offers support to this view. In particular, our results suggest that auditory information biases our action, even when the sound does not originate from the object to be manipulated (see Gallace & Spence, 2006). Hence, participants might have exploited the natural mapping between auditory pitch and visual size to integrate current multisensory information for actions, as reflected by the congruency effect in movement initiation. Critically, this occurred with non-natural sounds and in presence of visual feedback, indicating that prior pitch-size experience competes with online perceptual processing (i.e., the real object size) for driving action.

In an evolutionary perspective, implementing pitch-size correspondence at the motor level might have relevant advantages. Specifically, auditory pitch might be linked with size to speed up the programming of object-directed actions (see Morton, 1977). Accordingly, the motor facilitation on initiation times reported here might favor interaction with the environment, with pitch that timely signals the motor system about the action to be executed.

More generally, our results provide novel evidence supporting the role of auditory information in driving actions. Many object-related actions can be inferred by their sounds (Kohler et al., 2002), and, in turn, natural sounds have been shown to influence the execution of reach-to-grasp movements (Castiello, Giordano, Begliomini, Ansuini, & Grassi, 2010; Sedda et al., 2011). Furthermore, individuals can rapidly learn to plan reach-to-grasp movements directed to different sized objects from the frequency of an auditory cue (Säfström & Edin, 2006). In particular, humans can establish a novel audiomotor map that enables them to properly grasp different sized objects, on the basis of sound frequency (Säfström & Edin, 2006). In line with these findings, we found that an association between object size and auditory pitch already exists, likely because of the repeated interaction with the surrounding environment. Moreover, these findings extend prior literature supporting multisensory integration of tactile (Patchay, Castiello, & Haggard, 2003), olfactory (Castiello, Zucco, Parma, Ansuini, & Tirindelli, 2006), and auditory modalities (Sedda et al., 2011) for acting in the environment.

Further support about a tight connection between the motor and the auditory system comes from evidence showing that the kinematics of grasping movements can influence the kinematics of speech (see Gentilucci & Corballis, 2006, for a review). In particular, Gentilucci and colleagues (Gentilucci, Benuzzi, Gangitano, & Grimaldi, 2001; Gentilucci, Santunione, Roy, & Stefanini, 2004) found that grasping objects of different size and bringing them to the mouth induced significant modulations in voice spectra of syllables simultaneously pronounced. Interestingly, an influence was also found during the mere observation of the movements (Gentilucci, 2003; Gentilucci et al., 2004). A similar correspondence has been found between spatial perception and speech production (Shintel, Nusbaum, & Okrent, 2006). In particular, individuals tend to spontaneously change the fundamental frequency of their voice to better describe the direction of motion along the vertical space, creating an analogical mapping between vocal frequency and the conveyed direction of motion. For instance, speakers raised and lowered their voice pitch to describe objects moving upward and downward, respectively (Shintel et al., 2006). In line with these findings, the present study provides additional evidence for a strong interaction between manual actions and auditory pitch processing, extending this link also to nonspeech sounds.

In Experiment 4, we showed that auditory pitch modulates manual actions expressing abstract concepts of small and large. To explain how auditory pitch could influence manual gestures conveying abstract concepts, we first notice that in communication, humans frequently exploit manual gestures to further emphasize speech (Bernardis & Gentilucci, 2006). Interestingly, manual gestures are also used to reinforce concepts related to size (Winter et al., 2013). For instance, people can emphasize size-related words by modifying the space between hands (see Winter et al., 2013). Hence, it might be possible that auditory pitch could modulate manual gestures by altering in the first place the mental representation of the size to be expressed, and this altered representation would then translate into a correspondingly larger or smaller gesture. Accordingly, the reported effects might arise from a natural correlation between vocal frequency and manual gestures, while people communicate concepts of size. In fact, a tendency to use high-pitched vocal segments for words referring to the meaning small and low-pitched vocal segments for those referring to the meaning large has been documented in different languages (see Ohala, 1983). Yet, this natural correlation would also account for the motor facilitation reported here. Future research using linguistic stimuli will be useful to gain further insights on these hypotheses.

In terms of which brain areas could be responsible for the effect of auditory pitch on motor planning, existing evidence suggests the involvement of a fronto-parietal network in the audiovisual integration guiding action (Rizzolatti & Sinigaglia, 2010). Indeed, some neurophysiological studies have shown that audiovisual mirror neurons in the premotor area F5, respond to both actions accompanied by sounds and by the presentation of sounds alone (Kohler et al., 2002). Moreover, recent neuroimaging studies have demonstrated an activation in the intraparietal sulcus, an area involved in grasping movements, during both pitch processing (Foster & Zatorre, 2010) and size processing (Pinel, Piazza, Le Bihan, & Dehaene, 2004). Overall, this shared neuroanatomical network adds to behavioral evidence pointing to the relevance of audiovisual integration for acting efficiently in the environment.

Finally, unveiling the impact of auditory pitch in motor control, our study has practical implications for both neurorehabilitation of motor disorders and the development of virtual-reality interfaces. For instance, recent studies have shown a benefit of auditory contact cues on the planning and control of grasping movements (Zahariev & Mackenzie, 2003, 2008). Accordingly, auditory pitch might be exploited to facilitate the fulfillment of actions requiring size processing, such as grasping movements, or provide augmented feedback for actions performed in immersive virtual-reality.

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Received November 20, 2014
Revision received July 7, 2015
Accepted July 9, 2015 ■