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Weightlifting exercise and the size-weight illusion

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Abstract

In the size-weight illusion (SWI), large objects feel lighter than equally-weighted small objects. In the current study, we investigated whether this powerful weight illusion could influence real-lift behaviour; namely whether individuals would perform more bicep curls with a dumbbell that feels subjectively lighter than with an identically-weighted, but heavier-feeling dumbbell. Participants performed bicep curls until they were unable to continue with both a large, light-feeling 10lb dumbbell and a small, heavy-feeling 10lb dumbbell. Despite experiencing that the large dumbbell felt subjectively lighter than the small dumbbell, there were no differences in the amount of exercise participants performed with each dumbbell. Furthermore, in a second experiment, there were no differences in how subjectively tired participants felt after exercising for a set time with either dumbbell. There were, however, differences in the lifting dynamics, such that the small dumbbell was moved at a higher average velocity and peak acceleration. These results suggest that the SWI does not appear to influence exercise outcomes, suggesting that perceptual illusions are unlikely to affect one's ability to persevere with lifting weights.

Introduction

The subjective nature of our perception of heaviness is readily demonstrated by the size-weight illusion (SWI), where small objects will feel substantially heavier than equally-weighted large objects with identical mass. This illusion is experienced by most individuals, does not diminish over time, and is unaffected by the explicit knowledge of the objects' actual weight (Charpentier, 1891; Flournoy, 1894; Ross, 1969). Similar illusions can be evoked by manipulating the material properties of objects, such that a cube appearing to be made from polystyrene will feel heavier than an identically-weighted cube made from metal (Buckingham, Cant, & Goodale, 2009; Ellis & Lederman, 1999; Seashore, 1899). Although the mechanism underpinning the misperception of weight remains something of a mystery, there is compelling evidence to suggest that these weight illusions stem from how humans integrate their cognitive expectations to form their conscious perceptual experiences. In the context of the SWI, individuals expect the large object to be heavy, whereas they expect the smaller object to be relatively light, based on prior experience. When lifting the identically-weighted large and small objects these expectations are confounded – the large object weighs less than the lifter expected and the small object weighs more than the lifter expected. The lifters eventual perception of heaviness appears to contrast their initial expectation, resulting in the percept that the smaller object is heavier than the larger object.

Several recent studies have provided evidence for the importance of cognitive expectations in how individuals perceive an object's weight. Flanagan and colleagues examined the plasticity of the SWI by manipulating expectations about the properties of an entire set of stimuli (J Randall Flanagan, Bittner, & Johansson, 2008). In their experiment, subjects underwent days of training with objects which had an inverse density relationship (i.e., small heavy and large light objects), priming them to expect. Following this training period, subjects then lifted similar-looking identically-weighted large and small objects. After having their expectations redefined in this way, the SWI they experienced was at first diminished, and then eventually reversed so that the large object felt heavier than the identically-weighted smaller object. We have recently provided further indications of how expectations can affect weight perception, by demonstrating that the SWI can even be induced in a single medium-sized cube. In this study, participants were given a short visual preview of a larger or smaller cube, which they expected to eventually lift without visual feedback (Buckingham & Goodale, 2010a). Prior to actually lifting the cube without vision, however, the viewed large or small cube was discreetly replaced with the same lifted cube, unbeknownst to the lifter. When asked how heavy the lifted cube felt on each trial, participants reported that it felt significantly heavier when they were primed to expect to lift the small cube than it did when they expected to lift the large cube. In other words, simply altering lifters' expectations of what they are about to do can affect their perception of how heavy something will eventually feel.

In recent decades, there has been a surge of interest in how our perception guides (or retains independence from) the control of our actions. In the context of weight illusions, it has been demonstrated that a lifter's fingertip force rates appear to be independent from the illusory perceptions of heaviness (Buckingham et al., 2009; Flanagan & Beltzner, 2000; Grandy & Westwood, 2006; Mon-Williams & Murray, 2000). Initially, lifters apply grip and load forces in line with their expectations of heaviness – in the case of SWI-inducing stimuli, lifting the large object with more force than the small object. However, lifters rapidly adapt their forces from the expected weights to the actual (identical) mass of the illusion-inducing objects – never lifting the heavy-feeling small object with more force than the light-feeling large object. These findings suggest that the violated expectations which appear to cause these illusions are cognitive, rather than sensorimotor in nature.

Recent work examining perceptual and motor performance outside of the lab has shown that the careful application of visual illusions can affect the successful performance of sporting task. Using the famous Ebbinghaus illusion Witt, Linkenauger, & Proffitt, (2012) demonstrated that by surrounding the hole on a putting green with an annulus of small circles (making the hole appear larger) leads to more successful putting performance than when the hole is surrounded by an annulus of larger circles (making the hole appear smaller). Their explanation for this effect was that when the hole appeared larger (i.e., when surrounded by the annulus of small circles), the golfer's confidence in their ability to make the putt was raised, leading to enhanced subsequent performance. This finding provides an interesting extension on the classic debate surrounding the apparent independence of perception and action (see Carey, 2001), suggesting that cognitive factors might mediate perceptual-motor interactions.

Sporting and exercise performance is a combination of physiological and psychological factors – regular exercisers will be well aware that enjoyment and confidence are key factors in adherence to an exercise program (Woodman & Hardy, 2003). Although research in this area is limited, the importance of motivation in 'pushing through the pain' is particularly relevant to weight-lifting exercises. These considerations are important for exercise-based physiotherapy rehabilitation programmes, where perceived difficulty of the exercises may be a major hurdle to adherence.

Given the unchanging, powerful, and apparently cognitive nature of the SWI, we were interested to determine whether an object's subjective feeling of lightness could result in a stronger motivation to continue lifting weights. To this end, we created dumbbells from differently-sized weights which had been altered to have the same mass as one another. Because of the SWI, the smaller of the dumbbells felt subjectively heavier than the larger of the dumbbells. In separate experiments we then examined participants' weightlifting performance and perceptions of effort with the large and small dumbbells. If individuals' subjective perceptions of heaviness influenced their motivation to continue, we would expect them to exercise more, and feel less tired, after lifting the lighter-feeling large dumbbell than with the heavy-feeling small dumbbell.

Experiment 1 – illusion effects on weightlifting performance

Participants

Eighteen undergraduate and postgraduate students (7 male, 11 female; mean age: 21.3 years, SD: 3.6), recruited from the University of Western Ontario, participated in this first experiment. All participants except one were self-reported right-handers. All procedures were approved by the local ethics committee. All participants gave written informed consent prior to taking part in the study, and were compensated $10 for their participation.

Materials

In this experiment, participants lifted dumbbells made from pairs of circular plate-style yellow plastic weights attached to a black plastic handle (Figure 1A). The small dumbbell consisted of two unaltered 2.5 lb. weight plates, and the large dumbbell consisted of two 5 lb weights, which had half of the cement removed from their lateral surfaces to leave them weighing 2.5 lbs. each. This left the remaining cement evenly distributed around the central handle. The weights were fitted with infra-red emitting electrodes attached to their surface, which were tracked in 3D by an Optotrak 3020 system recording at 100-Hz. In total, each dumbbell weighed 6.4 lbs. During the experiment, participants lifted the weights in time to the beat of an auditory 1-Hz metronome which was played through computers speakers with a custom-written Matlab program. Prior to lifting, participants practiced the bicep curls with a dumbbell handle which was identical to those used in the experiment itself, without any weights attached.

INSERT FIGURE 1 HERE

Procedure

This experiment consisted of two separate testing sessions, one week apart. Participants saw and lifted only one of the dumbbells in each session, meaning that lifters never had the opportunity to directly compare the large and small weights. Before starting the experimental trials, participants first gave an estimate of how heavy the dumbbell looked in either lb. or kg. Participants then engaged in a practice set of 20 bicep curls at a rate of one flexion or extension per second (keeping time with the beat of an auditory metronome) with an empty handle. The purpose of these practice trials was to (1) warm up the critical muscle groups and (2) familiarize participants with the procedure and proper lifting form. After completing this warm-up, participants commenced with the lifting of a large or small dumbbell. Bicep curls were performed by each participant with one hand at a time, and only one set of lifts was performed per arm during each testing session. Lifting was always performed first with the right arm (supinated bicep curls), then the left arm (hammer-style bicep curls). The different exercise styles were included to provide some indication as to the generalizability of any effect (i.e., to ensure that the size manipulation did not only alter supinated bicep curls). Half the participants lifted the small dumbbell in the 1st session and the large dumbbell in the 2nd session, whereas the other half lifted the large dumbbell in the 1st session and the small dumbbell in the 2nd session.

Participants were instructed to perform as many bicep curls as possible while keeping in time with the auditory metronome beep that occurred once per second. The bicep curl is a commonly performed exercise in which the majority of the resistance due to gravity is placed upon the biceps brachii muscle. Secondary muscle recruitment involves the anterior deltoid muscle (shoulder) and forearm. The elbow joint is the pivot point, and the shoulder and back are held as still as possible. The muscles of the forearm and fingers are also engaged during the grip of the weight and experience tangential resistance during the lift while the participant holds the hand in line with the wrist. The curls were accomplished by gripping the dumbbell in a comfortable fashion, as close to the center of the handle as possible. For the supinated bicep curls, the right hand was in a supinated grip position and the inside of the forearm always faced upward (Figure 1B). Participants stood with feet shoulder width apart while lifting. The starting position of the weight was slightly below the waist, held such that the forearm was approximately 45 degrees below the horizontal. One repetition consisted of lifting the weight to approximately shoulder height until the forearm reached 45 degrees above horizontal. Participants were instructed to keep the movement as smooth as possible and have a consistent speed during lifting as well as when returning the weight to the starting position, and not to lock their joints at the start or end of the curl. When a participant could no longer effectively keep time with the metronome, stopped lifting the weight, or indicated verbally that they did not wish to continue, the trial was considered complete. Following a five-minute rest period, participants then performed hammer-style bicep curls to fail with their left arm. The hammer-style curls only differed slightly in the form, requiring lifters to orient the dumbbell such that they were lifting it along the vertical axis, keeping the inside of their forearm facing their body (Figure 1C).

When participants had completed both types of lifting in the first session, they were again asked to rate how heavy the dumbbell felt (in the same metric as their initial value). Participants then came back one week later to perform a procedure that was identical to the first session, but using the different-sized dumbbell. This second session was managed by a different experimenter, who was unaware of the participant's performance in the first session. The dumbbells were lifted in separate sessions by participants, and the testing was carried out by different experimenters in each session, in order to minimise the effects of experimenter bias. Differences across the perceptual and exercise effects with the large and small dumbbells were examined with 2-tailed t-tests performed in Microsoft Excel.

Results

When asked to give an estimate of how heavy the weight looked before lifting it, participants reported that the large dumbbell looked heavier than the small dumbbell (t(17) = 3.85, p<.005; Figure 2A). In contrast, when asked how heavy each dumbbell felt *after* completing the experiment, participants reported that the small dumbbell felt heavier than the large dumbbell (t(17) = 2.33, p<.05, Figure 2B). Thus, participants expected the dumbbells to weigh different amounts and experienced a SWI as a consequence (e.g., Buckingham & Goodale, 2010a).

INSERT FIGURE 2 HERE

In terms of participants' exercise output with the different weights, we detected no difference between the number of hammer-style bicep curls that participants were able to perform with the large dumbbell or the small dumbbells (t(17) = 0.62, p=.54, Figure 3A). Similarly, when comparing the total number of supinated bicep curls participants were able to complete, there was no difference between the amount of exercise achieved with the large and small dumbbells (t(17) = 0.29, p=.78, Figure 3B). Furthermore, there was no correlation between the perception of heaviness and the number of bicep curls accomplished for either the large dumbbell (r(17) = -0.02, p=.94) or small dumbbell (r(17) = 0.09, p=.72). In short, the size and perceived weight of the dumbbells had no impact on participants' ability or willingness to exercise.

INSERT FIGURE 3 HERE

Kinematic data for two participants was lost due to marker occlusion, leaving a sample of 16 for this portion of analysis. This data, averaged across the left and right hand bicep curls, allowed us to determine how various movement parameters were affected by the size of the weights (see Table 1). No differences were observed between the large and small dumbbells in terms of the total distance travelled by the dumbbell (t(15) = 0.93, p=.37) or total time spent lifting the weights (t(15) = 0.16, p=.87). There was, however, a difference in the average velocity and average peak acceleration used to lift the dumbbells; participants lifted the small weight at a higher average velocity (t(15) = 3.82, p<.005) and with higher peak accelerations (t(15) = 2.91, p<.05) than the large weight. None of the kinematic variables correlated with either the perceptual ratings of heaviness or the number of bicep curls performed for either the large or small dumbbell (all r's < 0.27).

INSERT TABLE 1 HERE

Experiment 2 – illusion effects on weightlifting effort

In Experiment 1, participants performed approximately the same number of bicep curls with a heavy-feeling small dumbbell as they did with a light-feeling large dumbbell – a finding which was replicated within subject in two different types of bicep curl. However, it is feasible that our participants were able to lift weights fully to the limits of their muscles' endurance, and any perceptual effect on weightlifting motivation may have been masked by a ceiling effect. Furthermore, the effect of the SWI might have been ameliorated by interacting with the large and small weights in separate sessions.

In order to examine the effect of perceptual illusions on weightlifting performance from a difference perspective, we undertook a second experiment where a new group of participants lifted the identically-weighted large and small dumbbells for a set number of repetitions and then rate their perceived level of exertion. We adapted our paradigm so participants saw and lifted both dumbbells in the same session one after the other in opposite hands, and received continuous visual feedback of the dumbbell's size by lifting in front of a mirror, in order to maximise the perceptual illusion.

Method

Participants

Eighteen undergraduate and postgraduate students from the University of Western Ontario (8 male, 10 female; mean age: 27.3 years, SD: 11.6) participated in the second experiment. All of the participants were self-reported right-handers. All participants gave written informed consent prior to taking part in the study, and were compensated $5 for their participation. None of these participants had taken part in Experiment 1.

Materials

The same materials were used in this experiment as in Experiment 1, with two additions. First, participants lifted the weights in front of a free-standing mirror in order to provide continuous visual feedback of the large and small dumbbells. Second, the Borg Rate of Perceived Exertion Scale (Borg, 1970) was used to measure participants' perceived exertion on a scale of 6 (no exertion at all) to 20 (maximal exertion).

Procedure

Prior to lifting any of the dumbbells, participants were asked to make the binary choice of which one appeared to be heavier. Participants undertook the same practice trial/warm up procedures reported in Experiment 1. Following completion of the practice curls, participants were shown a paper version of the Borg scale asked to verbally rate their level of perceived exertion from 6 to 20. Participants then were instructed to perform supinated bicep curls with either the large or small dumbbell with either their left or right hand. This procedure, including the rate of lifting, was largely the same as in Experiment 1. However, rather than lifting until they could no longer continue, participants were told to stop exercising by the experimenter after they had completed 30 bicep curls. Additionally, participants were also instructed to watch themselves in the mirror while they were doing the task. Participants then rated their post-exercise exertion on the Borg scale. Participants then received a 5 minute rest, after which the procedure was repeated for the other dumbbell, this time lifting with the other arm. Finally, in order to confirm that they experienced the SWI, participants were asked to make a binary choice about which of the dumbbells felt heavier to them. Lifting order and hand used to lift each weight was counterbalanced between-subject. All subjects completed the 30 bicep curls, except for three participants who were unable to complete the required repetitions for one of their sets (the large dumbbell in all cases).

Results

Prior to lifting the objects, all participants expected the larger dumbbell to be heavier than the smaller dumbbell. After the completion of the experiment, 17 out of the 18 participants felt that the smaller dumbbell was heavier than the larger dumbbell, with the participant who did not experience the SWI judging the dumbbells as having the same weight.

To account for within-subject differences in pre-exercise fatigue, participants' exertion after exercising with each dumbbell was normalized to each individual's rating of perceived exertion before they started lifting that particular weight. In other words, participant’s ratings reflected how much more tired they were than when they started the experiment. This yielded an unbiased measure of how subjectively difficult an individual felt the lifting exercise was with each weight. These results mirrored those of Experiment 1 - there was no difference in participants' increases of exertion after lifting the heavy-feeling small dumbbell or the light-feeling large dumbbell (t(17) = 0.12, p=.91; Figure 4). Similarly, when analysis was performed on the raw (i.e., non-normalized) Borg ratings, there was no hint of a statistical difference (13.3 ± 1.8 vs. 13.4 ± 3.1; t(17) = 0.28, p=.79). It is worth noting that the average values are both well below the maximum Borg rating of 20, effectively ruling out ceiling effects as an explanation for the lack of effort differences.

INSERT FIGURE 4 HERE

As in Experiment 1, we analysed various parameters of the dumbbells' kinematics during the lifting task (Table 2). Kinematic data from one participant was lost due to recording errors, leaving a sample of 17 for this portion of the analysis. As with Experiment 1, no difference was observed between the large and small dumbbells in total time spent lifting the weights (t(16) = 0.43, p=.68). Similarly, we again demonstrated that participants lifted the small weight at a higher average velocity (t(16) = 3.33, p<.005) and with higher peak accelerations (t(16) = 4.51, p<.001) than the large weight. In this experiment we also noted that participants moved the small weight significantly further than the large weight (t(16) = 3.02, p<.01. However, none of the kinematic measures correlated with the Borg values given by participants for the small or large weights (all r's < 0.18).

INSERT TABLE 2 HERE

Here, participants rated 30 bicep curls with the heavy-feeling small dumbbell as requiring just as much exertion as 30 bicep curls with the light-feeling large dumbbell. Both sets of lifts were lifted one after another in the same session, allowing the participants to have a reasonably direct comparison of the weights. Yet, despite all but one reporting that they experienced the SWI, there was no indication that the illusion had any effect on their exercise.

General discussion

In this manuscript, we describe a pair of simple experiments to test whether a powerful illusion of heaviness could influence individuals' ability and willingness to continue with prolonged strenuous weightlifting exercises. Participants performed continuous bicep-curls in separate sessions with larger and smaller dumbbells which had been adjusted to have the same mass as one another. Participants expected the large dumbbell to be heavier than the small dumbbell, and consequently felt that it weighed less than the small weight (i.e., they experienced the SWI). In Experiment 1, when invited to lift the dumbbells as many times as they could manage, participants lifted the large and small weights the same number of times. In Experiment 2, when asked to lift the weights a fixed amount and rate their exertion, participants rated 30 bicep curls with the heavy-feeling small dumbbell as requiring just as much effort as 30 bicep curls with the light-feeling large dumbbell. Thus, in both experiments, the perceptual SWI had no effect on individuals' exercise behaviour.

This finding is in line with the recent series of object lifting experiments examining individuals' fingertip force application during repeated lifts of SWI-inducing cubes (Flanagan & Beltzner, 2000; Grandy & Westwood, 2006). In these studies, lifters initially apply forces in line with their expectations of heaviness – lifting the large cube with more force than the small cube. After several repetitions, however, participants lift the cubes with identical forces, reflecting the cubes' identical weights. Thus, in the context of the classic SWI, participants never lift the heavy-feeling small cube with more force than the light-feeling large cube. In our tasks we find broadly the same pattern of results with different, and arguably more ecologically-relevant, metrics of effort.

Although we observed no difference in how the weights' sizes affected exercise outcomes (nor, indeed, the amount of time spent exercising with either dumbbell), there were subtle differences in the kinematics of the weightlifting exercises. Participants lifted the small weight with a higher average velocity and higher peak accelerations than the large weight in both experiments. Given that these dynamical differences occurred over approximately the same duration, participants presumably lifted the small dumbbell slightly faster in the up/down phase of the curl, and then rested for slightly longer between each repetition. From the current dataset, it is difficult to assess the degree to which these dynamical differences are a function of the perceptual SWI. It is conceivable that participants moved the smaller dumbbell at a higher velocity because they felt it was heavier and thus determined that it required more force to move. However, this interpretation is difficult to reconcile with the majority of SWI research, which demonstrates any illusion effects on action would result in the light-feeling but heavy-looking large dumbbell being moved more rapidly (e.g., Buckingham & Goodale, 2010b; Gordon, Forssberg, Johansson, & Westling, 1991; Plaisier & Smeets, 2012). It is, of course, equally plausible that these speed and acceleration differences may merely be an unforeseen consequence of wielding differently-sized dumbbells at a fixed rate. Regardless of the mechanism, as these dynamical differences did not affect participants' ability to exercise with the dumbbells, we can dismiss them as an important factor regarding illusions and exercise.

The current findings – that the SWI does not influence an individual's ability to perform weightlifting exercises, appear to be at odds with the recent findings of Witt and colleagues (Witt et al., 2012). In their experiment, they demonstrated that individuals holed more putts when they perceived the hole as larger – a manipulation achieved with a visual illusion. Their conclusions that perception could affect performance by altering the individuals' confidence in their ability to perform the task motivated the current work. It is thus worth considering why we found no evidence that a powerful perceptual illusion of weight had any impact on individuals' weightlifting abilities. It is plausible that manipulating perception can only affect performance outcomes related to skill, rather than effort. The tasks examined by Witt and colleagues (putting a golf ball) would seem to require more skill and less exertion, whereas our task (lifting weights) put more emphasis on physical effort than skill. Some tacit support for this proposition comes from a recent follow study examining the Ebbinghaus putting task (Wood, Vine, & Wilson, 2013), where the researchers demonstrated that the individuals fixated the perceptually larger hole for longer durations (i.e., better quiet eye performance), which may have mediated the subsequent performance improvement. Another possible explanation for the discrepancies between the current work and previous findings might be related to the lack of a control condition in the Witt et al. (2012) study. As their study lacked a condition where participants putted at non-illusory, normal, holes (i.e., without the flanking circles), it is difficult to determine whether the illusory increase in the hole size actually improved performance. It is possible that the golfers were just more distracted by the large flanking circles than the small flanking circles, which would have given yielded data equivalent to the better performance seen when the hole appeared larger than when it appeared smaller (for analogous discussions, see Haffenden, Schiff, & Goodale, 2001). Indeed participants in their study performed poorly in the putting study, holing fewer than 20% of their putts in both conditions where the illusory perceptual effect was observed. By contrast, our study does contain a control condition where lifters interact with a 'normal' dumbbell, as the smaller of the two weights was unaltered. Furthermore, neither our alterations of the dumbbells, nor our metric of motor performance, are subject to criticism about distractors.

Our findings indicate that an individual's sense of weight and their sense of effort during weightlifting are largely isolated from one another (Burgess & Jones, 1997). One intriguing possible utility for weight illusions, however, relates not to an individual's ability to continue exercising, but their motivation to begin exercising in the first place. Such a programme of experimental work could examine size variations in exercise environments where daily routines of self-motivated physical activity is the goal (e.g., physiotherapy), rather than more extreme or competitive forms of exercise. Furthermore, it remains to be seen how these illusory effects interact with weightlifting experience – it is possible that any effects may be limited to those who are particularly experienced at pushing themselves harder to complete as many reps as possible. As it stands, however, these are all interesting empirical questions relating to motivation, skill, effort, and perception, which shall be addressed in future work.

In conclusion, we have demonstrated that an individual's perception of how heavy an object feels appears to have no effect on their ability to continue lifting it, and that lifters will tire just as rapidly as when lifting heavy-feeling objects as they do when lifting light-feeling objects. This finding parallels lab-based work showing that individuals' lifting actions maintain a degree of independence from their perceptions of heaviness (Buckingham et al., 2009; Flanagan & Beltzner, 2000; Grandy & Westwood, 2006).

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References

Borg, G. (1970). Perceived exertion as an indicator of somatic stress. *Scandinavian journal of rehabilitation medicine*, *2*(2), 92–98.

Buckingham, G., Cant, J. S., & Goodale, M. A. (2009). Living in A Material World: How Visual Cues to Material Properties Affect the Way That We Lift Objects and Perceive Their Weight. *Journal of Neurophysiology*, *102*(6), 3111–3118. doi:10.1152/jn.00515.2009

Buckingham, G., & Goodale, M. A. (2010a). Lifting without Seeing: The Role of Vision in Perceiving and Acting upon the Size Weight Illusion. *PLoS ONE*, *5*(3), e9709. doi:10.1371/journal.pone.0009709

Buckingham, G., & Goodale, M. A. (2010b). The influence of competing perceptual and motor priors in the context of the size–weight illusion. *Experimental Brain Research*, *205*(2), 283–288. doi:10.1007/s00221-010-2353-9

Burgess, P. R., & Jones, L. F. (1997). Perceptions of effort and heaviness during fatigue and during the size-weight illusion. *Somatosensory & motor research*, *14*(3), 189–202.

Carey, D. P. (2001). Do action systems resist visual illusions? *Trends in Cognitive Sciences*, *5*(3), 109–113. doi:10.1016/S1364-6613(00)01592-8

Charpentier, A. (1891). Analyse expérimentale quelques éléments de la sensation de poids. *Archives de Physiologie Normales et Pathologiques*, *3*, 122–135.

Cousineau, D. (2005). Confidence intervals in within–subject designs: A simpler solution to Loftus and Masson’s method. Tutorials in Quantitative Methods for Psychology, 1, 42–46.

Ellis, R. R., & Lederman, S. J. (1999). The material-weight illusion revisited. *Perception & Psychophysics*, *61*(8), 1564–1576.

Flanagan, J. R., & Beltzner, M. A. (2000). Independence of perceptual and sensorimotor predictions in the size-weight illusion. *Nature Neuroscience*, *3*(7), 737–741. doi:10.1038/76701

Flanagan, J. R., Bittner, J. P., & Johansson, R. S. (2008). Experience can change distinct size-weight priors engaged in lifting objects and judging their weights. *Current Biology*, *18*(22), 1742–1747. doi:10.1016/j.cub.2008.09.042

Flournoy, T. (1894). De l'influence de la perception visuelle des corps sur leur poids apparent. *Annee Psychologique*, *1*, 198–200.

Gordon, A. M., Forssberg, H., Johansson, R. S., & Westling, G. (1991). Visual size cues in the programming of manipulative forces during precision grip. *Experimental Brain Research*, *83*(3), 477–482.

Grandy, M. S., & Westwood, D. A. (2006). Opposite Perceptual and Sensorimotor Responses to a Size-Weight Illusion. *Journal of Neurophysiology*, *95*(6), 3887–3892. doi:10.1152/jn.00851.2005

Haffenden, A. M., Schiff, K. C., & Goodale, M. A. (2001). The dissociation between perception and action in the Ebbinghaus illusion: nonillusory effects of pictorial cues on grasp. *Current biology: CB*, *11*(3), 177–181.

Mon-Williams, M., & Murray, A. H. (2000). The size of the visual size cue used for programming manipulative forces during precision grip. *Experimental Brain Research*, *135*(3), 405–410.

Plaisier, M. A., & Smeets, J. B. J. (2012). Mass Is All That Matters in the Size–Weight Illusion. *PLoS ONE*, *7*(8), e42518. doi:10.1371/journal.pone.0042518

Ross, H. E. (1969). When is a weight not illusory? *The Quarterly Journal of Experimental Psychology*, *21*(4), 346–355. doi:10.1080/14640746908400230

Seashore, C. E. (1899). Some psychological statistics II. The material weight illusion. *U Iowa Stud Psychol*, (2), 36–46.

Witt, J. K., Linkenauger, S. A., & Proffitt, D. R. (2012). Get me out of this slump! Visual illusions improve sports performance. *Psychological science*, *23*(4), 397–399. doi:10.1177/0956797611428810

Wood, G., Vine, S. J., & Wilson, M. R. (2013). The impact of visual illusions on perception, action planning, and motor performance. *Attention, Perception, & Psychophysics*, *75*(5), 830–834. doi:10.3758/s13414-013-0489-y

Woodman, T., & Hardy, L. (2003). The relative impact of cognitive anxiety and self-confidence upon sport performance: a meta-analysis. *Journal of sports sciences*, *21*(6), 443–457. doi:10.1080/0264041031000101809

Figure captions

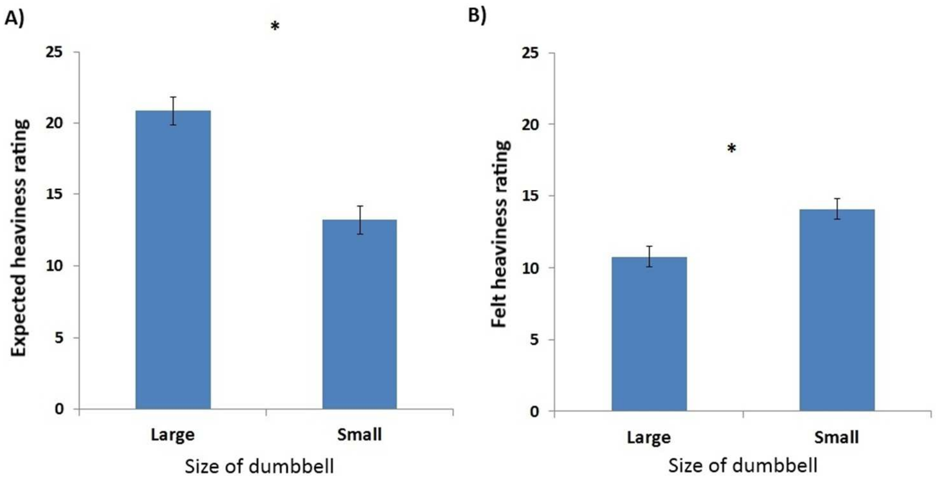
Figure 1. (A) The identically-weighted large and small dumbbells lifted by participants, (B) the supinated-type bicep curl participants performed with their right hand (demonstrated here with the large dumbbell), and (C) The hammer-type bicep curl participants performed with their left hand (demonstrated here with the small dumbbell).

Figure 2. (A) Participants' reports of how heavy they expected each dumbbell to be before lifting in the metric of their choice (lbs. or kgs.) at the start of each session and (B) participants' reports of how heavy each dumbbell subjectively felt at the end of each session (again, in lbs. or kgs.). Error bars represent the standard error of the means which have been adjusted to remove between-subject variance (Cousineau, 2005). *p<.05.

Figure 3. (A) The number of hammer-type bicep curls participants were able to perform with their left hand and (B) the number of supinated-type bicep curls they were able to perform with their right hand. Error bars represent the standard error of the means which have been adjusted to remove between-subject variance (Cousineau, 2005).

Figure 4. The percentage increase in effort reported after exercising compared to the effort reported before exercising. Error bars represent the standard error of the means which have been adjusted to remove between-subject variance (Cousineau, 2005).

Figure 1. (A) The identically-weighted large and small dumbbells lifted by participants, (B) the supinated-type bicep curl participants performed with their right hand (demonstrated here with the large dumbbell), and (C) The hammer-type bicep curl participants performed with their left hand (demonstrated here with the small dumbbell).
672x166mm (96 x 96 DPI)



(A) Participants' reports of how heavy they expected each dumbbell to be before lifting in the metric of their choice (lbs. or kgs.) at the start of each session and (B) participants' reports of how heavy each dumbbell subjectively felt at the end of each session (again, in lbs. or kgs.). Error bars represent the standard error of the means which have been adjusted to remove between-subject variance (Cousineau, 2005). *p<.05.
284x141mm (96 x 96 DPI)

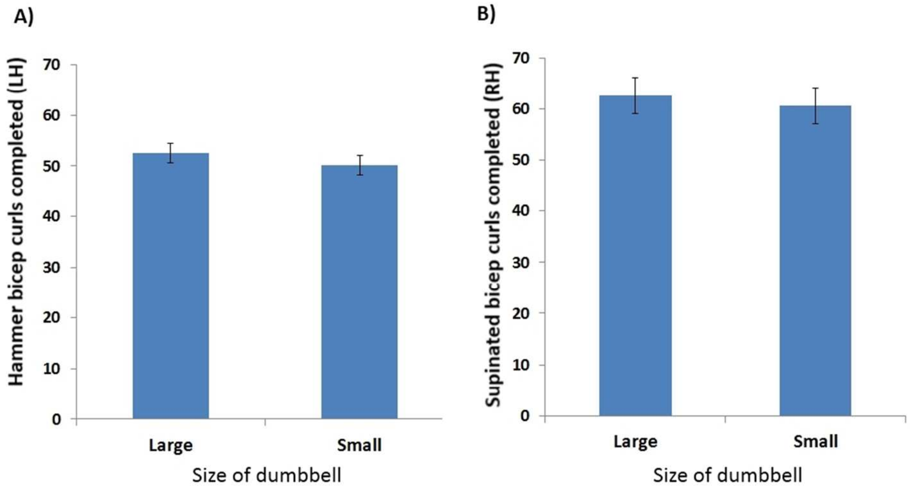


Figure 3. (A) The number of hammer-type bicep curls participants were able to perform with their left hand and (B) the number of supinated-type bicep curls they were able to perform with their right hand. Error bars represent the standard error of the means which have been adjusted to remove between-subject variance (Cousineau, 2005).
284x141mm (96 x 96 DPI)

Table 1.

Kinematic measures describing the dynamics of the bicep curls in Experiment 1 (collapsed across hand)

	Large dumbbell (SD)	Small dumbbell (SD)
Total time (s)	106.1 (60.4)	107.9 (80.5)
Total distance travelled (m)	66.8 (40.4)	75.4 (56.8)
Average velocity (mm/s)	616.1 (99.1)	699.4 (110.9) *
Average peak acceleration (mm/s^2)	3958.8 (587.6)	4448.6 (724.0) *

Note. *p<.05

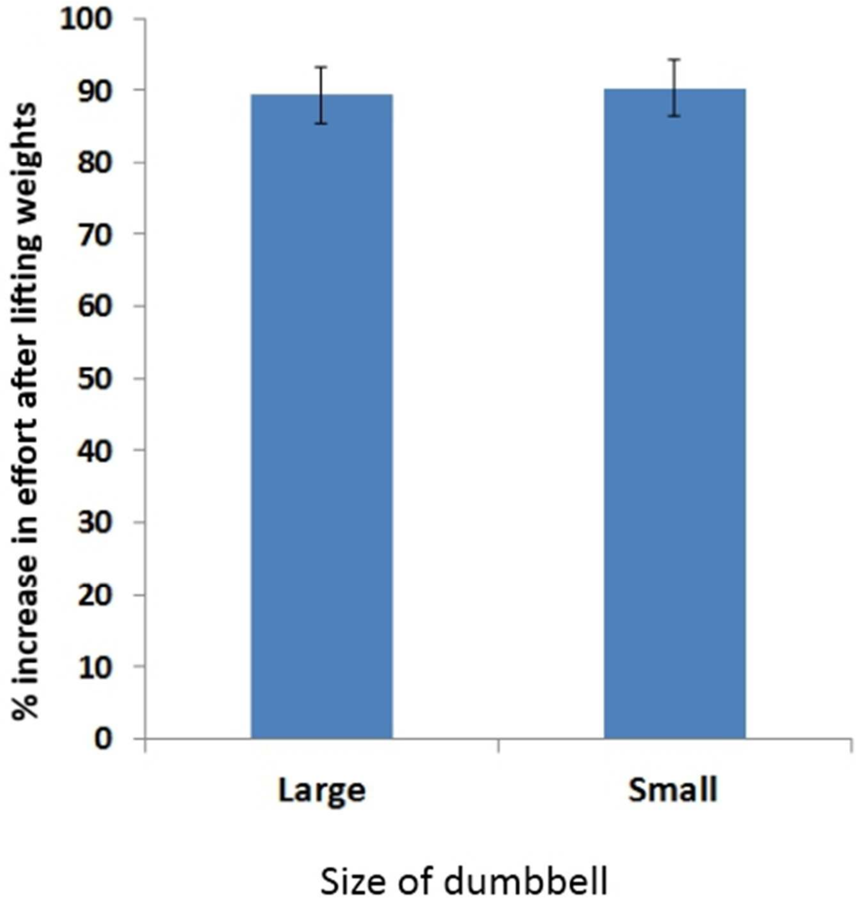


Figure 4. The percentage increase in effort reported after exercising compared to the effort reported before exercising. Error bars represent the standard error of the means which have been adjusted to remove between-subject variance (Cousineau, 2005).
147x140mm (96 x 96 DPI)

Table 2

Kinematic measures describing the dynamics of the bicep curls in Experiment 2 (collapsed across hand)

	Large dumbbell (SD)	Small dumbbell (SD)
Total time (s)	62.2 (7.0)	63.1 (4.6)
Total distance travelled (m)	35.2 (7.66)	38.7 (6.8) *
Average velocity (mm/s)	566.4 (102.6)	615.6 (113.5) *
Average peak acceleration (mm/s^2)	3503.3 (637.8)	4028.6 (842.4) *

Note. *p<.05