The Brightness-Weight Correspondence in Adults and Infants

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Declaration

I declare that this thesis is my own work and that it has not been submitted in substantially the same form for the award of a higher degree elsewhere.

Abstract

Adult participants report expecting darker objects to be heavier in weight and brighter objects to be lighter in weight (Payne, 1958; Plack & Shick, 1976; Walker, Francis & Walker, 2010; Wright 1962). Although there is evidence that young infants appreciate crossmodal correspondences between pitch and height, and sharpness, there is no evidence to date that infants appreciate the correspondence between brightness and weight (Walker, Bremner, Mason, Spring, Mattock, Slater, & Johnson, 2010; Walker, Bremner, Lunghi, Dolscheid, Barba, & Simion, 2018). The objective of the current thesis was to understand more about the correspondence between brightness and weight by examining the situations in which it is revealed and the age at which it emerges. In doing so, the intention was to uncover more information about the nature of the correspondence and its potential origins. Using verbal reports, Experiments 1 and 3 provided further evidence of a brightness-weight and material-weight correspondence in adult participants. By examining whether the correspondence is acted upon spontaneously, Experiments 2 and 4 revealed early evidence that adults selectively prepare for objects based on brightness and material. The potential reasons for the selective preparation are discussed in detail. In Experiments 5 and 6, infants' appreciation of the brightness-weight and material-weight correspondences were explored. Whilst the studies revealed no evidence for appreciation of the brightness-weight correspondence, Experiment 6 provided substantial evidence suggesting that infants selectively prepare for objects based on material. The implications of these findings, and the potential inferences that can be made about the nature and origins of the brightness-weight correspondence are discussed.

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List of Figures

List of Tables

Table of Contents

CHAPTER 1

Literature Review

1.1 Crossmodal Correspondences

Crossmodal correspondences are cases in which a sensory feature in one modality is matched with a sensory feature in another sensory modality. Crossmodal correspondences are documented across the majority of simple stimulus features (Parise, 2015). To name just a few, correspondences are found between: pitch and elevation, whereby high-pitch is associated with high visual elevation (Ben-Artzi & Marks, 1995; Chiou & Rich, 2012; Evans & Treisman, 2010; Melara & O'Brien, 1987; Patching & Quinlan, 2002); pitch and brightness, whereby high-pitch is associated with brighter stimuli (Collier & Hubbard, 2004; Marks, 1974; Marks, 1987; Wicker, 1968); auditory pitch and visual size, whereby high-pitch is associated with smaller stimuli (Evans & Treisman, 2010; Gallace & Spence, 2006), and loudness and brightness, whereby louder stimuli are associated with brighter stimuli (Marks, 1987; Root & Ross, 1965).

Crossmodal correspondences can be conceptualised along the same scale as more obvious intersensory correspondences. These are made between two or more sensory channels which provide information on the same physical property, meaning that there are redundant sensory cues. An example of such a correspondence is the one between auditory position and visual position (auditory-visual spatial co-location). By receiving auditory information from a stimulus, it is possible to know what to expect from the visual sensory modality (Parise & Spence, 2013).

Whilst crossmodal correspondences allow us to make predictions from one sensory modality to another, they differ in that modalities provide complementary information, meaning that associations between sensory cues are not entirely redundant or unrelated. For example, information regarding pitch and size are not redundant; pitch cannot be used to deduce the exact size of an object. However, matching of pitch and size by mapping high-pitch to a smaller object and low-pitch to a larger object has been demonstrated (Evans & Treisman, 2010; Gallace & Spence, 2006).

Both intersensory correspondences and crossmodal correspondences involve matching across sensory modalities, the difference between the two is in terms of the strength of the coupling of the modalities. As the difference is due to strength, both can be thought of along a spectrum. Whereas intersensory correspondences provide redundant information, crossmodal correspondences are thought to be formed from sensory cues which are not entirely redundant. This difference is explained by Ernst (2005) who suggests that if the mapping is known for sure, signals can be fused; this is termed here as intersensory correspondences. Whereas, if the mapping is unknown, signals are kept separate, this is defined here as crossmodal correspondences.

As shown in the examples above, most crossmodal correspondences are found to match to the same poles across participants. Spence (2011) suggests that the matching of basic stimulus attributes in the same direction should be classified as 'congruent matches.' These matches are those likely to be bound together across the majority of the population. For example, high-pitch is consistently associated with small stimuli and low-pitch with larger stimuli (Evans & Treisman, 2010; Gallace & Spence, 2006). 'Incongruent' refers to stimulus attributes that most people would consider not to match, for example low-pitch corresponding with high visual-elevation. Congruent and incongruent trials are often utilised in experimental tests to examine whether participants judge one as more likely or expected than another.

Although we suggest that correspondences have been found across the majority of modalities, Parise (2015) rightly suggests caution that significant results are published more often than null results. Consequently, this means there is an inevitable bias for demonstration of correspondences. There are a few examples of published work showing no evidence of a correspondence across dimensions, for example pitch and visual hue (Bernstein, Eason & Schurman, 1971), and pitch and visual contrast (Evans & Treisman, 2010). Later in the thesis, the specific methods used in studies of crossmodal correspondence and the results found will be discussed in more substantial detail.

1.1.1 Sound Symbolism Evidence

Early evidence of crossmodal correspondences comes from the research area of sound symbolism. Early sound symbolism research found that when asked which of two shapes was the 'baluba' and which was the 'takete,' participants tended to match the same words to the same shapes. The more rounded shape was matched to the word 'baluba,' and the jagged shape was matched to the word 'takete' (Köhler, 1929). There have been many variations of this study more recently, with research consistently finding that certain sounds are matched to certain shapes. Köhler later changed the 'baluba' label to 'maluma,' and again this word was matched to the more rounded shape (Köhler, 1947). Similarly, 95% of people match the word 'kiki' to a pointed shape and 'bouba' to a rounded shape (Ramachandran & Hubbard, 2001). There is also evidence that children as young as 2.5 years, make the same sound-shape matches that adults do (Maurer, Pathman, & Mondloch, 2006). One explanation for these findings is that cortical connections amongst adjoining brain areas unite the physical shape of the stimuli to the shape of the speaker's lips when producing the word, their tongue movements, and the phonemic inflection of the word. Furthermore, the evidence shows that nonsense words with rounded vowels, such as the [u] in bouba, match with rounded shapes and words with unrounded vowels, such as the [i] in kiki, match with more pointed shapes (Maurer et al., 2006; Ramachandran & Hubbard, 2001).

Findings of sound symbolism contrasts with what Saussure (1916, 2001) describes as 'the first principle of linguistics.' He argues that language is arbitrary, suggesting that there is no intrinsic connection between the signal (the sound pattern of a word) and the signified meaning (the concept which the sounds refer to). Evidence of a non-arbitrary link between how a word sounds and what it describes (sound symbolism), casts doubt on an entirely arbitrary theory of language.

1.1.2 Synaesthesia

Ramachandran and Hubbard (2001) argue that it is the sensory cortical connections described previously which sometimes lead to the rare phenomenon of synaesthesia. Individuals with synaesthesia experience 'a mixing of the senses' (Baron-Cohen, Burt, Smith-Laittan, Harrison & Bolton, 1996). In synaesthetic experience, stimulation of one sensory modality (the inducer) leads to automatic perceptions in either the same or another sensory modality (the induced). Associating numbers with colours and shapes with taste are just two examples of reported synaesthetic experience (Cytowic & Wood, 1982; Ramachandran & Hubbard, 2001). When colour-word hearing synaesthetes (sounds/letters evoke colours) complete verbal-only tasks, there is evidence of neural activity in the auditory cortex and the primary and extrastriate visual cortex (Aleman, Rutten, Sitskoorn, Dautzenberg, & Ramsey, 2001; Nunn et al., 2002). This demonstrates how verbal stimuli can evoke activity in both auditory and visual areas in colour-word hearing synaesthetes.

Synaesthetes agree on some of these sensory correspondences (Mondloch & Maurer, 2004), however synaesthetes also make correspondences which are unique to themselves. One synaesthete might see the number two as green, whilst another sees it as purple. A key feature of synaesthetic experience is that the correspondences remain consistent over time; for example, if an individual hears pain as high-pitched, it is consistently heard as high-pitched.

Though synaesthesia is rare, with estimates of prevalence ranging between 0.05%-2% of the population (Baron-Cohen et al., 1996; Rothen & Meier, 2010), appreciation and identification of crossmodal correspondences across sensory modalities as described previously is prevalent in the majority of the population.

1.1.3 Synaesthesia and Crossmodal Correspondences

There is much debate about whether to think of synaesthesia and crossmodal correspondences in adults as degrees of the same phenomena. Whilst both synaesthesia and crossmodal correspondences can broadly be described as associations across sensory modalities, there are also a range of differences between the experiences.

Martino and Marks (2001) argue that synaesthesia should be broken down into two types: strong synaesthesia and weak synaesthesia. They suggest that 'strong synaesthesia is characterised by a vivid image in one sensory modality in response to stimulation in another one.' On the other hand, 'weak synaesthesia is characterised by cross-sensory correspondences expressed through language, perceptual similarity, and perceptual interactions during information processing.' Their paper considers how strong and weak synaesthesia are both similar and different. In terms of the similarities between the two, they suggest that in both strong and weak synaesthesia, easily remembered and systematic crossmodal correspondences are present. They propose that the presence of crossmodal correspondences in both might suggest that the two have underlying neural processes in common. They also suggest that there is a case for the role of learning in both experiences.

Despite there being a few similarities, it seems that the number of differences between the two experiences is much greater. They suggest that strong synaesthesia is much less common than weak synaesthesia and is also a more idiosyncratic experience. They also identify that there are differences within the experience itself; whereas in strong synaesthesia, one stimulus is perceived and the other is experienced, in weak synaesthesia, both stimulus are perceived. Importantly, strong synaesthesia is unidirectional in processing as one stimulus might evoke another experience without being the same vice versa; whereas weak synaesthesia is generally thought to involve bidirectional processing.

Considering the similarities and differences between what Martino and Marks (2001) define as strong and weak synaesthesia, research has considered whether strong synaesthesia and crossmodal correspondences should both be thought of as types of synaesthesia which lie along a continuum, or whether they should be thought of as independent phenomenon. By labelling the two types strong and weak synaesthesia, Martino and Marks (2001) appear to favour a view that despite their differences, they draw on similar mechanisms. Supporting the view of a continuum are findings which show that crossmodal matches made by non-synaesthetes are often similar to those made by synaesthetes, for example the mapping of pitch and lightness (Ward, Huckstep, & Tsakanikos, 2006).

Others suggest that conceptualizing correspondences as a weak form of synaesthesia is not appropriate and that different mechanisms are likely to be responsible. In the case of synaesthesia, experience in one modality leads directly to an additional perception, either in the same or different modality. This has been regarded as a core feature of synaesthesia (Spence, 2011), and is known as the concurrent stimulus. The connection between the senses is therefore considered a significant aspect of perception (Ward & Mattingley, 2006). In contrast, crossmodal correspondences do not involve a concurrent stimulus and are often thought of as the appreciation of the links across sensory modalities, rather than the literal experience. Some therefore suggest that terms which rely less on neural causes are more appropriate than 'weak synaesthesia.' 'Crossmodal associations' and 'crossmodal correspondences' have been suggested as alternatives terms (Gilbert, Martin & Kemp, 1996; Martino & Marks, 2001).

Considering the numerous differences between synaesthesia and crossmodal correspondences, this thesis takes the view that they should not be thought of as degrees of a similar phenomenon. Though the experiences have 'superficial' similarities (Deroy & Spence, 2013) in that both reflect associations across sensory modalities; the absence of the core feature of concurrent stimulus, alongside the multitude of differences in terms of processing and suggested underlying mechanisms, leads us to conclude that conceptualisation of crossmodal correspondences as a weak form of synaesthesia should be avoided. By taking this view, it is suggested that correspondences should be studied as a separate phenomenon from synaesthesia.

Alongside this question, there has been much debate over whether the evidence of crossmodal correspondences in infants should be taken as evidence of an innate form of synaesthesia in infants. The thesis will later discuss 'the neonatal synaesthesia hypothesis' which proposes that infants are born with a form of synaesthesia which dissipates over the course of development. Researching the neonatal synaesthesia hypothesis and distinguishing which correspondences are likely to be innate, helps to provide more information on the mechanisms underlying correspondences. This enables the wider field to understand more about the similarities and differences between synaesthesia and crossmodal correspondences.

1.2 Kinds and Origins of Crossmodal Correspondences

As yet, there is no consensus on the origins of crossmodal correspondences. Spence (2011) suggests that there are various kinds of crossmodal correspondences: structural, statistical, semantic, and emotionally valenced correspondences. He suggests that they are likely to have different developmental trajectories, origins, and explanations.

As with many systems, Spence (2011) acknowledges there are exceptions which do not clearly fall into any category, pointing to pitch-brightness as an example. He also acknowledges the categories are not mutually exclusive as some correspondences appear to fall into two categories. For example, the correspondence between pitch and height is present in both language and the environment (Dolscheid, Shayan, Majid & Casasanto, 2013; Parise, Knorre & Ernst, 2014). In the following section, examples will be used to demonstrate the different types of correspondence and the absence of category exclusivity.

1.2.1 Statistical

Statistical correspondences refer to those which reflect natural correlations within the environment. For example, the correspondence between size and pitch is suggested to reflect the natural co-occurrence between small (large) stimuli and high (low) pitch sounds within everyday experience. It is thought that long-term exposure to these sensory co-occurrences in the environment could facilitate the coupling of dimensions, leading to the learning of correspondences (Haryu and Kajikawa, 2012). It is suggested that statistical correspondences are most likely to be universal due to the fact that object properties are determined by physics and not by culture (Spence, 2011).

Explaining where the natural correlation between size and pitch lies, is the suggestion that when smaller objects are struck they often produce higher pitch sounds than larger objects. For example, larger instruments such as the double bass produce lower pitch sounds than smaller instruments, such as the flute (Coward & Stevens, 2004; Rogowska, 2015; Smith, Patterson, Turner, Kawahara & Irino, 2004). Similarly, the longer bars of a xylophone produce lower pitch sounds than the shorter bars which produce higher pitch sounds. It is not a simply a coincidence that smaller objects tend to produce higher-pitch sounds; in the case of the xylophone, the lower-pitch produced by tapping the longer bars is the result of the slower vibrations (lower frequency) produced, and the higher-pitch sound from the shorter bars is the result of the faster vibrations (higher frequency).

The association between visual elevation and pitch is also partially attributed to statistical observations. Analysis of 50,000 sound recordings revealed a significant mapping between sound frequency and their average elevation in space (Parise, Knorre, and Ernst, 2014). Whilst the exact cause of this correlation in natural scenes is unknown, there has been speculation. It is suggested that the ground might absorb the higher frequency sounds when sources are lower down, or alternatively, when higher in space, more energy could be generated in high frequencies. Additionally, there is an intuitive correlation between the height of an animal's habitat and the sound frequency which they produce, although not consistently. Birds which are notorious for producing high-pitch tweeting sounds are found high in vertical elevation, whereas animals more often seen lower down such as dogs do not tend to produce such high-pitch noises.

Again, though not consistently, the association between high-pitch sounds and sharp shapes can be observed in the environment. It is suggested that sharper objects tend to be made of harder materials that produce higher-pitch sounds when struck (Walker et al., 2010). For some, the lack of consistency casts doubt that the co-occurrence could be responsible for the emerge of the correspondence. Evidence shows however that even short periods of repeated exposure can result in crossmodal activation, with absolute consistency not required. Results have shown that simultaneous exposure to stimuli in different sensory modalities can lead to crossmodal activation when later presented with just one of the components. When repeatedly presented with a sound alongside visual motion, illusory motion is later witnessed when presented with only the sound. The presence of the sound resulted in participants perceiving stationary stimuli to be moving in the direction previously observed, despite being in a fixed location (Teramoto, Hidaka & Sugita, 2010). Similarly, participants who saw an auditory-visual display, showed increased cerebral blood flow to the primary visual cortex when presented with only auditory stimuli. Those who did not experience the auditory-visual stimuli, showed only modality specific activation patterns (Zangenehpour & Zatorre, 2010). These studies demonstrate how even short periods of exposure to simultaneous sensory features can result in crossmodal activation. This supports the explanation that naturally occurring matching of stimulus in the environment could result in the formation of crossmodal correspondences, even if not observed frequently or consistently.

1.2.2 Semantic

Semantic correspondences are those thought to result when there is a verbal overlap in terms used to describe the matched stimuli. A commonly cited example of a semantic correspondence is that between pitch and vertical elevation, whereby high-pitch is commonly associated with high vertical elevation (Evans & Treisman, 2010; Walker et al., 2010). It is important to note that as discussed previously, pitch and vertical elevation is also suggested to have potential origins in statistical observations within the natural environment.

The sematic mediation for this correspondence is evidenced in many western languages for which the word ‘high’ can be used to refer to pitch and height (Martino & Marks, 1999). It is suggested that semantic correspondences are by nature almost exclusively determined by context, meaning that if they are truly semantic they are less likely to be universal than statistical correspondences, as they make use of language and culture (Spence, 2011). To examine the role of language in the pitch-visual elevation correspondence, Dolscheid, Shayan, Majid, and Casasanto (2013) conducted a cross-linguistic study of speakers of Dutch (pitch referred to in terms of height) and speakers of Farsi (pitch referred to in terms of thickness). Participants heard tones that varied in pitch and watched displays in which the height or thickness of a line was manipulated. Participants were then asked to sing back the note that they had heard. Results showed that pitch perception was modulated by height in Dutch speakers as they incorporated incidental height information into reproductions of pitch. In Farsi speakers, pitch was modulated by thickness as incidental thickness information was used. Taken alone, the finding that responses on a pitch task were modulated by language-relevant visual stimuli, suggests that language meaning could be responsible for the correspondence between pitch and visual elevation.

Despite this evidence, there is also a body of evidence against a semantic basis for crossmodal correspondences, with research again focussing on the correspondence between pitch and vertical elevation. Firstly, research has shown that the evidence for mediation of the pitch-height correspondence by neural processes involved in semantics is weak (McCormick, Lacey, Stilla, Nygaard, & Sathian, 2018). Secondly, findings from infant participants and participants who speak languages that do not have a verbal overlap between pitch and height, casts doubt on a semantic explanation.

Research showed that members of a remote tribe in Cambodia, who do not use spatial terms to describe auditory pitch, also demonstrated evidence of the pitch-height correspondence (Parkinson, Köhler, Sievers, & Wheatley, 2012), suggesting that the correspondence can arise independently of language. This at first seems discordant with the Dolscheid et al. (2013) study in which Farsi speakers (pitch referred to in terms of thickness) did not incorporate height information into the pitch of the note which they sung back. It is proposed that it might be the differences in methodology which led to these dissimilar results. Whereas in the Dolscheid et al. (2013) study, participants were asked to produce a musical sound, in the Parkinson et al. (2012) study they were asked to report on the changes in sound. It is therefore possible that there is a difference in utilisation of the correspondence in more passive or active interactions with the stimuli.

Infancy work has also shown that language is unlikely to drive the emergence of the pitch-vertical height correspondence. Newborn infants and 4-month-old, pre-linguistic infants look preferentially to congruent pitch-height displays (Walker et al., 2010; Walker, Bremner, Lunghi, Dolscheid, Barba & Simion, 2018). This evidence suggests that language is unlikely to be responsible for the correspondence as infants at this age would have had limited exposure to language, with no production themselves. Additionally, pre-linguistic, Dutch infants were sensitive to multiple space-pitch mappings, with preferential looking shown to both congruent pitch-height and congruent pitch-thickness displays (Dolscheid, Hunnius, Casasanto & Majid, 2012). The demonstration of both language-relevant and language-irrelevant correspondences before the development of language (Dolscheid et al., 2012), alongside incorporation of only language-relevant correspondences after the development of language (Dolscheid et al., 2013), is suggested to demonstrate that language might gradually change pre-existing mappings.

Though these findings suggest it is unlikely that the correspondence is solely the result of language, one consideration is that caregivers might use infant directed speech which reveals their own biases. For example, using lower pitch to demonstrate falling motion and greater amplitude for greater size. These correlations might subsequently help infants to acquire the associations before the development of language (Nygaard, Herold, & Namy, 2009; Shintel, Nusbaum, & Okrent 2006). However, recent research casts doubt on the assertion that infant directed speech could be responsible for the acquisition of the correspondence, as newborn infants (with an average age of just 44 hours), were sensitive to the pitch-height correspondence (Walker et al., 2018). It is suggested that infants at this age have a very limited opportunity to have learnt the relevant information to inform the correspondence, either in the form of language or co-occurrences.

Evidence of the pitch-visual elevation correspondence in speakers of languages which do not support the correspondence, and in pre-linguistic infants, casts doubt on the assertion that language meaning is entirely responsible for the correspondence. It has been suggested that language might only mediate the pitch-height correspondence, whilst not being the sole cause (Dolscheid et al., 2012). A further interpretation is that the direction of causality might be from correspondence to language, in other words, linguistic associations between pitch and height might reflect ‘universally predisposed perceptual correspondences’ (Parkinson et al., 2012). This consideration poses an interesting, currently unresolved question regarding why some languages use spatial terms to describe auditory pitch and others do not.

1.2.3 Structural

Structural correspondences are classified as those which result from peculiarities in how we code sensory information in the neural system (Spence, 2011). Possible structural causes which might explain the existence of this type of correspondence include: intensity matching, a magnitude system, and cross-wiring.

Whilst most studies have failed to show evidence of crossmodal correspondences in animals (Ettlinger, 1961; Farago et al., 2010), Ludwig, Adachi and Matzuzawa (2011) found evidence of a pitch-brightness correspondence in chimps. They propose that evidence in chimps suggests that it is unlikely to be purely a human or linguistic phenomenon; it is also unlikely that they have learnt this correspondence, due to the absence of a natural co-occurrence. They propose that instead of being the result of language or statistical observation (Spence & Deroy, 2012), correspondences might be a natural by-product of the way that the brain processes sensory information.

Some correspondences have been attributed to the matching of dimensions in terms of intensity. A distinction is made between prothetic dimensions, which can be matched in terms of intensity or magnitude, and metathetic dimensions which cannot be matched by intensity or magnitude. So-called prothetic dimensions (Stevens, 1975) are quantitative and possess well-ordered psychophysics. This means that they are usually describable in terms of magnitude by the use of 'more-less' terms, such as 'more volume' or 'more size' (Stevens, 1975). Matching prothetic dimensions in terms of both intensity and a generalised magnitude system (Walsh, 2003) has been considered to result in a variety of crossmodal correspondences. For example, bigger objects are matched to louder sounds as they are both 'more' of each dimension, whereas smaller objects are matched to quieter sounds as they are both 'less' of each dimension. When participants are asked to make noise loudness the same as brightness, they are both adjusted to be proportional to the cube root of the energy in the stimulus, suggesting that the comparable intensities might be responsible for the correspondence between loudness and brightness (Stevens, 1955).

Further evidence shows that experience of increased stimulus intensity is represented by increased neural firing, regardless of which modality the stimulus is presented to (Glazewski & Barth, 2015). Overlapping neural substrates are also identified across various magnitude dimensions; with the premotor cortex, insula, inferior frontal gyrus and the intraparietal sulcus being key components of the system (Skagerlund, Karlsson & Traff, 2016). These findings support the idea of a generalised system for processing magnitude and intensity.

In contrast, metathetic dimensions vary in terms of a change in quality, rather than a change in quantity and are more often talked of as 'different from' (Stevens, 1975), making them difficult to describe in 'more-less' terms. Commonly used as an example of a metathetic dimension is pitch. High-pitch is not typically considered to be more or less than low-pitch as an additive process does not create changes in pitch; rather it is a change in the quality of the pitch. As high-pitch is not typically 'more' or 'less' than low-pitch, it is less easily matched to the continua of more and less for other dimensions. Though some argue that pitch does have a 'more-less' continuum. The pitch of a sound depends on the frequency of the vibrations and as high-pitch sounds have a greater frequency of vibrations than low-pitch sounds, (see Figure 1) high-pitch sounds could be considered to have 'more energy' or 'more sound waves'. This explanation assumes that people are generally knowledgeable of specific properties of pitch, such as an awareness that high-pitch is linked to a greater number of vibrations, an assumption which is suggested to be unlikely.

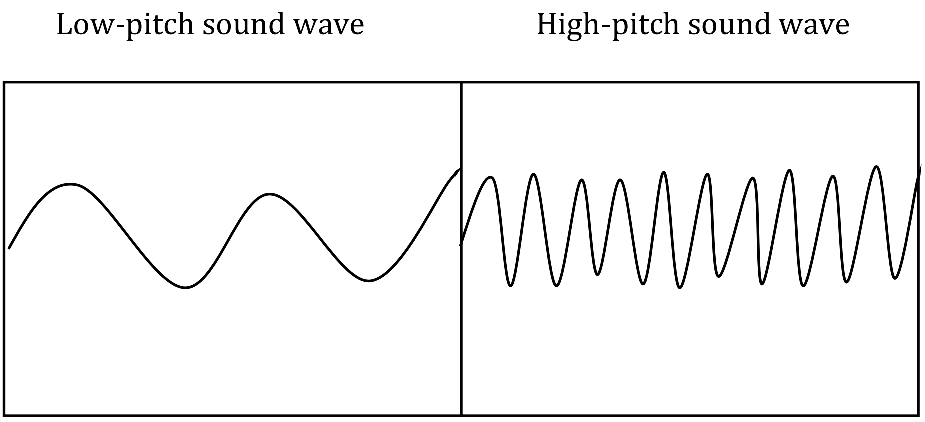


Figure 1. A visual demonstration of how low-pitch sounds contain less vibrations than high-pitch sounds.

Additionally, research shows that children learnt to order stimuli which varied in loudness more quickly than stimuli which varied in pitch (Riley, McKee, & Hadley, 1964); this demonstrates that loudness is more able to be quantitatively ordered than pitch. The difficulty in ordering pitch, compared to loudness, supports the view that the dimension of pitch is not commonly described in more-less terms and should therefore most appropriately be categorised as a metathetic dimension. The ease of ordering on the basis of loudness suggests that this dimension is more frequently described in more-less terms and should therefore be labelled as a prothetic dimension.

An alternative structural explanation is that crossmodal correspondences, as well as synaesthesia, might be the result of cross-wiring between nearby areas (Ramachandran & Hubbard, 2001; Spence, 2011). They point to evidence from colour-grapheme synaesthetes suggesting that is unlikely to be a coincidence that corresponding areas are situated right next to each other.

1.2.4 Emotional valence

The fourth type of correspondence is common emotional valence. Research has shown that preferred tastes will more often be matched to a round shape and less preferred tastes will be matched to more angular shapes (Velasco, Woods, Deroy & Spence, 2015), with a general preference for rounded shapes also demonstrated in product design (Westerman et al., 2012). Such correspondences have been suggested to be made on the property of hedonic value or stimulus pleasantness (Crisinel & Spence, 2010).

1.2.5 Remarks on kinds and origins of correspondences

What becomes clear from discussing the potential origins of crossmodal correspondences is that, as Spence (2011) advocates, it is unlikely that all crossmodal correspondences have the same origin. It also becomes apparent that far from having an explanation that covers the origins of all crossmodal correspondences, explanations for individual correspondences are difficult to agree upon with multiple correspondences falling under multiple 'kinds of correspondence.'

The explanation for semantic, statistical, and emotional valenced correspondences is that in one way or another, they are learnt; with the exception only of structural correspondences. However, alongside the structural account, a considerable body of research suggests that correspondences are not learnt and are present from birth. This view, called 'the neonatal synaesthesia hypothesis,' is discussed in more detail in the following section.

1.2.6 The Neonatal Synaesthesia Hypothesis

The neonatal hypothesis proposes that synaesthesia is universal in young infants and dissipates over the course of development (Maurer & Mondloch, 2005; Wagner & Dobkins, 2011). The strong form of the hypothesis suggests that infants perceive a direct sensory experience in one modality which is indistinguishable from the initially stimulating modality, just as synaesthetes do.

The weak form of the neonatal synaesthesia hypothesis proposes that there is a special, neonatal form of synaesthesia which is distinct from adult synaesthesia. It is thought that infants do not distinguish or understand what modality stimuli come from (Zelazo, 1996). Whereas in synaesthesia, experience in one modality induces another experience in another modality, in the weak form of the neonatal synaesthesia hypothesis, it is thought that infants experience one percept that is the result of total energy. When stimuli from different modalities produce equivalent amounts of energy, infants appear to detect crossmodal correspondences. The strong and weak forms of the neonatal synaesthesia hypothesis provide different explanations for how infants perceive corresponding stimuli; either as a synaesthete does, or as a mixture of combined energy.

It is also suggested that infant experience of synaesthetic and crossmodal perception might be underpinned by transient connectivity and decreased inhibition between cortical areas (Mondloch & Maurer, 2004). This is due to the cortex being both immature and limited in functioning. The functional organisation of brain systems is pruned throughout development as systems become more specialized, reducing sensory connectivity; this is thought to explain the disappearance of synaesthetic experience (Mills, Coffrey-Corina & Neville, 1997). Evidence for the development of functional organisation comes from the finding that whilst adults and infants both demonstrate large ERP responses over temporal regions in response to spoken language, spoken language only elicited responses in the visual cortex for infants (Neville, 1995). Similarly, when processing human faces, infants have been shown to activate areas which in adults are associated with language processing (Tzourio-Mazoyer, de Schonen, Crivello, Reutter, Aujard & Mazoyer, 2002), a further demonstration of interconnecting cortical areas.

It is thought that while strong synaesthetic experience disappears, the basic crossmodal correspondences observed in adults are remnants of neonatal synaesthesia (Maurer & Mondloch, 2005). It therefore follows that failure to prune neural connections and decreased inhibition are used as explanations for synaesthesia in adults. The presence of the exuberant connectivity means that strong connections between sensory modalities remain (Eagleman & Goodale, 2009; Huttenlocher, de Courten, Garey & Van der Loos, 1982; Mondloch & Maurer, 2004; Ramachandran & Hubbard, 2001).

Despite evidence of auditory-visual intensity matching across modalities as young as 20 days (Lewkowicz & Turkewicz, 1980) and evidence of the pitch-height correspondence in newborns (Walker et al., 2018), there are many who disagree that crossmodal correspondences reflect an unlearned aspect of perception. It has been proposed that given infants' sensitivity to statistical regularities in the environment (Aslin, Saffran, & Newport, 1998), it is possible that they might have learnt statistical correspondences during early development or in the womb (Spence, 2011). Alternatively, caregivers might have demonstrated to infants their own crossmodal biases when speaking to them using infant directed speech; therefore, helping infants to acquire the correspondences very quickly. For example, using lower pitch to demonstrate falling motion (Nygaard et al., 2009; Shintel et al., 2006). Spence & Deroy (2012) suggest that looking for the environmental source of what might be a 'surprising' correspondence could be preferable to claiming that it is simply innate. They add that because correspondences are transitive, the original source might not be immediately obvious. This means that two correspondences which are linked by one dimension, might cause the other two dimensions to become associated. For example, lightness-size and size-pitch correspondences which arguably have co-occurrences in the environment, could indirectly result in a correspondence between lightness and pitch. The original source of a correspondence between lightness and pitch might therefore not be obvious because it is the transitive result of two other correspondences.

1.3 Processing of Crossmodal Correspondences

Alongside confusion over where correspondences originate from is the discussion of how correspondences are processed. It has been suggested that different correspondences are processed at different levels.

At the lowest, most basic level, stimuli can be associated by amodal properties. Amodal properties can be processed in several modalities, for example, shape can be determined by vision and touch. Although initially distinct processing streams, modalities provide redundant information to one another, and therefore they combine to form a single representation of the object, meaning that streams lose their distinctiveness (Nudds, 2014). For example, visual and haptic sensory cues can be used to determine object size, however these cues are redundant to one another as they provide information about the same physical property. Other examples of amodal properties include duration, rhythm, intensity, and spatial location (Møller, Højlund, Bærentsen, Hansen, Skewes, & Vuust, 2018). This contrasts with modality specific information, which can only be processed by one sensory system. For example, colour can only be processed by the visual system (Kraebel, 2012).

At the other end of the scale are the correspondences between more complex stimulus, such as words and images (Köhler, 1929, 1947; Maurer et al., 2006; Ramachandran & Hubbard, 2001). It has been suggested that these correspondences might rely on higher-level, cognitive matching, based on meaning (Parise, 2015).

Crossmodal correspondences, such as those between auditory pitch and visual size, and between loudness and brightness (Evans & Treisman, 2010; Gallace & Spence, 2006; Marks, 1987; Root & Ross, 1965) are thought to lie at an intermediate level (Møller et al., 2018). They contain low-level, basic stimulus features which have been thought to rely on low-level perceptual mappings; however, they are also thought to be influenced by, and influence upon, higher level cognitive factors (Spence, 2011). As mentioned, these correspondences are thought to be associations between sensory cues which are not entirely unrelated or redundant.

Conclusion on the kinds, origins and processing of crossmodal correspondences

In summary, where crossmodal correspondences originate from, how they are processed, and what to fundamentally classify them as, is widely disputed. Whilst some correspondences can be explained relatively easily using Spence's type of correspondences, others struggle to fit easily into any category.

With most research focussing on auditory-visual correspondences, other correspondences have been left largely under-researched.

1.4 Bidirectionality and Core Correspondences

When conducting research into crossmodal correspondences, it is important to look at the wider picture, considering which other dimensions might be relevant to the correspondence under study. Most dimensions match with more than only one other and consideration of this is crucial in the research of any pair of correspondences.

Following on from this, more than simply matching with other dimensions, it has been proposed that there are a core set of correspondences which can be activated by accessing any one of them (Walker & Walker, 2012). Several dimensions have been shown to be aligned when judging sounds of different pitch. High-pitch is associated with: fast, hard, light, sharp, small, and bright. Walker (2012) proposes that if interactions amongst dimensions reflect extensive crosstalk of connotative meaning, then the same correspondences should be revealed regardless of which dimension is used to probe them. He also suggests that if there is a core set of correspondences, there should be transitivity in relation to the direction of dimension alignment. Therefore, correspondences should be bidirectional; for example, because high-pitch is aligned with sharp, presentation of sharp stimuli should also be matched with high-pitch.

In terms of the extensive crosstalk, sharp should also reveal the same correspondences as high-pitch stimuli, such as: brighter, higher, smaller, and lighter in weight. Findings did indeed show transitivity with effects of congruity between angularity and the other dimensions of hardness, pitch, and brightness. This supports the notion of a network of interconnected feature dimensions with related connotative meaning (Walker, 2012). Similarly, there is evidence that correspondences are bidirectional; for example, as well as darker being associated with heavier, heavier objects are also judged to be darker and make a lower-pitch sound, when the participant has no vision of the object (Walker, Scallon, & Francis, 2017). It is suggested that bi-directionality ensures sufficient coherence to guarantee transitivity occurs in terms of a core set of correspondences (Walker et al., 2017).

Here it is suggested that consideration of the network of interconnected dimensions is important in the study of any individual correspondence, and that the correspondence should not be thought of alone outside of the surrounding research. For example, when studying the size-brightness correspondence, it is important to consider that size has also been shown to match with the dimension of pitch. Therefore, it is important to consider whether pitch might indirectly interact with the correspondence between size and brightness, either in the same or opposite direction. To demonstrate how correspondences are interconnected, a subset of correspondences and how they connect with one another will be discussed in the following section. Importantly, how all of these correspondences appear inter-connected with one particular crossmodal correspondence will be discussed.

1.5 Related Correspondences

1.5.1 Size Correspondences

Weight is implicated in numerous correspondences, perhaps most notably for the correspondence between size and weight, in which larger objects are expected to be heavier than smaller objects. Naturally, this correspondence is widely observed as larger objects tend to be heavier than smaller objects. Whether weight is an aligned crossmodal dimension in its own right is therefore debated. Walker, Scallon, and Francis (2017) propose that it could be that weight correspondences with pitch and angularity are only formed with the expectation that heavier objects are larger. Therefore, rather than light weight directly being associated with high-pitch, it could be that small (which is associated with light weight), is associated with high-pitch. If true, this would be problematic for research into weight correspondences.

Speculating upon the role of size in weight correspondences raises questions about specifically which dimensions drive each correspondence. The dimension of size could be suggested to play a role in experience of the brightness-weight correspondence due to the association between size and brightness dimensions. The size-brightness correspondence refers to the finding that when asked to rate stimuli which participants could not see in terms of brightness, smaller size was aligned with brighter, and larger size was aligned with darker (Walker & Walker, 2012; Walker et al., 2017). The potential implication of this suggestion is that a correspondence between brightness and size could drive the correspondence between brightness and weight. If stimuli are expected to be brighter when smaller and darker when larger, it is possible that brighter is expected to be lighter in weight simply because it is smaller and therefore has less volume. There has also been evidence of brightness-size and size-weight illusions whereby after lifting, brighter is associated with more size and more size is associated with less weight (Walker et al., 2017).

Despite this suggestion, evidence supports the notion that heaviness is its own crossmodal dimension, without its relationship to size. Even when shapes were matched for perceived size; weight and shape were aligned, with curvedness aligned with heaviness (Walker, Walker, & Francis, 2012). Additionally, weight had a stronger influence on judgements of brightness and pitch than size did, providing supporting evidence that the relationships with weight are not solely the result of correspondences with size (Walker et al., 2017).

In conclusion, the concern regarding the implication of size in weight correspondences is reduced by the finding that weight had a stronger influence than size on a variety of dimensions, including pitch and brightness.

1.5.2 Pitch correspondences

In the previous section, the correspondence between brightness and weight was discussed. As per the core set of correspondences explanation, alongside corresponding with weight, brightness has also been shown to correspond with auditory pitch. Studies have shown that adults consistently matched higher-pitch with brighter stimuli and lower-pitch with darker stimuli (Collier & Hubbard, 2004; Marks, 1974; Wicker, 1968). Using dimension matching, participants rated higher-pitch tones as brighter than lower-pitch tones (Collier & Hubbard, 2004). Speeded classification studies with human participants and chimpanzees have also shown that when participants were asked to classify stimuli as black or white whilst irrelevant sounds were presented in the background (high and low-pitch), participants performed better on congruent than incongruent trials (Ludwig et al., 2011). For example, classification of black stimuli was quicker if a low-pitch sound was heard in the background, demonstrating how irrelevant information can either enhance or reduce performance depending on whether it is cross modally matching.

Similar results have been found in young children (Marks, Hammeal & Bornstein, 1987; Mondloch & Maurer, 2004). Using an explicit matching task, Mondloch and Maurer (2004) showed 33-36-month-old children displays of black and white balls bouncing simultaneously on a surface, with a high or low-pitch impact sound. When asked to point to the ball that was producing the impact sound, children matched congruently every time; matching the white ball to the high-pitch impact sound and the black ball to the low-pitch impact sound.

Infants as young as 10 months have also demonstrated evidence of the pitch-brightness correspondence. Looking times towards real-life and animated displays are utilised to examine whether infants look preferentially to congruent or incongruent crossmodal displays (Haryu & Kajikawa, 2012; Walker, Bremner, Mason, Spring, Mattock, Slater & Johnson, 2010). When shown displays in which black and white apples bounced on a surface with a high or low-pitch impact sound, 10-month-old infants looked longer towards incongruent displays in which the black apple is paired with the high-pitch sound and the white apple is paired with the low-pitch sound (Haryu & Kajikawa, 2012). This finding demonstrates that infants detect the congruity between the different displays and is therefore used as evidence that infants appreciated the pitch-brightness correspondence.

Whilst there is convincing evidence of the pitch-brightness correspondence, it is proposed that there is a possible link with the brightness-weight correspondence. This issue is like that posed earlier regarding the potential implication of size in weight correspondences. As the brightness of stimuli has been shown to correspond with perceived weight of stimuli (Payne, 1958; Plack & Shick, 1976; Walker et al., 2010), it is proposed that alongside the consideration of brightness, participants might inadvertently be considering the weight of the objects in pitch-brightness tests. For example, a black apple might be thought to be heavier, and this is the reason that it produces a low-pitch sound. Whilst there is no clear explanation for a correspondence between brightness and pitch, a correspondence between weight and pitch, although inconsistent, is observed within the environment. Heavier objects, which also tend to be larger, also tend to omit lower pitch tones. For example, as mentioned previously, the larger double bass produces a lower pitch sound than a smaller flute.

It is therefore proposed that the perceived heaviness, as a result of brightness, might mediate the correspondence between brightness and pitch. For this reason, it is critical that more is understood about the brightness-weight correspondence. If the brightness-weight correspondence is sufficiently implicated, it might be that this explains the absence of an obvious origin for the pitch-brightness correspondence.

As demonstrated in this review and in previous literature, correspondences do not appear to be individual associations across dimensions, rather there seems to be a network of interconnected features (Walker & Walker, 2012). In particular, the correspondence between brightness and weight was shown to pose potentially substantial implications for other correspondences which included the same features. Here it is suggested that the potential role of the brightness-weight correspondence in mediating a variety of other correspondences makes it a particularly important correspondence to focus upon. As suggested, understanding more about the brightness-weight correspondence is also expected to shed more light on size-weight and pitch-brightness correspondences. The following section will therefore review the literature focussing on the brightness-weight correspondence.

1.6 The Brightness-Weight Correspondence

As discussed previously, people tend to associate brighter stimuli with less weight and darker stimuli with more weight (Payne, 1958; Plack & Shick, 1976; Walker, Francis & Walker, 2010; Wright 1962).

Earlier research into the brightness-weight correspondence failed to make clear a crucial distinction between the different features of colour: value, chroma, and hue. This means that interpretable studies in the area are limited in comparison with other weight correspondences, such as size-weight and material-weight. It is therefore important that the distinction is made clear in this thesis as it was in the Walker et al. (2010) paper.

1.6.1 Terminology Clarifications

According to Munsell Colour Theory, colours have three features; hue, chroma, and value. Hue refers to the colour itself and chroma refers to the saturation or intensity of the colour. Value refers to the lightness/darkness of a colour along a continuum; the scale ranges from 0 for pure black to 10 for pure white. In contrast, brightness refers to the illumination of a surface. Walker et al. (2010) call their measure object 'brightness,' however to avoid implying that the illumination of an object is being measured, they purposefully comment that more correctly this refers to the surface lightness/reflectance. To remain consistent with previous literature and for this thesis, we will refer to the manipulated 'surface lightness' as 'brightness.' One must bear in mind that in the context we use 'brightness' this does not refer to luminance, it refers to surface lightness.

Alongside this terminology discrepancy is the inconsistency in words used to refer to mass, weight, and heaviness. Walker, Scallon, and Francis (2017) make an important distinction between the terms which are often used inaccurately to describe how heavy an object is. They describe the mass of an object as the 'principle 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.' Object weight is described as the 'objective measure of mass that is revealed when weighing scales support the object against gravitational forces.' Heaviness is described as a 'person's experience (perception) of an object's mass'.

It is proposed that the correspondence between brightness and weight is a correspondence between the perceived brightness and the perceived weight, as opposed to the actual brightness and actual weight. Referring to the previous definitions, it is therefore suggested that the brightness-weight correspondence, would more truthfully be described as the 'brightness-heaviness correspondence,' as perception of weight is most accurately termed 'heaviness.' Similarly, the brightness-weight illusion refers to the association between the perception of brightness and participants' perception of the experienced weight when lifted; therefore a more accurate description might be the 'brightness-heaviness illusion.' Throughout the thesis, reference is made to 'perception of weight' and 'weight judgement.' It is important to note that this terminology is used in order to correspond with previous literature, however more accurately these terms refer to perception of heaviness.

1.6.2 Evidence of the Correspondence

In the seminal study into the brightness-weight correspondence, participants were presented with pairs of balls in which the saturation was held constant, but the colour and brightness values varied. Black, white and grey balls were presented, as well as brightness-controlled chromatic balls. For both achromatic and chromatic colours, darker balls were judged to be heavier in weight than brighter balls. This could be predicted using the core set of correspondence logic that if brighter objects are thought as smaller and smaller objects are thought as lighter, then brighter objects would also be expected to be lighter (Walker & Walker, 2012). As pairs were matched for surface brightness, the separate contribution of hue could also be examined, revealing no effect on perceived weight (Walker et al., 2010). More recent research has also revealed evidence of correspondence bi-directionality as objects hefted without vision are judged to be darker and make lower-pitch sounds when they are heavier (Walker, Scallon, & Francis, 2017).

Payne (1958) conducted one of the earliest studies thought to demonstrate evidence of the brightness-weight correspondence using experimental design as opposed to subjective observation. However, it has since been argued that findings are not directly comparable to the brightness-weight correspondence as shown by Walker et al. (2010). Rather than focussing solely on the correspondence between brightness and weight, research examined how perception of weight could be influenced by a variety of colour features simultaneously. Participants were presented with pairs of cubes that differed in terms of hue, brightness, and saturation, and were instructed to write down which block looked the heaviest. A significant correlation was found between brightness of block surface and ranks of apparent weight as brighter cubes were rated as lighter in weight than darker ones. As a result of the indistinguishable features of colour, it is difficult to definitively say that the judgements of weight were based solely on the brightness of the blocks. That perceptual dimensions of colour are not clearly distinguished is identified as an issue across studies in this area (Payne, 1958; Wright, 1962). For this reason, conclusions can only be reached about how heavy specific colours are, rather than generalising to a feature of colour more broadly; for example, red and blue appear heavier than yellow.

Similar issues are evident in the research on children's appreciation of the brightness-weight correspondence. Plack and Shick (1976) examined how the hue and value of colours affect children's perception of weight. Blocks were presented in pairs and varied in terms of hue, value, or both. Children were asked whether they thought one block was heavier than the other. Analysis of means showed that darker blocks were rated as heavier than lighter blocks more often than lighter blocks were rated as heavier; and also more often than the blocks were rated as weighing the same. Although this result was significant, the authors suggest that results should be interpreted conservatively as pre-schoolers and kindergarteners were very inconsistent in their responses.

1.6.3 Kind of Correspondence

As discussed previously, there are a selection of correspondences which do not appear to fit smoothly into any of Spence's kinds of correspondence, and brightness-weight is an example of this. The review will discuss how current theories are inadequate for explaining the emergence of the brightness-weight correspondence.

Structural

The structural explanation of intensity matching falls short of providing a sufficient explanation for the brightness-weight correspondence. Dimensions such as size and volume can be described as having more/less size and more/less loudness. This means that the dimensions can be matched based on whether there is more or less of the dimension; correspondingly results show that more size is matched to more volume (Smith & Sera, 1992). In contrast, brightness is not so easily quantifiable in terms of more and less. Brightness can be described as having more brightness (brighter); however, equally it can be described as having more darkness (darker).

In the case of matching by intensity of brightness and weight, an incongruent pair is made, for example, more brightness would pair with more weight. The congruent correspondence between brightness and weight combines more and less terms; more brightness is associated with less weight and less brightness is associated with more weight. In the case of matching by intensity of darkness, a congruent match is made, for example, more darkness matches with more weight. As darkness is the absence of light, it is suggested to be unlikely that more absence of a dimension (more absence of light) would be used as a more end of a scale (darker).

It is suggested that there is no clear dimension that we would use preferentially to describe the brightness of an object. When comparing objects, people would be equally likely to say that one is 'brighter' or 'darker' than the other. The lack of a clear more/less scale of brightness/darkness suggests that it would be unlikely to be matched with the more and less scales of weight.

Semantic

The semantic-based account, with a focus upon language, also fails to satisfactorily explain the brightness-weight correspondence. The word 'light' has a verbal overlap as it is used to describe both brightness and weight in the English language. Describing brightness and weight as light results in a congruent match, for example light brightness matches with light weight. Findings from participants whose native language does not contain a verbal overlap across the terms used to describe brightness and weight however, provides evidence which refutes a language-based explanation. German participants also demonstrated evidence of the brightness-weight correspondence, despite there being no overlapping linguistic term between the two dimensions (Wright, 1962). Appreciation of the brightness-weight correspondence in these participants, indicates that it is unlikely that a linguistic overlap underlies the brightness-weight correspondence; however, the research in this area is limited.

Statistical

The statistical explanation that has been proposed for the brightness-weight correspondence is that people encounter co-occurrences between brightness and weight in the natural world. It is argued that whilst there are examples of correspondences which can be reliably observed in the natural environment (e.g. size-weight), consistent examples of darker objects being heavier than otherwise identical brighter ones are more difficult to pin-point. Although to date, little work has been done to examine correlations between brightness and weight in nature, Edlin's (1969) samples provide information regarding the colour and density of 40 types of wood. He states that whilst trees are still growing there is very little difference in density between them and only once cut does the density of the woods become more distinguishable. Walker et al. (2010) discuss a modest association between surface lightness and weight, with darker wood tending to be heavier than lighter wood. The association becomes insignificant however once a single wood, Ebony, is removed. It might be that because Ebony is an exceptionally dark (jet black) and dense (63lb per cubic foot) wood, this item is driving the association. Of the 'very light' and 'light' woods (below 30lb per cubic foot), three woods are 'whitish' and three woods are 'brownish.' The absence of a clear association between lightness and weight for the lightest woods, would further suggest that the association might be driven by the exceptional case of Ebony. Additionally, Ebony is not a general-purpose wood and is used for the finest decorative wood carving and high-grade furniture (Edlin, 1969); therefore, even occasional encounters with Ebony are unlikely to have been sufficient to link brightness to weight.

Alternatively, Walker et al. (2010) make reference to an observation that most absorbent materials become heavier and darker once they are wet, for example sand, wood, fabric, and soil. As the only cited examples however, these instances arguably do not provide convincing evidence of consistent, natural, co-occurrences of brightness and weight. Especially as individuals are likely to have a large amount of experience with manufactured materials, such as plastic, for which a co-occurrence between brightness and weight is not thought to occur. To evaluate the view that the correspondence is the result of statistical observation of co-occurrence, a more substantial review would need to be conducted into the natural and manufactured co-occurrences of brightness and weight.

Emotional valence

To our knowledge, research has not examined the potential role of emotional valence in the brightness-weight correspondence. Though it might be a research area worth pursuing, simple stimulus features of weight and brightness are not expected to elicit the same emotional properties that stimulus such as wine and music have been shown to elicit (Wang & Spence, 2017).

Experimental artefact

The suggestion that the correspondence might be an artefact of participants being incidentally encouraged to use brightness as a cue to weight in experimental designs is addressed. It could be suggested that when brightness is the only variable to change and participants are asked to indicate how heavy they expect an object to be, participants are likely to deduce that brightness could be an appropriate cue for determining weight. Whilst this might be true, these demand characteristics would not explain the convergence with regards to the direction of the correspondence. Brighter stimuli are consistently associated with less weight and less bright stimuli are associated with more weight. If participants guessed that studies were looking at the correspondence between brightness and weight, there is still an absence of cues to provide information about the direction of the correspondence.

The discussed accounts fail to fully explain the brightness-weight correspondence. If the correspondence does not have a semantic, statistical, structural, or emotionally valenced basis, its origins are puzzling. Understanding more about *when* the correspondence emerges through developmental studies would help to shed light on its potential origin. Understanding more about *how* the correspondence is evidenced would reveal more about the nature of the correspondence.

1.7 Rationale for the thesis

After reviewing the literature on the suggested origins and kinds of correspondences, it is evident that the brightness-weight correspondence does not fit clearly into any of the suggested types. The evidence for a semantic basis is refuted by cross-cultural studies, and there is very limited evidence for a reliable statistical co-occurrence of the two dimensions in the environment, similarly the structural explanation of intensity matching is not thought to sufficiently explain the correspondence. The literature review also reveals that research into the brightness-weight correspondence is currently fairly limited, with research to date not exploring whether the correspondence is revealed in different situations and through different measures. It is proposed that these large gaps in the literature could make the study of the brightness-weight correspondence an important priority in the crossmodal research field. As the correspondence also appears to have potential implications in a variety of related correspondences, it is thought to be a key correspondence to focus upon.

Broadly, the aims of the thesis are to understand more about the brightness-weight correspondence. The thesis aims to provide more information about the origins of the correspondence and the situations in which the correspondence is revealed. This will be achieved by testing adult and infant participants' appreciation of the crossmodal correspondence through verbal and kinematic measures.

Chapters 2 and 4 seek to provide further evidence of the brightness-weight correspondence and the brightness-weight illusion which have been demonstrated by previous research. Using similar methods to those utilised previously, the experiments in these chapters examine whether the correspondence and illusion are revealed consistently and whether they are evidenced with stimulus made from different materials. The experiments use wooden stimulus for which a natural occurrence between dimensions has been proposed, and plastic stimulus for which no natural co-occurrence has been documented to date. This distinction is made to examine the relative contribution of co-occurrence of dimensions. Stimuli used in these experiments are subsequently used in the kinematic studies in Chapters 3 and 5.

In Chapters 3 and 5, there is a focus upon examination of the brightness-weight correspondence through interactions with objects. As discussed earlier, the previous evidence of the brightness-weight correspondence is obtained through verbal reports of participant perception. These chapters discuss what the previous findings reveal about perception of the correspondence and furthermore what kinematic evidence can add to the literature. It is proposed that whilst verbal evidence of the correspondence is informative about the presence of an association across the modalities, it does not reveal information about whether the correspondence is utilised in a more natural, daily setting. The experiments in Chapters 3 and 5 examine how participants interact with objects which vary in brightness, looking specifically at whether actions are differentiated on the basis of object weight. As a focus upon weight is not made explicit, it is suggested that this reveals more about whether individuals spontaneously act upon the brightness-weight correspondence which they report, or whether the correspondence is only demonstrated through asking participants to distinguish weight. The methodological procedure in these experiments was developed to enable the study of the brightness-weight correspondence in infants as shown in Chapter 7.

Infants' appreciation of the brightness-weight correspondence is the focus of Chapters 6 and 7. The presence of the correspondence in infants is thought to reveal more information about the semantic basis of the correspondence. It is suggested that demonstration of the brightness-weight correspondence before the emergence of language would suggest that the verbal overlap of 'light' is unlikely to be responsible for the correspondence. Evidence of the correspondence in infancy would also cast doubt on the theory that observation of statistical co-occurrence of brightness and weight might be responsible for the correspondence, as infants will have had limited exposure to natural materials which demonstrate the correspondence. The experiment in Chapter 6 examines whether infants use object brightness as a cue to object weight, and subsequently whether they preferentially lift brighter or darker blocks. The final experiment in Chapter 7 uses the same technique as the experiments in Chapters 3 and 5 to examine whether infants differentiate actions towards objects with different surface brightness, on the basis of their anticipated weight.

CHAPTER 2

Perception of the Brightness-Weight Correspondence

2.1 Experiment 1: Perception of the Brightness-Weight Correspondence in Wooden Stimuli

2.1.1 Introduction

2.1.1.1 The Brightness-Weight Correspondence

The brightness-weight correspondence refers to the finding that darker objects are expected to be heavier than otherwise identical brighter objects. Research has also demonstrated evidence of an interesting weight illusion which occurs after lifting objects which vary in brightness (Walker, Francis, & Walker, 2010). Weight illusions have also been shown previously with a variety of different dimensions and the corresponding research will be discussed.

2.1.1.2 Weight Illusions

Expectations of weight can be based on a wide range of visual features, including size, material, density, and brightness. When the actual weight of an object does not match the expected weight, an illusion has been shown to occur whereby the perception of weight reverses. Charpentier (1891) was one of the first to discuss weight illusions using experimental data, suggesting that preliminary ideas about objects could explain the illusion. A typical weight illusion experiment involves gathering weight judgements for objects before they have been lifted, weight judgements are then gathered again after participants have been given the opportunity to lift the objects. A similar procedure is usually repeated over a series of multiple trials.

The size-weight correspondence is the finding that smaller objects are expected to be lighter in weight than larger ones. If objects are truly equally weighted, the perception of weight has been shown to reverse after hefting. This means that the larger objects are then judged to be lighter in weight that the smaller objects (Charpentier, 1891; Flanagan & Beltzner, 2000; Murray, Ellis, Bandomir & Ross, 1999), a phenomena which is referred to as the size-weight illusion.

Research has also found evidence for a material-weight correspondence in which objects made from a high-density material (e.g. metal) appear heavier in weight than objects made from a low-density material (e.g. polystyrene). Similarly to the size-weight illusion, a material-weight illusion has also been shown to occur whereby the material which initially appeared lighter is reported to feel heavier after hefting equally weighted objects (Buckingham, Cant & Goodale, 2009; Buckingham, Ranger & Goodale, 2011; Harshfield & DeHardt, 1970; Wolfe, 1898).

Comparatively less researched is the illusion that occurs after lifting objects of different surface brightness. As discussed earlier, darker objects are initially reported to appear heavier than brighter objects. However, after lifting equally-weighted objects, a similar illusion occurs. The darker object, initially thought to be heavier, is then judged to be lighter in weight, despite no difference in perceived weight when lifting without vision (Walker et al., 2010).

Understanding of weight illusions sheds more light on the crossmodal correspondence itself. The existence of weight illusions casts doubts on the theory that correspondences such as that between brightness and weight could be attributed to language. As discussed in Chapter 1, a possible semantic explanation for the brightness-weight correspondence is that in the English language, ‘light’ is used to refer to brightness and weight, and that therefore the correspondence is the result of matching of ‘light weight’ and ‘light colour’. Considering this alongside findings of a brightness-weight illusion however, there is no clear explanation why the correspondence would be reversed after lifting the object if the correspondence were the result of language.

Additionally, that lifting objects which vary in brightness with vision can cause changes in weight judgement, whilst lifting without vision does not, has been thought to suggest that there is a perceptual expectation which is derived from the appearance of the object (Walker et al., 2010). Therefore, it is the perceived heaviness rather than the actual weight which corresponds with perceptual qualities in other sensory modalities, such as brightness and size (Walker, Scallon, & Francis, 2017).

Although induced by different stimuli, the potential explanations for the cause of the size, material, and brightness-weight illusions can draw upon the same theories. The main distinction between the primary explanations is whether sensorimotor causes or cognitive underpinnings are thought to be responsible.

A sensorimotor explanation for why we experience weight illusions is that there is a mismatch between efference and afference; efference refers to the expected dynamics of the lift and afference to the sensory consequences of the lift. Flanagan and Beltzner (2000) suggest that the sensorimotor explanation can be described with reference to motor control theory. A prediction of weight is made using an internal forward model, whereby information on the planned action and the current state of the motor system allows for a prediction of the future state (efference) (Cooper, 2010). More force is therefore applied to items which are expected to be heavier, and less force applied to items expected to be lighter (Buckingham et al., 2011). If the visual cues are misleading and the object is lighter than expected, the object is lifted more easily and with greater acceleration and velocity (afference) than objects lifted with accurate visual cues (Davis & Roberts, 1976; Gordon, Forssberg, Johansson & Westling, 1991).

Weight judgements are then formed by considering the error signal between the anticipated sensory feedback and the actual sensory feedback. Misleading visual cues might lead to an incorrect forward model, resulting in a larger discrepancy between the actual and anticipated sensory feedback. Adaptation can occur when forward models are updated after experience; the models can then be used to generate accurate sensory predictions which can be used to estimate required forces for lifting objects. The weight illusion might therefore be the result of the mismatch between the prediction of weight and the feedback on actual weight.

Research has shown however that there is evidence of a dissociation between the adaptation rates of the perception and action systems in response to weight illusions; which suggests that the mismatch might not be responsible for the illusion. When lifting the same objects multiple times, sensorimotor corrections are made substantially earlier than corrections to inaccurate judgements of weight. For example, although the motor system adapted to the actual weights of objects relatively quickly, participants continued to report expectations consistent with a material-weight and size-weight illusion (Buckingham et al., 2009; Flanagan & Beltzner, 2000; Grandy & Westwood, 2006). It has therefore been suggested that the action system can use weight information in a more accurate way than the perceptual system (Buckingham et al., 2009).

Dissociations between perception and action have also been observed in other research on illusions, notably in the Ebbinghaus and Ponzo illusions. The Ebbinghaus illusion is the finding that equally sized circles are perceived as larger when surrounded by small circles than when surrounded by large circles. Haffenden, Schiff, and Goodale (2001) demonstrated that the Ebbinghaus illusion affects perception but does not affect grasp scaling; in other words, the circle surrounded by small circles is reported to appear larger but is also not approached with a wider grasp. Another example of an illusion which is purely a perceptual phenomenon is the Ponzo illusion, whereby two identical lines appear different lengths depending on the background lines they lie upon. Research showed that whilst incorrectly stating that one line appeared longer, grasping was tuned to the actual line length (Ganel, Tanzer, & Goodale, 2008).

It has been proposed that in the case of weight-illusions; actions are corrected faster than perceptions because the illusion has cognitive underpinnings (Buckingham et al., 2009; Buckingham et al., 2011). It has been suggested that individuals have long-held priors based on experience, which help them to predict how heavy an object will be. After lifting, we are more informed about the actual weight of the particular object, and if the prediction was incorrect, the motor system utilises this sensorimotor information, adapting to the actual physical requirements, and ignoring expectations of density that drove the initial lift (Baugh, Kao, Johansson & Flanagan, 2012; Flanagan, Bittner, & Johansson, 2008). Whilst it is important that the motor system is able to adapt to unexpectedly weighted objects; for the perceptual system, it is most important that our general expectations of object weight, based on material or size, are not so easily changed by one object which does not conform. The evidence that perceptual illusions occur long after motor corrections is therefore used as evidence that weight illusions have cognitive underpinnings.

Further evidence of the importance of cognitive priors in the experience of weight-illusions comes from Ellis and Lederman (1998). They asked non-golfers and expert golfers to compare the weight of identically weighted practice and real golf balls, (real golf balls are normally heavier than practice ones). They found that expert golfers reported that the practice ball felt heavier than the real ball, whereas the non-golfer group did not experience the illusion. It is suggested that this difference is due to one group having an expectation about weight that the other group did not.

These findings demonstrate how the study of interactions with objects during lifting can reveal more information about weight-illusions. Specifically, the studies cast doubt on the assertion that a mismatch of weight expectation and actual weight results in the illusion and that instead, cognitive underpinnings based on repeated experience might be responsible for the phenomena.

2.1.1.3 The Current Experiment

To address one of the key aims of the thesis, this experiment seeks to replicate the Walker et al. (2010) study to provide further evidence of the brightness-weight correspondence. This is particularly important considering how early work does not clearly distinguish hue, saturation and brightness. As discussed in Chapter 1, a study presented later in the thesis repeats the current experiment with stimuli made from an alternative material. This distinction was made to allow the examination of the correspondence in stimuli made from materials for which there is a potential statistical co-occurrence between brightness and weight in the natural environment (Experiment 1), and for materials whereby there is no clear demonstration of a co-occurrence (Experiment 3). This comparison will shed more light on the potential importance of the hypothesis that statistical observations of darker objects being heavier results in the brightness-weight correspondence.

Stimuli from Experiment 1 and Experiment 3 will also be used in future kinematic studies (Experiment 2 and Experiment 4) and it was therefore important to examine whether the correspondence was observed through classic measures. As stimuli will be used in the kinematic studies, it was important that stimuli were designed to be appropriate for both studies at this stage. Although we know that hue does not influence reported perceptions of weight when brightness is controlled (Walker et al., 2010), we could not be sure that it would not influence size or shape perception, which might affect reach and grasp kinematics. Therefore, in all of the studies throughout this thesis only achromatic colours (black, grey, and white) will be used to maintain consistency with the kinematic studies.

In the current experiment, the presence of a brightness-weight illusion will be examined alongside the presence of the correspondence. As demonstrated, weight illusions help to understand more about one of the key aims of this thesis: the potential origins of the brightness-weight correspondence. Additional evidence of the brightness-weight illusion would provide further support for refuting the semantic hypothesis on the basis that there is no obvious reason to explain why the correspondence would be reversed if it were based on language.

Based on the previous research, we expect to replicate findings of a brightness-weight correspondence and a brightness-weight illusion in adults (Walker et al., 2010). Before lifting, we expect to see that objects' weight will be rated on the basis of brightness; with the white block rated as the lightest, and the black as the heaviest. After lifting, we expect to see a reversal of this order, with black being rated as the lightest and white being rated as the heaviest.

2.1.2 Method

2.1.2.1 Participants

Fifty participants completed the experiment at Lancaster University. Two participants were removed from the experiment; one of the participants was under 18 and the other participant reported that he was colour blind. This resulted in a final sample of 48 participants (19 females, 29 males, M_{age} = 21.13 years).

This research gained approval from Lancaster University Ethics Committee. Participants were given information and consent forms upon arrival which they were asked to sign. At the end of the study, participants were given a debrief and were reminded of their right to withdraw their data from the study for up to one month after the study.

2.1.2.2 Stimuli and Apparatus

Figure 2 illustrates the three mid-weight wooden cubes (*M* = 100.6g, Range = 99.9g -101.6g; white cube = 101.6g, grey cube = 99.9g, black cube = 100.4g). The cubes measured 5cm height x 5cm width x 5cm depth, and varied only in terms of brightness. Brightness was measured in candela per square meter (cd/m^2), using a lux meter. A higher cd/m^2 reading equates to more luminosity/brightness than a lower cd/m^2 reading. Wooden blocks were painted with black paint to give a darker surface ($27.46cd/m^2$), white paint to give a brighter surface ($364.9cd/m^2$), and grey paint for a mid-brightness surface ($103.23cd/m^2$).

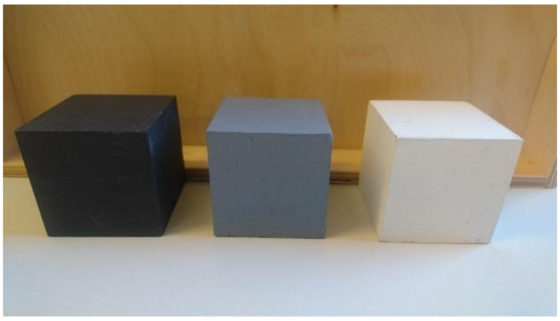


Figure 2. The black and white test blocks and the grey familiarisation block used in Experiment 1.

On presentation to participants, the cubes were spaced evenly apart (5cm) on a wooden tray which measured 34cm x 26.5cm x 4.5cm.

2.1.2.3 Design

All participants saw the same three cubes. Participants were assigned to one of six conditions, which varied only in terms of the position of objects in relation to one another. For example, one group saw the black to the left, white in the middle, and grey to the right. All combinations of order for the three objects produced six conditions.

2.1.2.4 Procedure

Participants were given information sheets and consent forms and were told that the study would take no longer than ten minutes. Participants were given a simple instruction: 'Point at the three cubes, starting with what you think is the least heavy, going up to what you think is the most heavy. Make your decision only by looking at the objects and do not lift them.' The decision to use the term 'heavy' as opposed to 'light' was made considering the verbal overlap of light referring to brightness and weight, as mentioned previously.

As participants provided their decision, an experimenter recorded their responses. Participants were then asked to lift all three objects, starting from the left, working their way across to the right. After they had lifted the objects, participants were asked 'What do you think of the weight of the objects now? Point at the three cubes, starting with what you think is the least heavy, going up to what you think is the most heavy.' Participants' responses were again recorded by the experimenter. Participants were allowed to lift the objects multiple times if they wished and were not required to distinguish the weights, if they felt there was no difference.

2.1.3 Results

Ratings of weight were examined before and after lifting the objects. Participants' weight ranking were compared to the expected ranking, using Kendal's tau. If the ratings were ordered exactly as expected (white < grey < black), a score of 3 was assigned, demonstrating that all three pairs were in the expected order. If the ratings were the exact opposite of what was expected (white > grey > black), a score of 0 was assigned, demonstrating that none of the pairs were in the expected order. Scores could range from 0-3 depending on the number of pairs that were in the expected order. For example, if white was rated as heavier than grey but as lighter than black, and black was rated as heavier than both, the participant would receive a score of 2, as two of the pairings are in the expected order (black > grey, black > white). Each pair rated as the same weight was given a score of 0.5 and therefore if participants stated that all objects weighed the same, a score of 1.5 was assigned. A tau score of 1.5 is the null value, which suggests that the order of weight expectations is random. A score of 1.5 reflects the null value, that the order is random. The same scoring system was applied after lifting; however, we hypothesized that the order would be reversed, due to the brightness-weight illusion.

The tau values before and after lifting were each compared to the null value (1.5) using a one sample t-test. Figure 3 indicates the tau values before and after lifting. Before lifting, the tau value was shown to be significantly greater than the null value ($t(47) = 5.83$, $p < .001$, $d = 0.84$, on a two-tailed one sample t-test). After lifting, the tau value was significantly lower than the null value ($t(43) = -2.20$, $p = .034$, $d = -0.33$, on a two-tailed one sample t-test). This suggests that before lifting, participants matched above chance in the expected order; they rated black as heavier and white as lighter. After lifting, they matched above chance in the reversed order; stating that white was heavier and black was lighter.

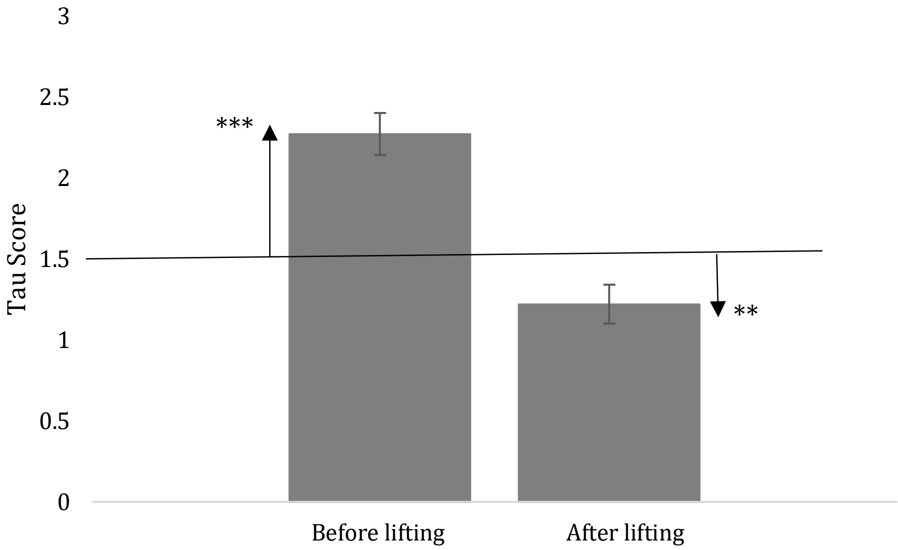


Figure 3. The change in rating of weight before and after lifting objects which vary in brightness. A tau value of 3 represents the expected order and a tau of 0 represents the reverse of the expected order.

2.1.4 Discussion

In this experiment, we replicated evidence of the brightness-weight correspondence. Before lifting, participants rated the objects' weight in the expected order; white rated the lightest, grey in the middle, and black rated as the heaviest. As stimuli in the current experiment were made from wood, there is evidence of a correspondence in objects for which there is a potential natural co-occurrence of brightness and weight. As discussed in Chapter 1, it has been suggested that when wood absorbs moisture it simultaneously becomes darker and heavier. Similarly, there is a modest association between the lightness of wood and the weight of the wood (Walker et al., 2010). These co-occurrences have been proposed as potential explanations for the correspondence. As discussed, Experiment 3 will examine whether this correspondence is also observed in objects made from a material which has no obvious signs of a co-occurrence in daily life.

Alongside the evidence of the brightness-weight correspondence, we also showed evidence of the brightness-weight illusion (Walker et al., 2010). Once participants had lifted the objects, their perception of the objects' weights was reversed. After lifting, the black object was rated as the lightest, grey in the middle, and white as the heaviest. As discussed previously, reversal of the association after lifting, suggests that the correspondence has a perceptual component. If participants expected the black block to be heavier before lifting and had no differential sensory experience when lifting, they would still rate this object as heavier after lifting. If participants rated objects in the same order after lifting as they did prior to lifting, it suggests that participants sensory experience did not refute their initial expectations of weight. This would not support the idea that the correspondence contains a perceptual component. If participants rated objects in the expected order before lifting but in a random order after lifting, it might suggest that there was a perceptual experience which casted doubt on initial expectations. However, results in this case would less clearly reflect the sensory experience which participants encountered.

The illusion also casts doubt on the idea that that the brightness-weight correspondence has origins in semantics, and more specifically language. It seems unlikely that a lexical overlap could be responsible for the correspondence as there is no clear reason why this would then reverse after lifting as light weight would still refer to the object with the light surface.

CHAPTER 3

Selective Preparation For the Brightness-Weight Correspondence

3.1 Experiment 2: Examining the Brightness-Weight Correspondence in Wooden Stimuli Using Kinematic Measures

3.1.1 Introduction

Previous research examining the brightness-weight correspondence (including the experiment in Chapter 2), has used verbal reports to gather data regarding weight expectations based on brightness (Payne, 1958; Plack & Shick, 1976; Walker et al., 2010; Wright, 1962). This demonstrates that when explicitly asked to make a distinction between the weight of objects which vary in brightness, there is evidence of a correspondence between brightness and weight.

Although demand characteristics cannot explain consistency in terms of the direction of the reported correspondence, it is possible that the initial identification and determination of brightness as a cue to weight is the result of the specific experimental conditions, i.e. that participants have been asked which object they expect to be heavier. It is possible however that this correspondence would not have been considered or acted upon in other conditions. To understand more about the circumstances under which the correspondence is revealed, the experiments in the current chapter and Chapter 5 look at whether the correspondence is revealed under very different conditions, using an alternative set of measures.

In the present study, we hope to shed more light on the brightness-weight correspondence by observing whether actions are selectively prepared based on object brightness in a reach-grasp-lift style task. To examine selective preparation for objects varying in brightness, we will measure various features of the reach, grasp and transport of objects, which have previously been shown to vary as a function of expected object weight. It is important to consider how the weight of objects is typically predicted and also what happens when we make an incorrect assumption about an objects' weight.

3.1.1.1 Weight Expectation and Object Transport

Predicting Weight in Old and New Objects

Objects that have been experienced before can be identified and corresponding weight predictions can be formed, based on sensorimotor memory (Flanagan, King, Wolpert, & Johansson, 2001). This means that the approach, grasp and transport of previously experienced objects is usually relatively accurate and smooth as the load force is correctly scaled to the object's weight.

There are also many occasions in which particular objects have not been previously manipulated; however even in such situations, predictions about object weight are made prior to contact. Size (Cole, 2008; Flanagan, Bittner, & Johansson, 2008; Gordon, Forssberg, Johansson, & Westling, 1991), shape (Salimi, Frazier, Reilmann, & Gordon, 2003), and material (Fikes, Klatzky, & Lederman, 1994; Paulun, Gegenfurtner, Goodale, & Fleming, 2016) can provide information about physical properties, such as weight, which are useful for predicting the required force for manipulation. It is important that actions are prospective, considering the expected future task demands and action goals. This avoids erratic lifts which occur before our bodies are able to provide feedback, which takes a relatively long time to correct (Gottwald & Gredeback, 2015; Gottwald, 2018). The use of vision to predict weight relies on learned associations between visual cues and object properties; associations which might be acquired through statistical correlations in the natural environment. (Johansson & Flanagan, 2009).

Incorrect Prediction of Weight

Although there are a variety of ways in which we can derive the expected weight of an object, there are occasions when erroneous reaches and lifts are made if the weight of an object is unexpected. In natural object interactions, most people will have experienced an event in which they incorrectly predicted the weight of an object as it was lighter/heavier than expected. For example, an empty bottle of water that was expected to be full but is much lighter than expected. Previous experimental designs have involved manipulating objects so that ones which would typically be expected to be heavier are lighter, and ones which would typically be lighter are heavier. Once the object has been lifted, the true weight of the object is revealed, however it takes time for the body to make sensory-based adjustments to the lift which had been planned.

Measures have revealed the kinematic outcomes when an object is heavier or lighter than expected. If an object is heavier than expected, an increase in load force and fingertip force must be applied to reach the necessary threshold, this means that the lift-off will be slower than if the correct forces were applied (Johansson & Flanagan, 2009; Johansson & Westling, 1988; Vollmer & Forssberg, 2009). The delay between object contact and lift off with a heavier object, even if correctly lifted, has also been shown to be longer, thought to be the result of ensuring a secure grip position (Eastough & Edwards, 2007; Weir, MacKenzie, Marteniuk, Cargoe, & Frazer, 1991).

When an object is lighter than expected, the lift is faster and higher than intended, as excessive lift force is transformed into acceleration (Vollmer and Forssberg, 2009). In reference to the size-weight illusion, it has been suggested that 'any illusion effects on action would result in the light-feeling but heavy-looking large '[object]' being moved more rapidly' (Buckingham, Byrne, Paciocco, van Eimeran, & Goodale, 2014). Consequently, sensory events related to lift-off occur before the expected time. To correct the error in lifting and as a compensatory process, the load and grip forces are reduced, intending to bring the object back to its planned position.

Correcting Incorrect Predictions During Lifting

By looking at the time-period before our bodies can make the corrective actions to the lift, we are able to establish how individuals initially approached and lifted the objects. The exact time when individuals stop reacting automatically in response to stimuli and begin making sensory-based adjustments is not fully established. Research has suggested that the sensorimotor system makes fingertip corrections or modifications after approximately ~ 100ms of contact with the object. Transforming visual events into actions can take longer, with delays of ~ 200ms (Johansson & Cole, 1992; Johansson & Flanagan, 2009; Johansson & Westling, 1987). There is also evidence that 60-100ms after a weight is added to the hand or arm of a subject, there is a strong grip force increase, reaching a maximum within 50-100ms, with responses before this time being largely automatic (Cole & Abbs, 1988; Johansson & Westling, 1988; Pruszynski & Scott, 2012).

Estimates of motor adjustments to changes in stimuli in adults therefore appear to occur around ~100ms, however corrective action in infants has been suggested to take ~ 500ms (Mash, 2007). As Mash does not discuss the adult time-period for corrective action, is not clear whether a developmental effect is suggested. It is possible that the combination of this literature suggests that infants take longer to make sensory-based adjustments (500ms), a response which quickens with development to just 100ms in adulthood. Alternatively, it might be that the measures which are taken across studies take different amounts of time to correct. In the paper by Johansson and Flanagan (2009), they suggest that 'grip force output is modified about 100ms after contact with the object and tuned for the actual object properties.' In contrast, Mash (2007) suggests that the 500ms interval 'reflects actions implemented before sensory-based adjustments could have rescaled a majority of the movement that was measured.' The sensory-based adjustments that Mash refers to might take longer to correct than the grip force modification described by Johansson and Flanagan (2009). The absence of clarity regarding the appropriate measurement interval will be considered within this experiment, with an examination of the kinematics within both time frames.

3.1.1.2 Weight Expectation and Approach

Approach velocity

Alongside considering what the lift of the object reveals about expected weight, researchers have also looked at how the approach towards an object is differentiated for objects of different weights. Though initially it was thought that expected weight did not influence the planning of the reach prior to contact with the object (Weir et al., 1991), research has more recently demonstrated ways in which prior-to-contact measures can vary depending upon weight of the target object.

Approach velocity has been examined as a relevant measure for determining the prospective control used in the approach towards objects of different weights. Findings appear to diverge however, across the multiple studies depending on object type and scale of object weight (Eastough & Edwards, 2007; Fleming, Klatzky, Behrmann, 2002; Paulun et al., 2014; Paulun et al., 2016). Discussed are results which show both evidence of a slower approach towards heavier objects, and no evidence of differentiated speed for differently weighted objects. We also propose a theory that under certain circumstances, lighter objects might be approached more slowly.

Lighter objects with a rough surface have been shown to be approached more quickly and with shorter movement durations than heavier objects with a slippery surface which are approached more slowly (Fleming, Klatzky, Behrmann, 2002; Paulun et al., 2014; Paulun et al., 2016). It is acknowledged however that because the lighter objects also had a rougher surface, the contribution of weight and friction towards the differentiated approach velocities cannot be disentangled. We propose that the slower approach for the slippery, heavy, object could be due to the greater precision requirements for this object, which might be a result of the weight, or might be a result of the surface texture. As more precision is required for the slippery, heavy object, this is thought to be evidence of the speed-accuracy trade off.

One explanation for why heavier objects might be approached more slowly is that more importance is placed on grasping these objects more closely to the centre of mass (COM). A slower approach helps to increases precision which enables the establishment of a more accurate grasp. When objects are grasped away from their centre of mass (COM), this can cause a rotation. The amount of rotation, or torque, is the result of the distance of the grasp from the COM (either above or below), multiplied by the weight of the object (Lederman & Wing, 2003). Therefore, grasping a heavier object further from the COM will result in a larger torque than grasping an equally sized but lighter weighted object in the same position. Heavier objects are therefore grasped closer to the objects' COM, or slightly below it. Preferentially grasping a heavier object marginally below the COM, rather than marginally above it, prevents the fingers slipping off the top of the object, and also enables the hand to get under the weight of the object to aid with the lift. These decisions are thought to avoid potential slippages and rotations (Eastough & Edwards, 2007; Paulun, Gegenfurtner, Goodale & Fleming, 2016). Smeets and Brenner's (1999) model also suggests that grasping at the centre of mass is the most efficient for successful lifting and maintaining of a horizontal position with minimal rotation. For non-symmetrical objects such as a hammer, the location of the COM must be interpreted by predicting the weight of the hammerhead.

Whilst there is evidence that participants reach more slowly for heavier objects (when they are also more slippery), other studies have also found no significant effect of weight on the peak speed at which objects are approached (Weir et al., 1991). This is despite finding evidence that grasp height is closer to the COM for heavier objects (Eastough & Edwards, 2007). This suggests that the speed of the reach is not altered to adapt to the higher precision requirements of heavier objects.

With the absence of a clear effect of weight on reach velocity, another alternative theory can be considered; that in certain circumstances, very light objects could be approached more slowly as greater precision is required to ensure that they are not knocked, causing them to fall or displace. Evidence that heavier objects are approached more quickly has also been shown in infants, however no explanation for why this might be has been offered (Mash, 2007).

Approach maximum grip aperture (MGA)

Another measure which can be obtained prior to contact with the object is maximum grip aperture (MGA). Eastough and Edwards (2007) found that heavier objects (475g) were approached with a wider MGA than lighter objects (140g). It has been suggested that the wider grasp is made as an attempt to ensure that objects are gripped more precisely and securely (Eastough & Edwards, 2007; Smeets and Brenner, 1999). In contrast, findings have also shown evidence of a lighter object being approached with a wider MGA than a heavier object, (Paulun et al., 2014), however as discussed previously, the contribution of weight and surface texture are difficult to distinguish in this study. Additionally, research has also found no differentiation of MGA across objects of different weights (Paulun et al., 2016; Weir et al., 1991). Similar to the findings with approach velocity, the consistency of the MGA as a measure of expected weight is not reliable.

In summary, it can be said that the effect of expected weight upon the measures during the approach towards an object is not easy to disentangle. The precision requirements appear to tell a simpler story whereby greater precision requirement equates to a slower approach speed and larger MGA, and less precision requirements equates to a faster approach with a smaller MGA. It is therefore proposed that the precision requirements of differently weighted objects are an important consideration when examining anticipation of expected weight.

3.1.1.3 The Current Experiment

Aims

The primary aim of the present study is to examine whether participants selectively prepare for differently weighted objects, using the cue of brightness. The study will examine whether participants act upon the differences in weight expectations which they report; that darker objects are expected to be heavier in weight than brighter objects. This will add to the current literature on the brightness-weight correspondence by demonstrating whether people spontaneously act upon the correspondence or whether it is only revealed by direct probing about an association between brightness and weight.

The characteristics of reach and transport kinematics for objects with different levels of surface brightness will be analysed to examine this question. Using motion capture, it will be possible to examine whether prior-to-contact, maximum grip aperture (MGA), velocity, and acceleration vary for darker and brighter objects. It will also be possible to examine during transport whether participants applied more force to the objects which they expected to be heavier. As black and white objects are equally weighted, selectively preparing with less force for the objects which are expected to be lighter would result in less acceleration and less velocity during the lift; preparing with more force for the objects which are expected to be heavier would result in more acceleration and more velocity during the lift.

Possible Outcomes

There are multiple possible outcomes from this experiment. It might be that participants' approach and transport of darker objects suggests that they expected them to be heavier, and the approach and transport of brighter objects suggests that they expected them to be lighter. In this case, an effect of object on the chosen measures is expected. Darker objects would be lifted more quickly as they are lighter than expected, and brighter objects would be lifted more slowly, as they are heavier than expected. We might also expect to see differences in the approach measures in this case, although the direction of these measures is not predicted based on the conflicting results.

A second potential outcome is that a difference in kinematic measures is observed between black and white objects for a portion, but not all of the experimental trials. As discussed previously, the motor system adapts more quickly to actual object weight than participants' judgements of weight do. Evidence shows scaling for an object's true weight occurs whilst participants still incorrectly report weight, as demonstrated by the size-weight and material weight illusions (Buckingham et al., 2009; Flanagan & Beltzner, 2000; Grandy &

Westwood, 2006; Johansson & Westling, 1988). For example, when lifting equally weighted large and small objects, fingertip forces were scaled to the true weight of the object, despite a persisting size-weight illusion (Grandy & Westwood, 2006). Research has also shown that sensorimotor memory becomes more salient as an indication of required force than the association between size and weight; therefore, the kinematic system acts on the knowledge of the true weight of the object rather than relying upon the correspondence (Flanagan, King, Wolpert, & Johansson, 2001). During judgements of weight however, it appears that the correspondences between size/material and weight are utilised more often. Therefore, it might not be expected that kinematic differences for brighter and darker objects would be observed after the motor system has had sufficient experience with objects to make corrections to weight predictions.

An alternative outcome is that despite stating an expectation that darker objects would be heavier, they act upon the objects as though they are the same weight. There are a few explanations which might clarify an absence of differences in the kinematic measures for darker and brighter objects. Firstly, it might be that participants do not use brightness as a cue for weight, unless specifically asked to distinguish weight expectations. Alternatively, although participants might expect objects to be marginally different in weight, the magnitude of this difference is not great enough to elicit differences in kinematics. Similarly, it might be the case that the correspondence is not recognised at all levels of processing. As discussed in the literature review, different types of crossmodal correspondences are thought to be processed at different levels. Correspondences between complex stimuli, such as words and images, are thought to rely on high-level cognitive matching, which is based on meaning (Parise, 2015). Crossmodal correspondences between stimulus features, such as pitch and brightness, are thought to be processed at an intermediate level, as they contain low-level, basic stimulus features, but they have also been suggested to be influenced by and influence upon higher-level cognitive factors (Spence, 2011). If correspondences are processed at an intermediate to high-level, it is possible that action is not guided by these processes. In other words, it is possible that action is a more automatic process which is largely unguided by higher level processes.

Any of the mentioned outcomes will help to shed more light on the brightness-weight correspondence and the situations in which it is revealed. The current research is exploratory, and as such we do not predict whether we expect to see evidence of the brightness-weight correspondence through kinematic analysis. Although verbal reports show evidence of the brightness-weight correspondence, it is not clear whether the correspondence will affect actions.

To help to understand the results, it is considered important that there are test objects which any effects of brightness on kinematics can be compared against. Objects which vary obviously in terms of expected weight, are expected to elicit a variety of differences across kinematic measures, for example differences in grip aperture and approach velocity. Data on such objects allows a comparison of what kinematic differences are observed between objects which clearly vary in terms of expected weight, and which if any, kinematic differences are observed between objects which have a less obvious cue to weight (brightness). The obvious weight cue chosen for this experiment was volume. Objects which had identical grip requirements but varied in overall volume were thought to be a strong indication of expected weight.

Summary of Study Rationale

In summary, the current study aims to examine whether participants selectively prepare their actions for differently weighted objects, using the cue of brightness. As the black and white stimuli are equally weighted they have identical lifting requirements and are otherwise identical in appearance. Consequently, any significant differences in the chosen kinematic measures can be attributed to the selective preparation made based on the cubes' surface brightness. The measures discussed previously will be used to assess selective preparation; this includes both approach measures, taken before contact is made with the object, and transport measures, taken before sensory-based adjustments are made to the lift.

3.1.2 Method

3.1.2.1 Participants

Twenty-six undergraduate students (24 females and 2 males, aged 18 to 20 years) at Lancaster University completed the experiment. Data from eight participants were excluded from analysis; five due to technical or experimenter errors (e.g. presenting in wrong order, failure to record), one because they were left-handed, and two because they did not correctly follow the instructions regarding how to lift the object. This meant that the final sample consisted of 18 undergraduate students (17 females and 1 male, aged 18-20, M_{age} = 18.28 years).

Handedness was assessed with the Edinburgh Handedness Survey. Only right-handed participants were included in the experiment as previous research shows differences in the experience of weight illusions across left and right handers, with only right handers experiencing asymmetry for their dominant and non-dominant hand (Buckingham, Ranger, & Goodale, 2012).

This research gained approval from Lancaster University Ethics Committee. Participants were given information and consent forms upon arrival which they were asked to sign. At the end of the study, participants were given a debrief and were reminded of their right to withdraw their data from the study for up to one month after the study. Participants were reimbursed for their time.

3.1.2.2 Stimuli

To help adults to become familiar with the task, the twelve grey objects illustrated in Figure 4 were presented to participants. These were three cubes (5cm height x 5cm width x 5cm depth), three cylinders (4cm diameter, 5.5cm height), three spheres (16cm diameter, 5cm height) and three egg shapes (6.5cm height, 16cm diameter). The sphere and egg shapes had small disks on the base to keep objects upright and stop them from rolling. Each object had three weighted versions: a light (50g), medium (100g), and heavy version (150g).

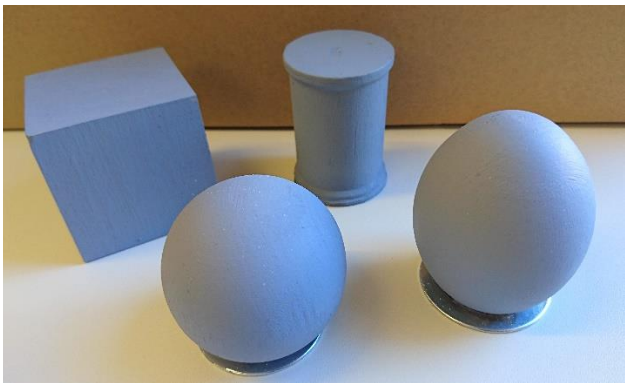


Figure 4. The familiarisation blocks presented before test trials in Experiment 2.

Differently weighted and differently shaped items were presented to encourage participants to think about the weight and hence the control requirements of test objects during the task. This emphasis on thinking about possible control requirements was considered to be important for the test phase. The familiarization phase was therefore important for two reasons, firstly to get participants used to the task at hand, and also to cue participants to think about control requirements. Repeated presentation of the same object of the same weight for the familiarization phase might lead participants to act automatically without considering these requirements.

Figure 5 illustrates the test objects, each measuring 5cm x 5cm x 5cm and weighing ~ 100g (Black – 100.4g; White – 101.6g). These were the same as the test objects from Experiment 1. One of these test cubes had a darker, black surface (27.46cd/m^2), and the other had a brighter, white surface (364.9cd/m^2).

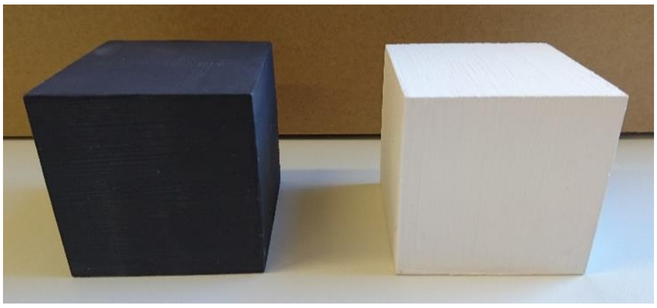


Figure 5. Black and white blocks presented alternately in test trials.

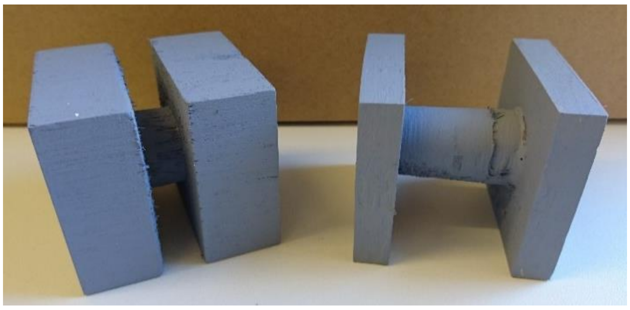


Figure 6. High (short rod) and low-volume (long rod) blocks presented alternately in test trials.

There were two additional objects that were thought to vary more obviously in terms of perceived weight (see Figure 6). Each object had two blocks connected by a thin rod. One object had wider blocks (2cm width) and a short connecting rod; the other object had thinner blocks (1cm width) and a longer connecting rod. The object with wider blocks was heavier as it had a greater volume (74.92g), than the object with thinner blocks which had less volume (44.84g). The width of blocks was thought to be a relatively clear indication of weight based on volume of identical material. The objects were both grey with the same overall grip diameters (5cm width x 5cm height), with volume and weight being the only obviously defining properties between the two. Other obvious weight cues, such as size, have different grip requirements thought to influence the approach towards the object, regardless of weight.

3.1.2.3 Apparatus

A Flex 3 OptiTrack Motion Capture System, recording at 100Hz, was used to measure participants' hand movements when reaching for and transporting objects. Four cameras were placed around the lab, sufficient for capturing the entirety of the movement. The participant wore a velcro wristband and two velcro rings on the thumb and index finger, each with one reflective dot. The infrared from the motion capture cameras picked up and recorded the movement of each of these reflective markers.

The objects were individually presented to participants on a flat table. They were always placed 29cm from the near edge of the table and at the participant's midline. Piloting revealed that it was best to place objects straight on to ensure that the connecting rod could be seen. The task was to lift the objects onto a 10cm high grey platform, placed 42cm from the edge of the table.

Participants were asked to wear a pair of glasses throughout the experiment, which the researcher could mist and demist when required. The researcher would mist the glasses during presentation of the object to prevent participants from using any indirect cues from the researcher to deduce how heavy the object was. Once the object was placed in front of the participant, the glasses would demist so the participant could see and lift the object. Once the participant had lifted the object onto the platform, the glasses would mist again, ready for presentation of the next object.

3.1.2.4 Design

The dependent variables in this study were the kinematics of participants' reach, grasp, and transportation of objects. These included: peak and average velocity of approach and transport, peak and average acceleration of transport, and maximum grip aperture on approach to object (MGA). These variables were used to examine whether kinematics vary alongside the brightness/volume, and therefore anticipated weight of the object.

Participants were all given the twelve grey familiarisation objects in a pseudo-random order, whereby no same shape was experienced after another. Half were presented with the grey objects in the random order, and half in the reversed version of this random order. The medium weight cube was always presented first and then again last to ensure that the most recent weight and shape would not guide expectations in one direction for the test objects presented next. It was also thought that the first object experienced might also be more likely to guide expectations, so a neutral, medium weight cube was presented.

There were two test sections within the experiment: the brightness stimuli presentation and the volume stimuli presentation. The brightness cubes were always presented before the volume objects, as they were the primary test objects of interest. Ten participants were presented with the black cube first and eight were presented with the white cube first. Within these two groups, ten received the short rod object first and eight received the long rod object first. This produced four groups distinguished by order: black first and long rod first, black first and short rod first, white first and long rod first, white first and short rod first.

3.1.2.5 Procedure

Participants were given information and consent forms and given a short verbal description of what the study would involve. They were also asked to complete the Edinburgh Handedness survey.

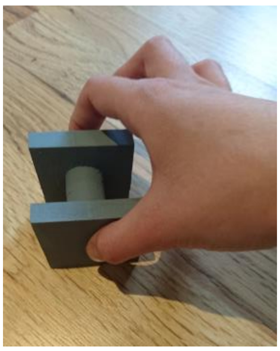


Figure 7. Photograph shown to participants to illustrate a pincer grip.

Participants were instructed to place their finger and index finger together on a small bump in the centre of the near-edge of the table until each lift began; they were also instructed to return to this position once the lift had taken place. When the glasses demisted, participants were asked to lift each object presented to them onto the grey platform ahead. They were asked to lift using a pincer grip, with the thumb and index finger. As illustrated in Figure 7, they were also shown a photograph of a pincer grip to clarify how the objects should be lifted. They were informed that once they let go of the object, the glasses would mist again until the next object was presented.

Firstly, participants were presented with all twelve of the grey familiarisation objects. Once the grey objects had all been placed onto the platform, the brightness-weight test objects were presented. After the presentation of twelve grey objects, it was anticipated that a black or white object might come as a surprise. The variety of object weights was intended to cue participants that weight would vary across this experiment. Participants were presented with either the black cube followed by the white cube or the white cube followed by the black cube. Alternation of black and white cubes was repeated eight times with each object. Participants were then presented with the objects that varied in terms of volume. Participants were either presented with the long rod and then the short rod or the short rod and then the long rod. Alternation of long rod and short rod was repeated eight times with each object.

Throughout the experiment, the motion capture cameras recorded position data from the reflective markers which capture the movement of the participant's wrist, finger, and thumb.

When participants completed the experiment, they were debriefed and reminded of the right to withdraw their data from the study.

3.1.2.6 Data Coding

Reflective markers were placed on the wrist, thumb and index finger to examine kinematics during the action sequence. The finger and thumb markers determined the grasp kinematics, including grip aperture. The wrist marker determined the reach and transport kinematics, such as acceleration and velocity. Motive software provided an output for each marker, with xyz coordinates for each.

An experimenter coded three time phases in each trial: the reach phase, grasp phase and transport phase. The reach phase started when the participant began moving towards the object and ended when the participant first contacted the object. The grasp phase began at first contact with the object and ended as the object began to lift-off. The transport phase began as the object moved and ended when the object was placed on the platform. Within the transport phase there were two sub-phases, the first 500ms and the first 100ms of transport. As discussed previously, both of these times have been suggested as periods before which, actions are automatic and cannot be corrected. We chose to look at the kinematics during both time periods to examine whether they revealed different patterns.

3.1.2.7 Key Formula and Kinematic Information

The formulas and key information regarding how the kinematic measures were extracted from the motion capture output is discussed in the following section and displayed in Figure 8. The motion capture cameras provide raw data which contains only the position with regards to time for each of the three axes, for each of the three markers. A large amount of manual editing is therefore required to transform the position data into the chosen meaningful measures.

Velocity is a vector quantity which measures the rate of change in position in a particular direction; speed is a similar measure however it is a scalar quantity in which the direction is not distinguished. Acceleration is also a vector quantity which measures the rate of change of velocity, with respect to time.

As acceleration and velocity measurements from one axis (x, y, or z), provide information about magnitude and direction, it is possible to distinguish acceleration (+ value) from deceleration (- value), and velocity in one direction (+ value) from velocity in another direction (- value). However, it has been difficult to find a formula which adequately combines the x, y, z coordinates of position to calculate overall acceleration and velocity, whilst also keeping information regarding the direction of the movement. This is because individual coordinates must be squared during the addition process (see Figure 8). The resultant acceleration and velocity values only describe magnitude and omit direction, making it indistinguishable whether the object is accelerating in the positive direction (accelerating) or accelerating in the negative direction (decelerating), and also which direction the velocity values are in.

In the current experiment, acceleration and velocity are measured within the first part of the lift to see whether participants apply more force to objects that they expect to be heavier, subsequently displaying greater maximum values during transport, due to the equal weight of the objects. Because of the lack of direction, it is plausible that by using the resultant accelerations and velocities, maximum acceleration and velocity values could in fact be deceleration and velocity in the opposite direction, respectively.

1.Velocity Y $= \frac{Position\ Y_2 -\ Position\ Y_1}{Time\ taken\ Y} = \frac{Change\ in\ position\ Y}{Time}$

2.Acceleration Y $= \frac{Velocity\ Y_2 -\ Velocity\ Y_1}{Time\ taken} = \frac{Change\ in\ velocity\ Y}{Time}$

3. 3D Velocity= $\sqrt{\left(\frac{Change\ in\ position\ X}{Time\ taken}\right)^2 + \left(\frac{Change\ in\ position\ Y}{Time\ taken}\right)^2 + \left(\frac{Change\ in\ position\ Z}{Time\ taken}\right)^2}$

4.3D Acc= $\sqrt{\left(\frac{Change\ in\ velocity\ X}{Time\ taken}\right)^2 + \left(\frac{Change\ in\ velocity\ Y}{Time\ taken}\right)^2 + \left(\frac{Change\ in\ velocity\ Z}{Time\ taken}\right)^2}$

5.MGA: $\sqrt{((Position\ X\ thumb - Position\ X\ finger)^2 + (Pos\ Y\ th - Pos\ Y\ fin)^2 + (Pos\ Z\ th - Pos\ Z\ fin)^2)}$

Figure 8. Formulas used to calculate velocity (1) and acceleration (2) measures from a single axis or direction (y-axis) and formulas used to calculate velocity (3), acceleration (4), and MGA (5) measures using all three axes (x, y, and z).

It is suggested however, that in the current experiment, clear, pre-determined instructions on how the object should be moved from the starting point to the platform are described. It is therefore highly unlikely that a participant would choose to quickly move their hand in the opposite direction. Additionally, the average upwards (y axis) velocity is positive in the first section of the lift for 99.66% of trials. The 3D measures of acceleration and velocity were therefore used in the analysis.

There is a relationship between velocity and acceleration measures, however the measures have the potential to show different results. Between the start of movement and the maximum velocity, the acceleration is positive and reaches a maximum (see Figure 9). At the point of maximum velocity occurrence, there is zero acceleration. After the maximum velocity has occurred, the acceleration becomes negative (deceleration). As can be seen in Figure 9, peak acceleration and peak velocity occur at different time points.

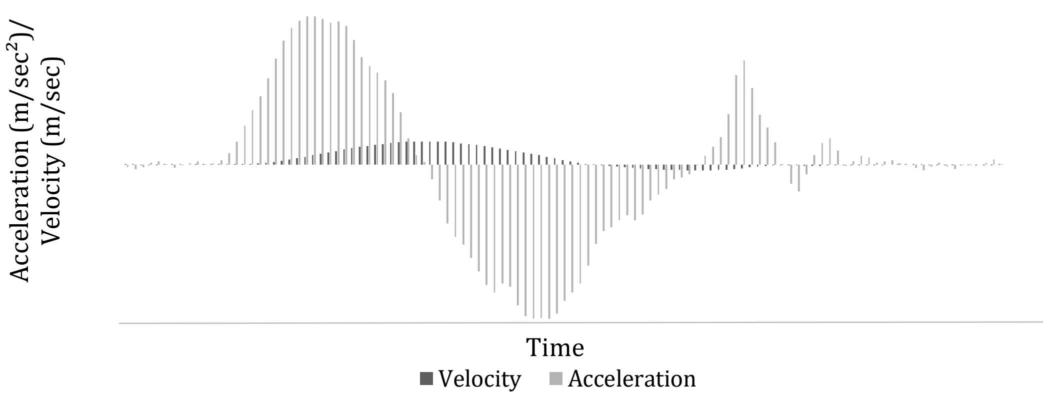


Figure 9. An example of the relationship between acceleration and velocity in the y axis for one participants' lift of an object.

3.1.2.8 Data Editing

Labelling

Occasionally, markers would become disconnected due to marker occlusion, if this occurred, the markers would be reconnected using the 'Quicklabel' function in Motive. Participants with substantial occlusion during the reach and grasp movements were excluded, those with occlusion before or after the lift were included in analysis. Markers were then labelled by a coder who went through data and labelled each marker as ‘wrist,’ ‘thumb’ and ‘finger.’ This was done post-processing as pre-defined rigid bodies were not used.

Fill gaps

Gaps in the data were interpolated using the ‘fill gaps’ function in Motive. Only gaps of 10 frames (0.1 seconds) or less were interpolated to avoid the reconstruction of inaccurate data.

Filtering

Initially these data were not filtered as the importance of this process was not identified. In hindsight, the filtering process was completed to reduce the noise in the data. The steps in this process and the decision regarding filter cut-off is discussed in more detail in Chapter 5. To summarise, a Butterworth low-pass zero-lag filter at 14Hz was applied to the data.

3.1.3 Results

3.1.3.1 Volume

Maximum grip aperture (MGA)

A repeated measures ANOVA revealed that there was a significant effect of volume on the maximum grip aperture (MGA) across all trials, $F(1, 16) = 33.398$, $p < .001$, $\eta_p^2 = .676$. The object with greater volume was approached with a significantly smaller MGA (M = 11.5cm) than the object with the smaller volume (M = 11.8cm). This finding was consistent across all trials as there was found to be no significant interaction between object volume and trial, $F(7, 112) = 1.720$, $p = .111$, (see Figure 10). There was also a significant effect of volume on

MGA in the first pair of trials, F (1, 16) = 19.891, $p < .001$, $\eta_p{}^2 = .554$.

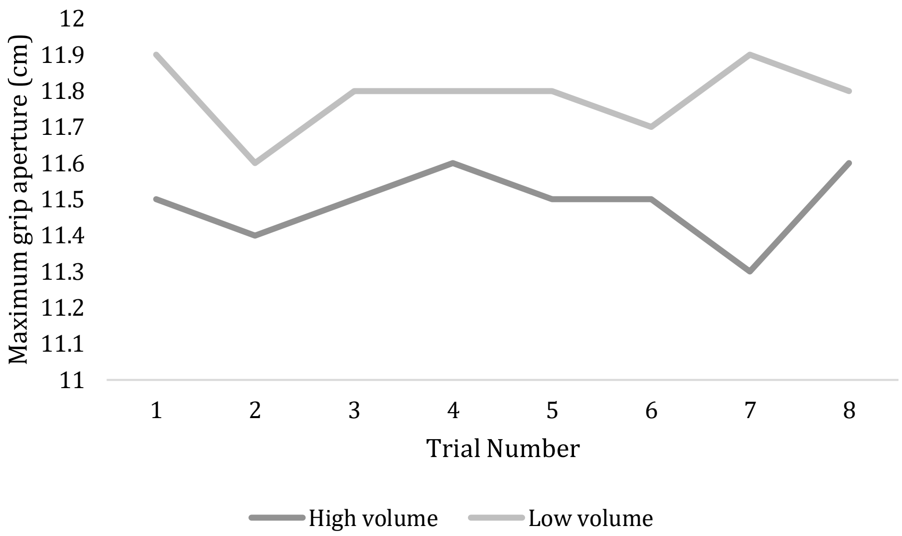


Figure 10. The significant effect of object volume on MGA and the absence of an interaction between object volume and trial.

There were no significant differences in the peak velocity during the approach to the objects, (see Table 1).

3.1.3.2 Brightness

There were no significant differences in the approach towards black and white objects, (see Table 1).

Table 1.

Mean values and p values for each kinematic measure during approach to objects which vary in volume.

	Object Width			Object Brightness		
	Short-rod	Long-rod	*p*	Black	White	*p*
All Trials						
Peak approach velocity (mm/s)	698	699	.820	706	710	.562
MGA (cm)	11.5	11.8	*****< .001**	11.5	11.4	.178
First Pair of Trials						
Peak approach velocity (mm/s)	684	651	.123	680	690	.553
MGA (cm)	11.5	11.9	*****< .001**	11.4	11.4	.946

Note: Bold entries are significant or marginally significant results ($p < .001$ ***, $p < .01$ **, $p < .05$ *).

Time before sensory-based adjustments are made

Examination of the data revealed that in the first 100ms of the lift, 37% of maximum wrist velocity values were less than 50mm/s. This is problematic because previous research has suggested that the point of lift-off should be identified from the moment when velocity reaches a minimum threshold of 50mm/s (Mash, 2007). A maximum velocity of less than this in the first 100ms of the lift suggests that by typical criteria, lift-off has not yet taken place. We therefore propose that whilst the rater who coded the data frame-by-frame might have identified the very first frame at which lift-off was thought to occur; this time point is earlier than what is typically used to identify take-off.

In the current experiment, the decision was therefore taken to examine the acceleration and velocity measurements only in the first 500ms, for which the maximum velocity was more than 50mm/s in almost all trials. The maximum velocity for the first 500ms was the same as the maximum velocity for the entire transport across most of the trials, and it was therefore not necessary to look at the entire transport phase separately.

To enable the examination of earlier sections of the lift, a subsequent solution was implemented in Experiment 4. The rater still manually examined the videos to establish the important time points (reach begins, first contact with object, take-off with object); however measurements for the take-off are not examined until the velocity has also reached 50mm/s. Measurements 100ms and 500ms from this point are then examined.

The analysis in the current experiment initially examined whether there was a difference in reach and transport measurements on the first pair of trials, which included one black and one white lift. The analysis subsequently focussed upon whether there was a difference in measures for black and white cubes across all trials. This distinction was made to enable the analysis of whether there was evidence of corrections to initially erroneous lifts, based on expected weight.

Lift Velocity

A repeated measures ANOVA revealed a marginally significant effect of brightness on the average lift velocity (first 500ms) in the first pair of trials, F (1,

16) = 4.001, p = .063, $\eta_p{}^2$ = .200. The black cube (M = 358mm/s) was transported with a greater average speed than the white cube (M = 333mm/s), (see Figure 11). There was no interaction between brightness and condition, suggesting that whether participants were presented with black or white first did not alter the effect of brightness on average velocity, F (1, 16) = 1.197, p = .290.

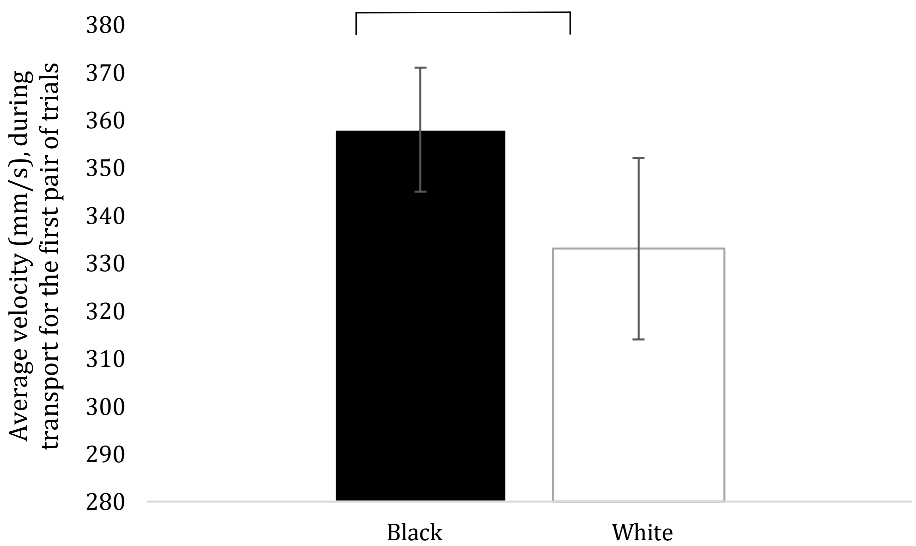


Figure 11. A graph demonstrating the marginally significant difference (p = .053) between the average transport velocity of black and white blocks in the first pair of trials.

A repeated measures ANOVA also revealed a marginally significant effect of brightness on the average lift velocity (first 500ms) across all trials, F (1, 16) = 4.367, p = .053, $\eta_p{}^2$ = .214. The average speed of transport for the black object (M = 363mm/s) was again greater than for the white object (M = 354mm/s), (see Figure 12).

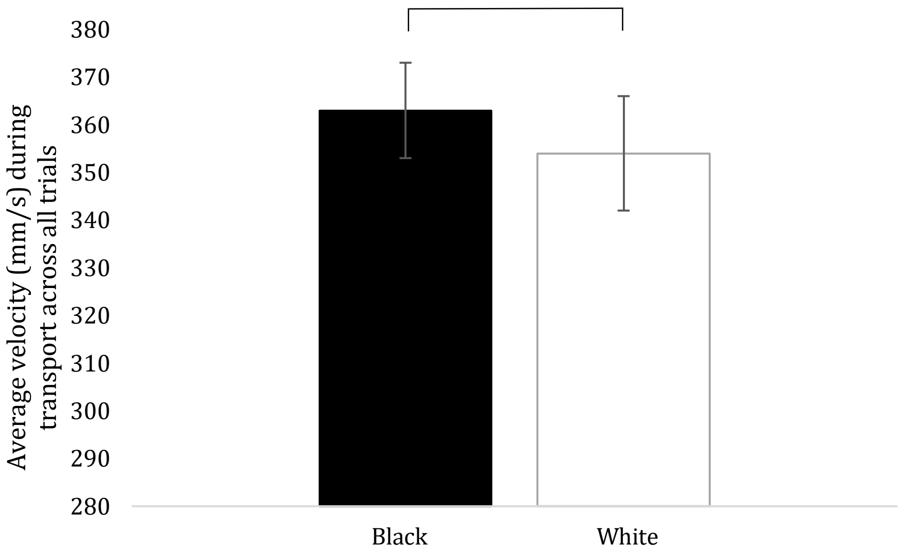


Figure 12. A graph demonstrating the marginally significant difference (p = .063) between the average transport velocity of black and white blocks across all trials (p < .001 ***, p < .01 **, p < .05 *)

Whilst the average lift velocity was greater for the black cube than the white cube, there was no significant effect of brightness on maximum lift velocity, $F (1, 16) = .152$, $p = .702$, (see Table 2).

Table 2.

Mean values and p values for each kinematic measure during transport of objects.

	Object Brightness		
	Black	White	*p*
All Trials			
Maximum acceleration	3.385	3.457	.484
Average acceleration	1.964	1.964	.983
Maximum velocity	582	580	.702

Average velocity	363	354	**.053**
First Pair of Trials			
Maximum acceleration	3.221	3.743	.277
Average acceleration	1.921	1.912	.917
Maximum velocity	583	581	.876
Average velocity	358	333	**.063**

Note: Bold entries are significant or marginally significant results ($p < .001$ ***, $p < .01$ **, $p < .05$ *).

3.1.4 Discussion

3.1.4.1 Volume

As discussed previously, the findings regarding the influence of weight expectation upon maximum grip aperture are mixed. Whilst there is evidence that heavier objects are approached with a wider grip to ensure a precise and secure grip (Eastough & Edwards, 2007), there is also evidence of lighter objects being approached with a wider grip aperture when the object also has a rougher surface (Paulun et al., 2014). It was therefore difficult to predict if and how the grip aperture might vary across the stimuli used in the current study.

The results of this study demonstrate that the high volume, heavier, object is approached with a smaller grip aperture than the low volume, lighter, object. As the object with greater volume was rated as heavier by 95% of participants (see note on data not analysed), it is extremely unlikely that the smaller grip aperture is the result of expecting a lower weight. Although possible therefore, that the smaller grip was an adjustment to the heavier weight of this object, to our knowledge no suggestion has yet been made regarding why heavier objects would be approached with a less precise grip in this way. Two alternative explanations are thought to better explain the difference in grip aperture. The first explanation suggests that although the high volume object is heavier, it is also less fragile than the low volume object. In hind-sight the low volume object appears substantially less stable than the high volume object due to the longer rod supporting the side blocks. In the introduction, the suggestion was made that grip aperture might be adjusted to suit the precision requirements of the objects. In this case, it is suggested that participants might have approached the low volume object more cautiously, with a wider grip aperture, to ensure a secure, precise, grip on the more fragile object.

Another potential explanation is that participants experienced a visual illusion whereby the lower volume object, which had a longer central rod, was perceived as wider. Upon closer inspection, the longer rod appeared to extend the overall width of the low volume object. If participants perceived the object with less volume as being wider, it would follow that they would most likely approach with a wider grip aperture, regardless of weight.

The MGA was wider for the lower-volume object both in the initial pair of trials, and across all successive trials. If the greater MGA was the result of either of the previous explanations, it follows that the grip would remain wider for the low-volume object across subsequent trials. In the case of the first explanation, the low-volume object remains equally fragile throughout the entire experiment, and the requirement to establish a secure grip remains across all trials. Alternatively, if participants perceived the low-volume object as wider than the high-volume object, the wider grip aperture would also persist, unless the participants realised that there was no difference in actual width.

Both possible explanations for why the low-volume block is approached with a wider MGA, suggest that interpretation of the approach to objects based on weight is problematic. These stimuli were designed to be identical in terms of lifting requirements, other than in terms of weight. The stimuli were included to allow for the comparison of approach to objects which have a clear cue to weight (volume), and objects which have a potentially less clear cue to weight (brightness). However, it is proposed that the fragility and perception of width created different perceived requirements for the high and low-volume objects, making the data uninterpretable in terms of weight. Therefore, in Experiment 4, alternative stimuli were used to examine selective preparation based on an obvious cue to weight (material).

3.1.4.2 Brightness

Although the approach did not appear to be selectively prepared for the cubes with differing surface brightness, there was a marginally significant difference in the transport of the two cubes. In the first 500ms of the lift, the average velocity of the wrist was greater for the black cube, compared to the white cube. As discussed extensively in the introduction, 500ms has previously been suggested to be the time point before which sensory-based adjustments to unexpected weight cannot be made. It is therefore suggested that black objects are lifted with greater force, due to the larger expected weight, and are therefore lifted at a greater initial speed. In contrast, white objects are expected to be less heavy and are therefore lifted with less force, resulting in a lower initial speed.

It is important to discuss the fact that greater velocity for the black cube was observed both in the first pair of trials, when the objects were experienced for the first time (p = .063) and across all subsequent trials (p = .053). Previously, research has suggested that the motor system adapts relatively quickly to inaccurate weight predictions, utilising sensorimotor information received from previous lifts to adapt to the physical requirements of the object (Baugh et al., 2012; Flanagan et al., 2008). The number of lifts required before corrections are made is thought to rely at least in part on the specific features of the object and its weight. Whilst it is unlikely to be consistent how many lifts it takes for the motor system to make the relevant corrections, previous research has found evidence that by the 10th lift, forces were appropriately scaled to actual object weight. It is not clear however, at which point this correction is made (Baugh et al., 2012). Some might therefore find it surprising that erroneous lifts were observed in the current study across the duration of the experiment, suggesting there was not an adaptation to the actual weight of objects. One suggestion is that the variation in actual weight from expected weight in this study would not be especially high. For example, if participants expected the black cube to be heavier than the white cube, it is unlikely that they would expect it to be a lot heavier. Participants might therefore not notice that the speed of transporting the black (M = 363mm/s) and white cubes (M = 354mm/s) differs as the difference between mean values is only 9mm/s. Subsequently, participants might persist with slightly erroneous lifts. If the object was substantially lighter than expected, it might be transported substantially more quickly, and therefore noticed and corrected earlier in the lift sequence. For example, if the difference in transport speed was 100mm/s, the difference might be observed and corrected.

3.1.4.3 Concluding Remarks

Taking the results of Experiment 1 and 2 together, evidence is provided of appreciation of the brightness-weight correspondence, and also early evidence of selective preparation for weight on the basis of brightness.

Additional research is required to establish why the brightness-weight correspondence acts on some measures and not on others. Further work into this will help to establish which are the most appropriate measures when studying this area. Research is also required to establish the extent to which this finding can be generalised more broadly. Chapters 4 and 5 discuss the further research which was conducted to attempt to address some of these questions.

Note on additional data not analysed

In the previous size-weight literature, verbal and action data are collected simultaneously by gathering kinematic data as participants reach for objects and then asking participants about their perception of the objects' weight after each lift is complete. The benefit of such an approach is that it provides evidence of the independence of the visual and motor systems by showing the time-course of the kinematic adaptations alongside the verbal report of either a correspondence or an illusion (Buckingham et al., 2009; Flanagan & Beltzner, 2000; Grandy & Westwood, 2006). By doing so, however, an explicit focus is placed on weight. As we wanted to examine the more natural occurrence of a correspondence between brightness and weight, we chose not to collect verbal measures throughout the study. This means that we will be unable to draw any conclusions about the rate of adaptation of the motor system, in comparison to the perceptual system.

To attempt to examine verbal perceptions of weight, we asked participants to rate the weight of four objects at the end of the kinematic experiment: 2 wooden spheres (black and white), and 2 volume-weight objects (same as in the kinematic study but larger in scale).

Unfortunately, we concluded that the analysis of this data was not feasible as it was not clear whether participants made judgments based on the objects they had already seen or whether they were treating the objects as new. It is proposed that Experiment 1 more accurately examines participants' weight perception, before any interference from interacting with the objects.

3.1.5 Follow-up Study From Experiment 2

Resulting from Experiment 2, a short follow-up study was conducted. The black and white stimuli used in the experiment were almost identical in weight, but there was a very small difference of 1.1g. The white cube weighed 101.6g, but the black cube was slightly lighter at 100.4g. It has previously been suggested that the Weber fraction at 100g is around 0.10, meaning that individuals can only detect a difference in stimulus intensity, in this case weight, of 10% or more (Ross & Brodie, 1987). According to this finding it would be expected that a difference in weight would only be identified at less than 90g or more than 110g, however it was thought to be important to confirm this. At heavier weights the Weber fraction has been shown to get smaller; for example the Weber fraction for weights ranging between 8.6kg to 29.1kg is between 0.03 and 0.04, meaning that a difference of between 3%-4% can be detected (Karwowski, Schumate, Yates, & Pongpatana, 1992).

Unfortunately, because of the direction of the difference, the difference in weight could plausibly be used to explain the finding of differentiated velocity during transport. As the black cube was slightly lighter, it is possible that if the same amount of force were used, the black cube would subsequently be transported more quickly.

The following study therefore addresses this question by examining whether participants could detect the small difference in weight between the three cubes used in Experiment 2, when they could not see them. Twenty-seven participants took part in the study and all were included in the analysis (7 males and 20 females, M_{age} = 21.3 years).

Participants were given the three cubes from Experiment 2 in pairs (5cm x 5cm x 5cm), and all combinations of cubes were presented with each cube presented on both the left and the right sides, producing six trials. They were randomly allocated to the order of cube presentation in one random order or the reverse order. Participants wore the misted glasses for the duration of the experiment, so they could not see the objects during the lift. They were asked to lift the objects consecutively and respond when asked ‘Which object feels heavier?’

Analysis of responses revealed that there was no significant effect of object weight on participants’ judgements of weight, without vision, $F(2, 50) = 1.647$, $p = .203$. There was however a significant effect of side on participants’ judgements of weight, $F(1, 25) = 9.869$, $p = .004$, $\eta_p^2 = .283$. Participants reported that the object was heavier when it was presented on the left significantly more often than when it was on the right.

The results of this follow-up study suggest that participants are unable to distinguish the maximum weight difference of ~1g when asked to make a perceptual decision. Whilst this suggests that the small difference in weight was most likely unnoticeable during transport; it is still possible that the difference in weight is responsible for the effect of brightness on transport velocity. As discussed previously, the marginally higher weight of the white block might explain why it was transported with less velocity than the black block. It was therefore considered necessary to absolutely equate the weights to test this argument in Experiment 4.

CHAPTER 4

Perception of the Brightness-Weight and Material-Weight Correspondences

4.1 Experiment 3: Perception of the Material-Weight Correspondence, and the Brightness-Weight Correspondence in Plastic Stimuli

4.1.1 Introduction

Experiments 1 and 2 have demonstrated evidence of a brightness-weight correspondence revealed through verbal report and kinematic measures, when stimuli are made from wood. This chapter discusses the potential issues which arise with assuming that finding a brightness-weight correspondence with wooden objects means that the correspondence will be observed with objects made from other materials. The following two chapters explore the possibility of the generalisation of the brightness-weight correspondence to other, manufactured materials, by conducting further experiments which feature stimuli made from plastic.

It has been proposed that surface brightness and weight might be linked in the natural world, although not consistently. For example, when many common materials become wet, they simultaneously become darker and heavier; examples include fabric, wood, soil, and sand (Walker et al., 2010). However, other commonly encountered materials such as plastic, metal, and glass do not experience this transformation. It is therefore suggested that whether a material naturally reflects the brightness-weight correspondence should be considered when choosing stimulus material.

Experiments 1 and 2 used wooden stimuli, a material for which natural changes in colour have also been associated with changes in weight, both in terms of what happens when it becomes wet, and in terms of density differences between types of wood (Edlin, 1969; Walker et al., 2010). As mentioned in the literature review, an analysis of Edlin's (1969) wood samples showed that darker wood tended to be heavier than lighter coloured wood. The stability of this association can be questioned as the density of woods do not vary substantially in all conditions, and importantly when Ebony is removed from the sample, the association becomes insignificant. Though it seems that there might be some relationship between the colour of wood and its weight, the evidence thus far is inconclusive. Subsequently, it is not yet possible to establish the possible causal role that a naturally occurring relationship might play in the brightness-weight correspondence. Using wooden stimuli, it is difficult to generalise findings of a correspondence to objects made from materials which do not have such a co-occurrence.

The following experiment will replicate the methodology from Experiment 1 with stimuli made from plastic. This change in stimuli will enable the examination of whether the brightness-weight correspondence occurs in objects which are made from a material which does not have a natural co-occurrence of brightness and weight. As the evidence for a natural association in wood is so far very slim, we expect to replicate the findings from Experiment 1 and from Walker et al. (2010), showing evidence of a brightness-weight correspondence, and a brightness-weight illusion.

Evidence of the brightness-weight correspondence when presented with plastic objects might have multiple interpretations. An initial interpretation might be that naturally occurring differences in weight correlated with brightness do not cause the correspondence, as it is observed in materials whereby environmental changes do not have the same impact. However, such an interpretation should be made with extreme caution. It is still possible that observation of the correspondence between brightness and weight in natural materials, such as wood or sand, are used to form expectations about the weight of objects; even when objects are made from materials whose weight does not vary alongside brightness naturally.

The material chosen for these experiments is plastic (specifically, Polylactic Acid, PLA). PLA is less absorbent than wood, with an absorption rate of ~1% in 24 hours for raw PLA, compared with ~25% for wood (Klyosov, 2007; Wang, Sun & Seib, 2002). Subsequently, PLA has less variation in weight and less changes in colour alongside water absorption. It therefore follows that weight and colour are less likely to change substantially alongside one another, overcoming concerns of a direct link between the material, brightness and weight in the environment. Objects made from PLA or similar materials should be relatively familiar to participants as it is becoming increasingly popular across a range of different industries, partially due to being biodegradable. It is used for a variety of different purposes, including but not restricted to: the casing of electronic devices, children's toys, gift cards, bottles and food packaging (Tin Sin, Rahmat, & Rahman, 2013).

An additional reason for using plastic objects as an alternative to wood is how convincing their brightness is. The previous experiments in this thesis used wooden stimuli with a painted surface. It has since been considered this method might not persuade participants that the entirety of the object is made of that shade, and that rather the cubes are identical, covered in different paints. If the whole object is perceived to be composed of the surface brightness, then more of the object has the variation in object brightness. It is proposed that in this situation, a stronger brightness-weight correspondence might emerge than when only the surface appears to vary. The PLA objects were made using black, white, and grey filament on a 3D printer (Lancaster Product Development Unit, Lancaster University Engineering Department), and therefore did not need alterations made to their surface.

The compromise of using the 3D printing method is that the filaments come in a more limited range of colours. The black and white objects are very similar in colour to the paints used in the wooden studies, however the grey plastic cube (155.98cd/m^2) is considerably lighter than the grey wooden cube (103.23cd/m^2). This causes problems if trying to make direct comparisons of the results from the wooden and plastic studies. As the brightness of the grey plastic cube is more closely aligned to the white cube than the black cube, we might expect to see a smaller distinction between the perceived weight of these two cubes than in the wooden version of the study, whereby the grey cube was darker. As the grey cube is primarily included as a comparison object, this should not be problematic, especially considering the white (382.93cd/m^2) and black (8.15cd/m^2) test objects are closely aligned to the brightness levels in the previous wooden study (364.9cd/m^2 and 27.46cd/m^2, respectively).

As in the previous studies, it was thought to be important to also have a pair of stimuli which were expected to vary obviously in terms of weight. These stimuli enable the comparison of weight judgements when there is an obvious cue to weight and when there is a less obvious cue to weight (e.g. brightness). Without any comparison stimuli it would be difficult to disentangle whether the potential absence of an effect of brightness on expected weight was due to the method or due to the lack of a correspondence. Any differences found in the objects which vary obviously in expected weight may therefore be expected to be seen across objects which vary in brightness if there is a brightness-weight correspondence. Similarly, any illusory effects after lifting these objects can be compared with the presence or absence of illusory effects after lifting brightness-weight objects.

Whilst in the previous experiments volume was used as an obvious cue to weight, in the current experiment, material (sand and pompoms) was used as a cue to weight. Previous research demonstrates evidence of a material-weight correspondence whereby objects made from denser materials are judged to be heavier than those made from less dense materials before lifting. Research also demonstrates evidence of a material-weight illusion where objects made from a denser material are judged to be lighter than those made from a less dense material after lifting (Baugh et al., 2012; Buckingham et al., 2009; Buckingham et al., 2011). Whether participants use material as a cue to weight and whether they report evidence of a material-weight illusion after lifting the objects will therefore also be examined within this study. Evidence of a material-weight correspondence and an illusion is expected to be demonstrated, based on the previous findings (Baugh et al., 2012; Buckingham et al., 2009; Buckingham et al., 2011).

4.1.2 Method

4.1.2.1 Participants

Forty-eight participants completed the experiment at Lancaster University. The sample included 30 males and 18 females, with an age range of 18–64 years (M_{age} = 23.5 years).

This research gained approval from Lancaster University Ethics Committee. Participants were given information and consent forms upon arrival which they were asked to sign. At the end of the study, participants were given a debrief and were reminded of their right to withdraw their data from the study for up to one month after the study.

4.1.2.2 Stimuli and Apparatus

Brightness-weight

Three polylactic acid (PLA) plastic cubes were used for the brightness-weight element of the study. The cubes measured 5cm x 5cm x 5cm, as in the previous study. The weights of the cubes were an average of 100.75g (White = 100.74g, Grey = 100.74g, Black = 100.76g). The cubes varied only in terms of brightness: white (382.93cd/m^2), grey (155.98cd/m^2), and black (8.15cd/m^2), (see Figure 13).

Figure 13. Black and white plastic test blocks and grey plastic familiarisation block used in Experiment 3.

Material-weight

The material-weight stimuli were designed to provide a more obvious cue to weight difference. The stimuli were two 125ml, transparent, food boxes which measured 6.8cm x 6.3cm x 6.3cm. Boxes were turned upside down so that the lid was at the bottom, each box appeared to be filled with either 7mm red pompoms or red sand (see Figure 14). These materials were thought to be obvious cues to weight, with sand expected to be heavier and pompons expected to be lighter. The boxes were manipulated so that their weight was the same, despite the large original weight difference. A cork was placed in the centre of the cube, out of view, and weights were added to this in the pompom tub and removed from the sand tub to make the boxes weigh the same. The sand box weighed 154.73g and the pompom box weighed 154.72g. This difference is substantially less than the 10% which has previously been found to be detectable at around 100g (Ross & Brodie, 1987). The colour and brightness of the sand (94.85cd/m^2) and pompoms (75.92cd/m^2), were controlled to be as close as possible, to ensure that this did not interfere with the perceived weight. The sand (expected to be heavier) was marginally brighter than the pompoms (expected to be lighter), however because of the direction of this difference, brightness could not explain any congruency effects between material and weight.

Objects were presented on a wooden tray which measured 34cm x 26.5cm x 4.5cm. Cubes were spaced evenly on the tray, each 5cm apart.

Figure 14. Sand and pompom test blocks used in Experiment 3.

4.1.2.3 Design

All participants saw all the stimuli but were split into two counterbalanced conditions: those who saw the material-weight objects first and those who saw the brightness-weight objects first. Within these conditions there was also counterbalancing of the position in which the objects were shown. For example, one group saw the black on the left, white in the middle, and grey on the right. All combinations of the brightness-weight objects produced six conditions. For the material-weight part of the task, there was counterbalancing of the position of the sand box and the pompom box; this produced an additional two conditions. An equal number of participants were assigned to each group.

4.1.2.4 Procedure

The procedure was very similar to the procedure in Experiment 1. Participants were given information sheets and consent forms and were told that the study would take a maximum of fifteen minutes. For the brightness-weight element of the experiment, participants were asked to 'Point at the three cubes, starting with what you think is the least heavy, going up to what you think is the most heavy. Make your decision only by looking at the objects and do not lift them.' The experimenter recorded participants' responses and then asked participants to lift each object up and then place it back down again. Participants were then asked 'What do you think about the weight of the objects now? Point at the objects starting with what you think is the least heavy and going up to what you think is the most heavy.'

The identical procedure was followed with the material-weight objects. Participants were asked to 'Point at the object which you think is more heavy.' They were then asked to lift both objects and then asked 'What do you think about the weight of the objects now?' In both parts of the study, participants could lift the objects multiple times and were not required to distinguish the weights of the objects, if they felt that they weighed the same.

4.1.3 Results

4.1.3.1 Brightness

During the analysis, ratings of weight were examined in pairs, before and after lifting the brightness objects. Ratings were compared to the expected order using Kendal's tau, as in Experiment 1. If the rating order was as expected (white $<$ grey $<$ black), a score of 3 was assigned. If the rating was the exact opposite to the expected order (white $>$ grey $>$ black), a score of 0 was assigned, demonstrating that none of the pairs matched in the expected order. Scores could range from 0-3, depending on how many pairs matched in the expected order. For example, if black was rated as heavier than white and grey, but grey was rated as lighter than white (black $>$ white, grey $<$ white, black $>$ grey), a score of 2 would be assigned as two of the pairs were in the expected direction. Each pair that was rated as the same was given a score of 0.5 and therefore if participants stated that all the objects weighed the same, a score of 1.5 was assigned. A tau score of 1.5 is the null value, which suggests that the order of weight expectations is random.

Using a one sample t-test, the tau values before and after lifting were compared to the null value (1.5). Figure 15 indicates the tau values before and after lifting. Before lifting, the tau value was shown to be significantly greater than the null ($t(47) = 4.56$, $p < .001$, $d = 0.66$). After lifting, the tau value was not significantly different from the null value ($t(47) = -0.17$, $p = .864$, $d = -0.02$). This finding suggests that before lifting, participants matched above chance in the expected direction; stating that the brighter block was lighter in weight than the darker block. After lifting, participants did not rate the weight of objects significantly differently from chance. They did not report that objects weighted in the expected order more than chance, nor did they report that the objects were the reverse of the expected order more than chance.

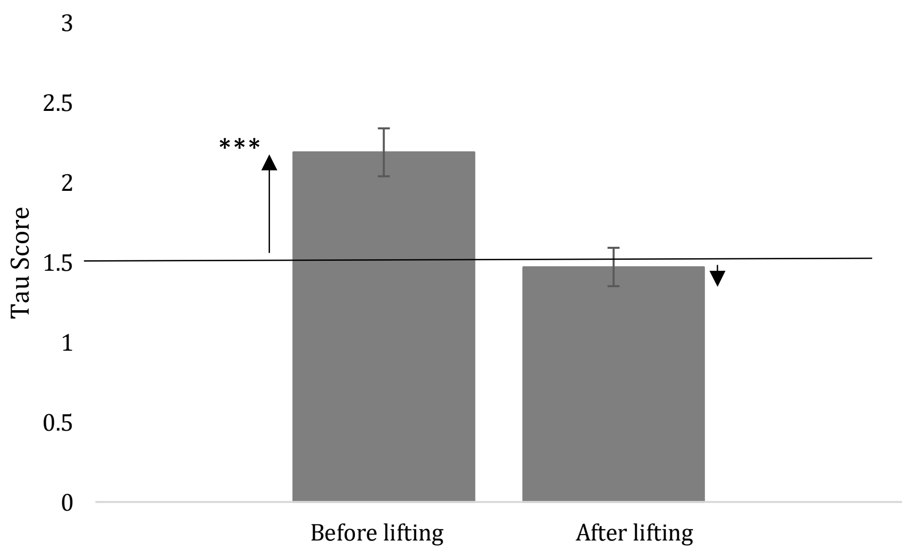


Figure 15. A graph demonstrating the change in rating of weight before and after lifting objects which vary in brightness ($p < .001$ ***, $p < .01$ **, $p < .05$ *).

4.1.3.2 Material

Ratings of weight were examined before and after lifting the material objects. Participants' ratings of weight were compared to the expected order using Kendal's tau. If the rating order was as expected (pompom < sand), a score of 1 was assigned. If the rating was the opposite of what was expected (pompom > sand), a score of 0 was assigned. If participants reported that the objects weighed the same, a score of 0.5 (null) was assigned. The tau value could range from 0-1, with 0 representing the opposite of the expected order, 1 representing the expected order, and 0.5 representing the null value, that the order is random.

The tau values before and after lifting were compared to the null value (0.5) using a one sample t-test. Figure 16 indicates the tau values before and after lifting. Before lifting, the tau value was found to be significantly greater than the null ($t(47) = 15.73$, $p < .001$, $d = 2.27$). After lifting, the tau value was significantly less than the null ($t(47) = -2.72$, $p = .009$, $d = -0.39$). This finding suggests that before lifting, participants matched above chance in the expected order, they rated the pompom block as looking lighter in weight than the sand block. After lifting, they matched above chance in the opposite direction, reporting that the pompom block now felt heavier than the sand cube.

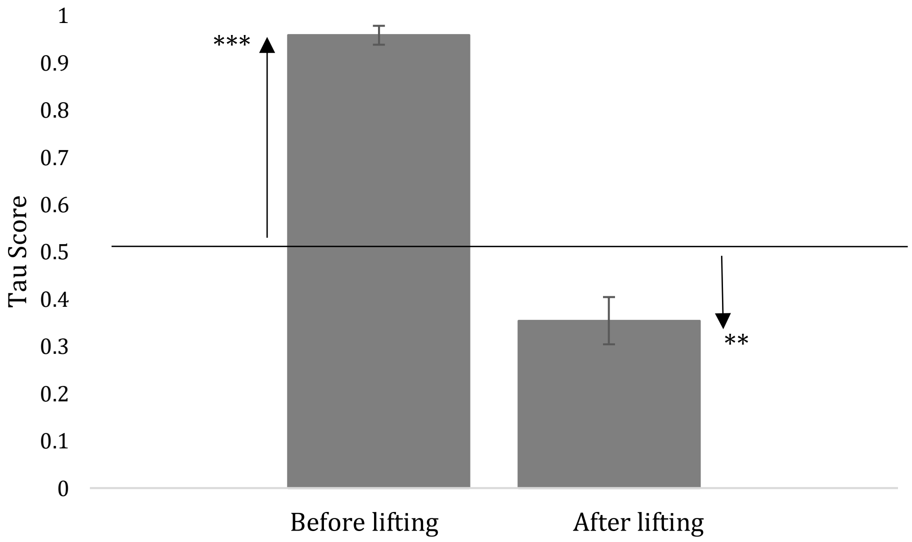


Figure 16. A graph demonstrating the change in rating of weight before and after lifting objects which vary in material ($p < .001$ ***, $p < .01$ **, $p < .05$ *).

4.1.4 Discussion

4.1.4.1 The Material-Weight Correspondence

The present study sought to examine the presence of the material-weight and brightness-weight correspondence, with plastic stimuli. For the material-weight stimuli, we chose two materials that we felt differed obviously in terms of expected weight. The primary reason that we asked participants to rate the weight of the pompom block and the sand block was to check that the expected weight difference was as clear as we had hoped. The matching of perceived weight in the expected direction (95.8% of participants) can be used as evidence that participants make a correspondence between material and expected weight, with the sand block being rated as heavier than the pompom block. After lifting, there was also evidence of a classic material-weight illusion (Baugh et al., 2012; Buckingham et al., 2009; Buckingham et al., 2011), whereby participants reversed their perception of weight from their initial judgements, reporting that the pompom block felt heavier than the sand block. The reversal of participants' expectations provides further support that participants truly did expect the sand block to be heavier before lifting.

4.1.4.2 The Brightness-Weight Correspondence

This study also provided further evidence of the brightness-weight correspondence in adult participants. Before lifting, participants rated the objects' weight in the expected order significantly more often than would be expected by chance; white cubes were rated as lighter and darker cubes rated as heavier.

4.1.4.3 The Brightness-Weight Illusion

In contrast to Experiment 1, however, there was no evidence of a brightness-weight illusion. A large portion of participants reported that the blocks felt equally heavy after lifting them. Additionally, the number who reported the expected order and the reversed order was almost equal. This finding is difficult to explain, particularly as with the wooden objects there was evidence of the illusion.

One explanation is that the correspondence with the plastic blocks was less persistent than with the wooden blocks. In other words, it is possible that although there was a brightness-weight correspondence before lifting, this correspondence was not strong enough to elicit an illusion effect when lifting. There are two possible explanations for why the influence of the correspondence upon creating an illusion might have been less likely with plastic blocks.

Firstly, it can be explained by the relative brightness of the grey cubes. As mentioned previously, PLA material is available in a restricted number of colours and although we chose the grey plastic which was most central in terms of brightness between the black and white, this was still substantially brighter (155.98cd/m^2) than the grey paint (103.23cd m^2) used to cover the wooden objects. It is therefore possible that because the white and grey values were less distinct, the impact of their brightness upon the implications of the expected weight were reduced. Therefore, there was less surprise when lifting that the objects were equal weights.

Secondly, it is possible that the reinforcement of the brightness-weight correspondence in the natural environment for the wooden stimuli might have resulted in a more convincing correspondence before lifting. As discussed, there is some evidence that darker woods are heavier than lighter coloured woods (Edlin, 1969; Walker et al., 2010), however less absorbent materials, such as plastic, are anticipated to be less likely to reflect this co-occurrence. Although plastic blocks were rated in the expected order, it might have been that the physical action of lifting the identically weighted blocks did not cause the same level surprise as the wooden blocks,

This mismatch identifies a possible area for future research. Although in both the wooden (Experiment 1) and plastic (Experiment 3) studies there was a significant effect of brightness upon expected weight ranking, it is not clear what size the expected weight difference is. It is proposed that the illusion effect observed in the wooden study suggests that the correspondence might have been stronger, or more prominent, than in the plastic study whereby no illusion after lifting was observed. Studies which focus on the scale of expected weight differences are anticipated to shed more light on this question.

An alternative explanation is that there was an order effect. In Experiment 1, participants saw only brightness-weight objects, whereas in the current study, half of participants saw the material-weight objects first. It was considered that after experiencing the strong material-weight illusion, participants might be less susceptible to the less prominent brightness-weight illusion. Similarly, if a participant reported a reversal of weight judgement for the material-weight stimuli, they might be less inclined to report a second illusion. An independent samples t-test was conducted to examine the tau scores after lifting the brightness stimuli, to see whether this varied depending on the order condition that participants were assigned to. The t-test revealed that there was no significant difference between the tau values of the brightness stimuli after lifting for those who saw the brightness stimuli first (M = 1.48, SD = 0.91) or those who saw the material stimuli first (M = 1.48, SD = 0.77), $t(46) = 0.000$, p = 1.00. This suggests that the presence of the brightness-weight illusion was not affected substantially by the order of presentation as the illusion was equally absent across both order conditions. Similarly, there was no between group difference between the tau scores before lifting, for the brightness-weight or material-weight stimuli, $t(46) = -.687$, $p = .496$, $t(46) = .000$, $p = 1.000$, respectively. Nor was there a between group difference between the tau score after lifting the material-weight objects, $t(46) = .000$, $p = 1.000$.

Whilst the order of stimulus presentation does not appear to have influenced the results in this case, it does reinforce the importance of controlling for order within experimental design. Unfortunately, another counterbalancing condition was omitted from the current study and Experiment 1. All participants were asked to 'Point at the three cubes, starting with what you think is the least heavy, going up to what you think is the most heavy.' In retrospect, this should have been counterbalanced between participants, with half pointing from least to most heavy, and half pointing from most to least heavy. Though not expected to alter the findings substantially, there is a possible argument that always ordering from least to most might have reinforced the correspondence. It is possible for example that arranging shades from lightest to darkest (white-grey-black), is the preferred way of ordering, regardless of weight. Though there is no obvious reason why this would be the case, it is theoretically plausible and it is therefore recommended to be included in subsequent studies as a between groups factor.

4.1.4.4 Concluding Remarks

It has been a concern that findings from brightness-weight studies with wooden objects might not be generalisable to objects made from other materials. This is due to material properties specific to wood, including a modest association between lightness of wood and weight; and also the observation that when wood becomes wet, it becomes darker and subsequently heavier. To address the concern of using wood as the material for stimulus, plastic cubes which are much less absorbent of water (Klyosov, 2007; Wang, Sun & Seib, 2001), were used as an alternative. It was interesting to see evidence of the brightness-weight correspondence, as in Experiment 1, when stimuli were composed of this material.

Evidence of the correspondence in stimuli whose material properties do not typically reflect the correspondence in the environment, raises new questions about the correspondence. It suggests that direct observation of the correspondence with similar material in the natural environment is not necessary for the formation of the correspondence. The finding does not however rule out the possibility that the correspondence is the result of observation of statistical co-occurrence of brightness and weight in the natural environment. It is still plausible that correspondences between brightness and weight in natural materials (e.g. wood, sand, soil) could be responsible for the formation of the correspondence in non-natural materials (e.g. plastic). Such an explanation would suggest that the co-occurrence of the two dimensions in any material might be sufficient to create a brightness-weight correspondence across other materials.

Despite finding evidence of the brightness-weight correspondence, explanations for diverging findings regarding the brightness-weight illusion across plastic and wooden stimuli still remains unclear. As discussed, to shed more light on potential explanations, it would be useful to replicate the studies with absolute matching of brightness values, also asking participants to rate the scale of the differences between their judgements of weight.

CHAPTER 5

Selective Preparation for the Brightness-Weight and Material-Weight Correspondences

5.1 Experiment 4: Examining the Brightness-Weight and Material-Weight Correspondences in Plastic Stimuli Using Kinematic Measures

5.1.1 Introduction

Experiment 2 showed early evidence that selective preparation is made for objects which vary in brightness, on the basis of weight. Black blocks were transported more quickly than white blocks, which was suggested to reflect that more force was used to transport the black block, which participants expected to be heavier.

As discussed in Chapter 3, due to an error in measurement, there was a minor difference in weight of ~1g between the weight of the white and black blocks. Unfortunately, because of the direction of this difference (white weighed more than black), it is possible that the difference could explain the greater velocity of the black object during transport. If equal amounts of force were used to lift both blocks, the black object might have been transported more quickly, simply because it was marginally lighter. To examine whether the result can be replicated under conditions whereby object weights are equalised, a similar experiment was conducted.

Experiment 3 replicated evidence of the brightness-weight correspondence, with plastic objects, which was earlier demonstrated in Experiment 1, with wooden objects. Additionally, Experiment 3 also demonstrated evidence of a material-weight correspondence in which a block filled with sand was expected to be heavier than a block filled with pompoms. Experiment 4 in the current chapter therefore aimed to examine kinematic, selective preparation for plastic objects on the basis of weight, using cues of brightness and material.

It is intended that the current study will rectify the issues from the previous kinematic study to examine whether brightness is used as a cue to weight when lifting objects. The study will also add to the current literature on selective preparation on the basis of material.

5.1.1.1 The Material-Weight Correspondence

Previously, research has shown that participants reach for objects differently based on their material and expected weight, grading the load phase for the weight of objects and using greater load force for heavier objects (Baugh et al., 2012; Buckingham et al., 2009). For example, findings have shown that greater force is used to lift metal blocks than polystyrene blocks on initial presentation.

Much of the research looks at how prehension varies alongside object material, considering both the weight and the friction of the material. This has yielded interesting results suggesting that the lift of heavier objects with low friction (e.g. brass) requires higher levels of precision and planning. This results in reaches which have a longer approach duration and a grasp either close to the objects' centre of mass, or below it, to provide support for any potential slippages (Paulun, Kleinholdermann, Gegenfurtner, Smeets, & Brenner, 2014; Paulun, Gegenfurtner, Goodale, & Fleming, 2016). Paulun et al. (2016) do not clarify whether it is thought that the expected friction or weight of the material primarily drives the kinematic differences. Therefore, we have chosen to hold the level of friction constant whilst varying only the apparent weight of the material.

5.1.1.2 The Current Experiment

In the present experiment, we wanted to examine whether the sand stimuli which participants rated as appearing significantly heavier before lifting in Experiment 3, were reached, grasped and transported as though they were heavier objects, using our chosen measures. As well as being of interest in its own right, this part of the experiment was designed to be comparable to the brightness-weight part of the study. Pompoms were rated as significantly lighter than the sand, as the white cube was rated as significantly lighter than the black cube. Though both results were significant, a relationship between pompom-type materials as light and sand-like materials as heavy is more regularly reinforced in everyday life through experience with density, than is a relationship with brightness and weight. Therefore, Experiment 4 sought to compare the kinematics of lifting objects with an obvious weight cue (pompoms and sand), with objects that have the less obvious weight cue of brightness (black and white).

A couple of improvements were also made to the current study as a result of the previous kinematic study (Experiment 2). The previous familiarisation objects were 4 grey shapes, each with a light, medium and heavy version. An improvement was made to this after consideration that a series of differently weighted grey shapes might teach participants that object weight does not vary alongside brightness, therefore discouraging participants from using this cue.

Instead, we chose to use objects whereby the weights vary concurrently with the objects' size, familiarising participants with the experiment and the relationship between size and weight, but without giving them any additional expectations of cues to object weight.

Additional to the previous study, we have added another kinematic measure; lift height of the object during transport. Rosenbaum (2017) refers to the everyday phenomena that most people will have experienced whereby an object which is lighter than expected is lifted to an accidentally exaggerated height, due to an overshoot in the required force.

Empirical research has also looked into this phenomenon and finds the same; when an object is lighter than expected, it is lifted higher than an object whose weight is accurately predicted. When participants expected to lift an object of 800g but were actually presented with an object weighing 200g, the movement becomes both faster and higher than intended (Johansson & Flanagan, 2009).

In a size-weight illusion study, large objects were lifted higher than equally weighted small objects (Davis & Roberts, 1976), suggesting that greater force is applied to the larger of the two objects, with the expectation that it will be heavier. Interestingly, the difference in height only emerges when the size-weight illusion does not occur. If participants report that the small object felt heavier, then the lift has a rapid deceleration period causing almost identical lift heights. They suggest that peak height is the summation of the initial forces applied when lifting.

As discussed, another key reason for repeating this study with plastic objects is that although very close in weight, the test objects in Experiment 2 were not quite identical in weight. The white object weighed 101.6g and the black object weighed 100.4g. Though a very small difference, the weight difference could explain the observed effect as the black object was ~1g lighter and was also transported with a faster average velocity. A necessary improvement of using stimuli of equal weights was therefore made to allow the examination of whether the black object was lifted more quickly because it was marginally lighter or because additional force was used to lift the black object.

Aims and Rationale

As in Experiment 2, the current experiment sought to examine whether objects which vary in brightness are approached, grasped, and transported differently, alongside their expected weight. Findings from Experiment 3 show that participants report expecting the darker, plastic object to be heavier. Therefore, in the current experiment kinematic measures will be analysed to examine whether participants act upon such predictions. Based on the findings from the previous experiment, we might expect to see differences in the transport velocity of black and white objects. Measures previously shown to vary alongside expected weight will also be examined across object brightness, including: MGA, peak velocity on approach to the object, peak and average velocity and peak acceleration when transporting the object. The additional measure of lift height will also be examined in this experiment. If more force is used to transport the darker object, we might also expect to see a greater lift height for this object.

In Experiment 3 participants also reported expecting the sand block to be heavier than the pompom block. Therefore, the effect of material on approach, grasp, and transport kinematics will also be compared. If there are differences in the kinematics for the less obvious cue of brightness, we could also expect to see differentiation for objects of different materials.

5.1.2 Method

5.1.2.1 Participants

Twenty-seven students at Lancaster University completed the experiment (7 males and 20 females, aged 18 to 29). Ten participants were excluded from the analysis, 5 participants because of experimenter error (e.g. presenting in wrong order, failure to record), 3 due to equipment issues, and 2 because they were left-handed. This meant that the final sample included 17 participants, (5 males and 12 females, aged 18 to 24, M_{age} = 20.94 years).

Only right-handed participants were included in the analysis as previous research has shown differences in the perception of illusion across left and right-handed participants; right handers experience hand asymmetry for size-weight illusions, that left handers do not (Buckingham, Ranger & Goodale, 2012). Handedness has also been shown to affect other measures such as perceived distance (Linkenauger, Witt, Stefanucci, Bakdash & Proffitt, 2009). Handedness was measured using the Edinburgh handedness scale.

This research gained approval from Lancaster University Ethics Committee. Participants were given information and consent forms upon arrival which they were asked to sign. At the end of the study, participants were given a debrief and were reminded of their right to withdraw their data from the study for up to one month after the study. Participants were reimbursed for their time.

5.1.2.2 Stimuli

Participants were initially presented with four grey objects to help them to become familiar with the task. The objects included: a cube (5cm x 5cm x 5cm), a cylinder (11cm circumference, 5.5cm height), a sphere (16cm circumference) and an egg shape (15cm circumference, 6cm height). At 65% density, a cube was produced which weighed 100g (designed to be the same as Experiment 2). The cylinder (40.80g), sphere (50.89g), and egg (51.67g), had an unaltered weight with a density of 65%. This was thought to be an improvement on the differently weighted objects from Experiment 2, as discussed previously.

The same three polylactic acid (PLA) plastic cubes from Experiment 3 were used for the brightness-weight element of the study. The cubes measured 5cm x 5cm x 5cm and the weights of the cubes were an average of 100.75g (White = 100.74g, Grey = 100.74g, Black = 100.76g). These indistinguishable weights minimised the risk of obtaining different lift kinematics for different objects, purely because of differences in object weight.

Figure 17. Black and white test blocks and grey familiarisation block used in Experiment 4.

The cubes varied only in terms of brightness, the cubes were black (8.15cd/m^2), grey (155.98cd/m^2), and white (382.93cd/m^2), (see Figure 17).

Additionally, there were two other test objects which varied in terms of material; they were designed to vary more obviously in terms of perceived weight. The stimuli, also used in Experiment 3, were two 125ml, transparent, food boxes which measured 6.8cm x 6.3cm x 6.3cm and were filled with either 7mm red pompoms or red sand, (see Figure 18). The final weights of the sand (154.73g) and pompom (154.72g) boxes were manipulated so that they were equalised, despite the large original weight difference. In Experiment 3, these materials were shown to be obvious cues to weight, with sand rated as heavier and pompoms rated as lighter, before lifting ($p < .001$).

Figure 18. Sand and pompom test blocks used in Experiment 4.

5.1.2.3 Apparatus

As in Experiment 2, a Flex3, OptiTrack, Motion Capture System (4 cameras) was used to measure participants' hand movements. Participants each wore a Velcro wristband which had a small reflective dot on the top; they also wore two Velcro bands with reflective dots on the end of their thumb and index finger. The cameras picked up the reflections from these markers and tracked their movements. In addition to the previous experiment, the objects also had one reflective marker on top of each object, to allow for the measurement of lift height.

The objects were presented to participants on a table, 29cm from the edge. The requirement of participants was identical to Experiment 3. They were asked to move the objects from their initial position onto a 10cm high grey platform, placed 42cm from the edge of the table. They were asked to wear a pair of misting glasses for the duration of the experiment. The experimenter would mist the glasses as they placed the object in front of the participant, to prevent the participant from using indirect cues to infer the weight of the object. The experimenter would then demist the glasses so that the participant could see the object to lift it onto the platform. The glasses would then mist again once the participant had lifted the object onto the platform.

5.1.2.4 Design

The dependent variables in this experiment were the kinematics of participants' reach, grasp and transport of objects. This included peak velocity towards the object, grip aperture, grasp height, peak lift height of the object, and peak and average lift velocity and peak acceleration (during the first 100ms and 500ms of transport).

Participants were presented with the 4 familiarisation objects in a random order, with the same object never presented immediately after itself. Each object was presented 3 times, except the grey cube which was presented 4 times. The grey cube was presented 4 times for two reasons. Firstly, it was important that the grey cube was the first object experienced as it was considered that the first object experienced might guide the reach and transport of subsequent objects. Secondly, it was important that the grey object was the final shape that was experienced before the black and white test cubes. This precaution was taken to minimise the chance that recent shape experience would guide the approach towards the test object.

Although we were interested in the kinematics for the material-weight objects (sand and pompoms), the main aim of this study was to look at the kinematics for the brightness-weight objects (black and white cubes). As this was the primary area of interest, the brightness-weight objects were presented before the material-weight objects in all conditions. It was also considered that placing the objects which would be expected to be more different in weight first might be more likely to influence the results for the brightness-weight objects.

Approximately half of participants (8 participants) saw the black cube first and the other half (10 participants) saw the white cube first. Within these conditions, half of these participants (9 participants) saw the sand block first and the other half (9 participants) saw the pompom block first. This counterbalanced design produced two brightness-weight groups and two material weight groups.

5.1.2.5 Procedure

The procedure was identical to Experiment 2, so it is simply summarised here.

Participants were given information and consent forms and informed that the study would take no longer than 30 minutes to complete. Additionally, they were asked to complete the Edinburgh Handedness Survey.

Participants were instructed to place their finger on a small bump at the edge of the table. This bump was a reference for where participants should reposition their finger after lifting each shape. The experimenter misted the glasses as they presented each object in front of the participant. When the glasses demisted, this was the cue for participants to lift the object in front of them onto the platform ahead.

Firstly, participants were presented with the grey familiarisation objects, in a random order. The glasses misted as the first object was presented. When the glasses demisted the participant lifted the object onto the platform and then the glasses misted again. The next familiarisation object was then presented.

Once the familiarisation objects had all been presented to the participant, the brightness-weight stimuli were presented. This part of the experiment was not distinguished from the rest of the experiment, participants did not receive a break and were not told that objects would now change. Participants were presented with either a black cube or a white cube, depending upon their counterbalancing assignment. They were then presented with the alternate cube. This procedure was repeated 8 times with each object.

Participants were then presented with either the sand or pompom block, dependent upon counterbalancing assignment. They were then presented with the alternate object. Again, this procedure was repeated 8 times for each object.

Each trial was recorded on the motion capture cameras as a separate take, this was to help with the analysis. The cameras recorded the movement of the hand and object throughout the experimental trials. When participants completed the experiment, they were debriefed about the aims of the experiment and were reminded of their right to withdraw from the experiment.

5.1.2.6 Data Coding

As in the previous experiment, the researcher coded three time phases; the reach phase, grasp phase, and transport phase. The reach phase began as the participant started moving towards the object and ended on first contact with the object. The grasp phase began at first contact with the object and ended when the object began to lift-off. The transport phase began as the object was lifted off the table and ended when the object was placed onto the platform. The start of the transport phase was defined as the moment when velocity went above 50mm/s (as in Eastough & Edwards, 2007), but when the researcher also coded that lift-off had taken place. Within the transport phase there were also two additional sub-phases, the first 500ms seconds and the first 100ms of transport. As discussed in Chapter 3, these time periods have both been proposed as points before which actions are automatic and cannot be corrected, therefore we chose to compare the acceleration and velocity measures across both of these points.

5.1.2.7 Data Editing

Labelling

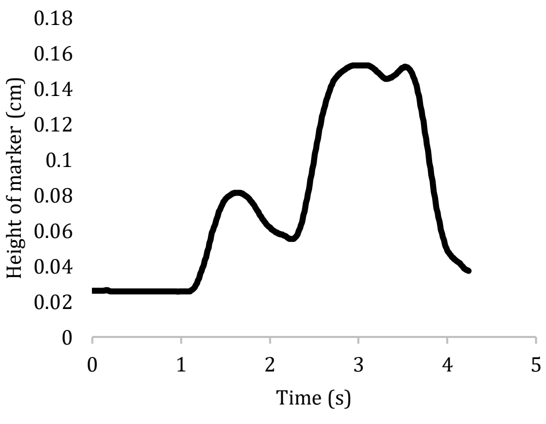
As in Experiment 2, the first step in the editing of data was to re-connect and label the markers. Each marker was labelled as ‘wrist’ ‘thumb’ ‘finger’ or ‘object.’ A more thorough description of this process is available in the data coding and editing section of Experiment 2 (Chapter 3).

Fill gaps

The next stage in data editing was to fill the gaps in the data. Again, a maximum gap size of 10 frames (0.1 seconds) was used to avoid reconstructing inaccurate data.

Filtering

Motion capture data should be filtered to reduce the noise in the data and choosing the filter with the correct cut-off value is important. Too much filtering can result in an inaccurate reconstruction of data and too little filtering can result in data with excessive noise. Similar reach and grasp experiments have used a fourth order, zero-phase lag, low-pass Butterworth filter with a 14Hz cutoff (Grandy & Westwood, 2006; Platkiewicz & Hayward, 2014). However, Flatters et al. (2012) looked at similar measures to the current study (e.g. grip aperture and wrist velocity) and used a Butterworth second order filter with a cutoff of 16Hz (equivalent to fourth order, zero-phase lag, with a cutoff of 10Hz). Similar research with infants uses a cutoff of 10Hz (Gottwald, 2018; Grönqvist, Strand Brodd, & von Hofsten, 2011; Mash, 2007).



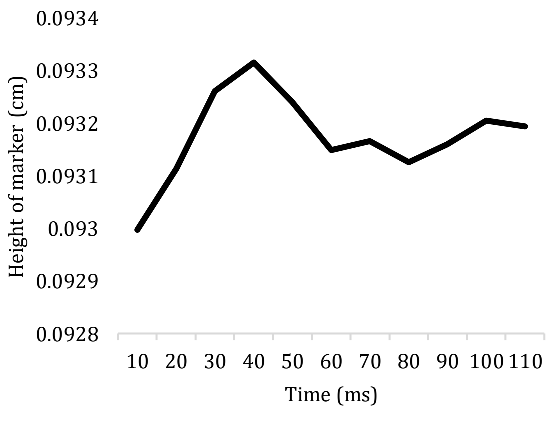


Figure 19. These graphs demonstrate the unfiltered trajectory of the wrists' Y axis for a single participant on a single trial. The left graph shows the whole trial (two sharp increases in height represent the reach and lift components of the movement.), and the right graph shows the trajectory for a portion of the lift (0.1 seconds).

On initial inspection of the raw, unfiltered data, it appears the data has little noise. This is evident through the absence of sharp contours and presence of smooth curves, (see Figure 19). The necessity to filter becomes apparent once we zoom in much closer on small segments of the data, whereby the trajectory is sharp, (see Figure 19). As the graph represents only 0.1 seconds of time, it is highly unlikely that the wrist is moving up and down as rapidly as is suggested, demonstrating why it is necessary to filter the data. Such error is typical with motion capture data.

The unfiltered, portion of the trajectory from Figure 19 was filtered with four different cutoff values so that we could visually inspect the curves to see which provided the most accurate reflection of the data.

At the lowest cutoff levels (8Hz and 10Hz), the shape of the curve has changed dramatically and does not accurately reflect the initial data. This suggests that the data have been filtered too far. Changing the cutoff rate to 12Hz, the data more accurately represent the initial curve, with limited noise. However, the 14Hz cutoff seems to most accurately reflect the data; the curve is smoother, with less sharp movements, however it also still represents the shape of the initial data, displaying a height drop after a sharp increase.

We examined a selection of trials to ensure that we selected the most appropriate filter. Most sections of the movements were relatively smooth and needed minimal filtering, supporting the idea that a high cutoff should be used (See Figure 20). Considering both the previous research and our own analysis of curves, we decided to apply a Butterworth low-pass zero-lag filter at 14Hz to the

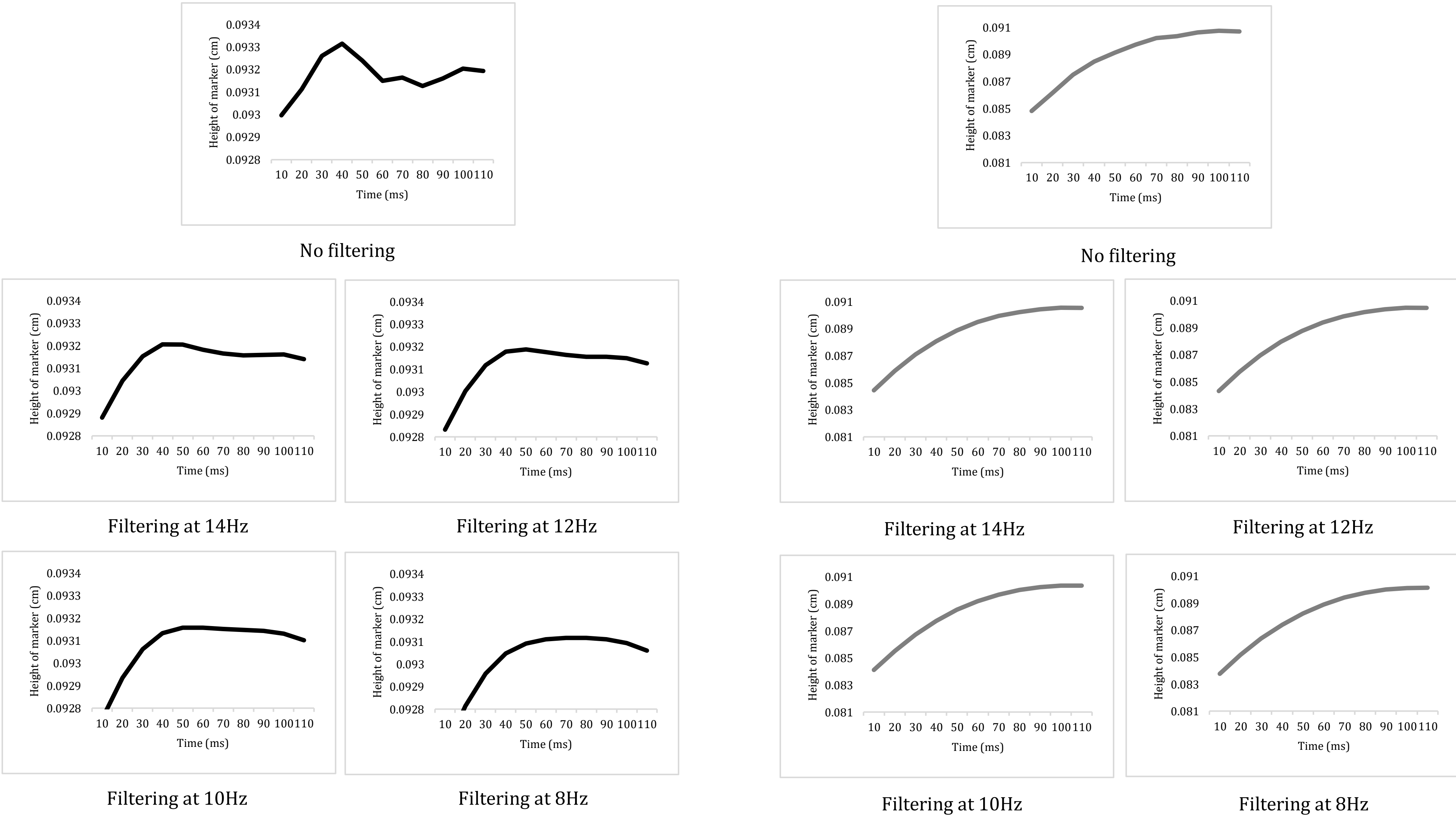


Figure 20. These graphs demonstrate the effect of filtering on a portion of one participant's reach in the Y axis, whereby there is a large amount of noise (black lines), and a little amount of noise (grey lines).

position data. The benefits of this cutoff value is that it eliminates the noise, without creating data which is artificial.

5.1.3 Results

In the results section, the material results and the brightness results will be discussed separately and then compared to one another in a detailed discussion. In both sections, results are analysed using the same tests.

First, preliminary analyses were conducted using a binomial test to look at the percentage of outcomes which were in the expected direction. For example, the percentage of all reaches which were faster towards the black object than the white object. For each pair of trials (pompom and sand, or black and white), the trial was labelled as either matching in the expected direction, or in the opposite direction. The total number of trials in the expected direction were counted as 'successes' and the total number of trials was always 136 (17 participants, 8 pairs of trials).

A more detailed analysis then looked at whether there was an overall effect of material or brightness on the specified measure. The chosen analysis is a repeated measures ANOVA with the between factor of condition and the within factors of trial and material/brightness.

5.1.3.1 Brightness

Preliminary analysis showed that there was a significant effect of brightness on max approach velocity (p = .048, on a two-tailed binomial test), with 58.82% of reaches being faster towards the black block than the white block.

A more in-depth analysis using a repeated measures ANOVA revealed the same result; there was a significant effect of brightness on the maximum approach velocity, F (1, 15) = 5.61, p = .032, $\eta_p{}^2$ = .272. Analysis of means revealed that black cubes

(719mm/s) were approached with a significantly greater maximum speed than white cubes (703mm/s), (see Figure 21). There was no interaction between trial and brightness, F (7, 105) = .664, p = .702, suggesting that the greater speed of approach towards black objects was consistent throughout the experiment, and was not corrected through experience with actual object weight. The corresponding results from the preliminary and in-depth analysis suggests that participants reach with a substantially faster maximum speed towards black objects on a large portion of trials.

As shown in Table 3, there was no significant effect of brightness on the MGA, grasp height, peak lift height, peak or average lift velocity, or peak lift acceleration.

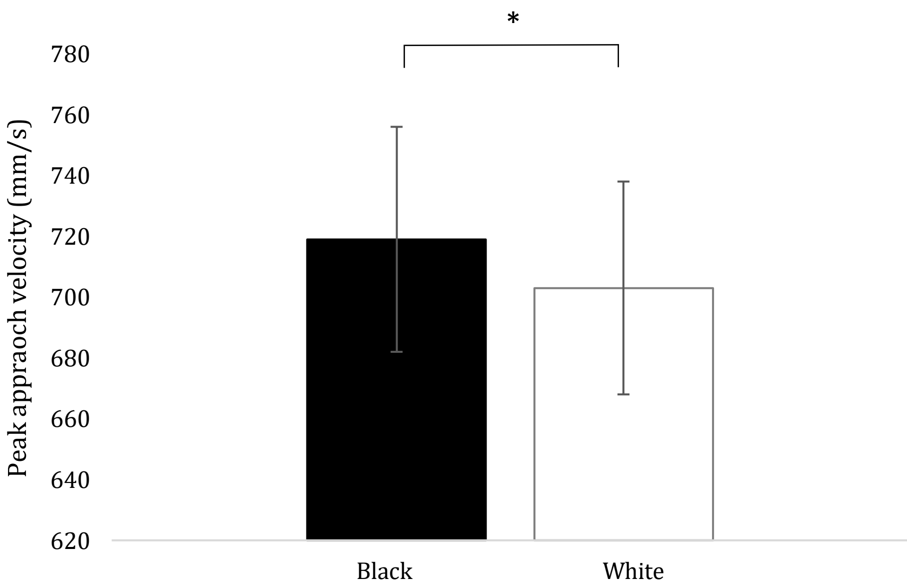


Figure 21. A graph demonstrating the significant difference between the peak approach speed towards black and white cubes (p < .001 ***, p < .01 **, p < .05 *).

Table 3.

Mean values and p values for each kinematic measure during approach, grasp, and transport of objects which vary in brightness and material.

	Object Brightness			Object Material		
	Black	White	*p*	Sand	Pompom	*p*
Approach						
Peak approach velocity (mm/s)	719	703	***.032**	701	689	.154
Grasp						
MGA (cm)	11.7	11.6	.316	11.2	11.2	.242
Grasp height (cm)	4.2	4.2	.996	5.0	5.0	.851
Transport						
Peak lift height (cm)	18.3	18.4	.257	20.3	20.2	***.011**
Peak lift velocity (100ms) (mm/s)	313	317	.540	289	282	.553
Peak lift velocity (500ms) (mm/s)	700	699	.873	669	678	.213
Average lift velocity (100ms) (mm/s)	174	177	.576	165	159	.435
Average lift velocity (500ms) (mm/s)	455	454	.626	437	442	.331
Peak lift acceleration (100ms) (m/sec^2)	3.69	3.56	.358	3.2	3.23	.856
Peak lift acceleration (500ms) (m/sec^2)	3.88	3.75	.347	3.45	3.5	.667

Note: Bold entries are significant or marginally significant results ($p < .001$ ***, $p < .01$ **, $p < .05$ *).

5.1.3.2 Material

Preliminary analysis showed that there was no significant effect of material on maximum lift height during transport (p = .797 on a two-tailed binomial test), with 51.47% of lifts being higher for the sand block.

However, a more in-depth repeated measures ANOVA revealed a significant main effect of material, F (1, 15) = 8.392, p = .011, $\eta_p{}^2$ = .359, (see Figure 22). Analysis of means revealed that the sand block (M = 20.3cm) was lifted significantly higher than the pompom block (M = 20.2cm). The difference in results obtained from the preliminary analysis and detailed analysis is discussed in more detail within the discussion.

As shown in Table 3, there was no significant effect of material on the peak approach velocity, MGA, grasp height, peak or average lift velocity, or peak lift acceleration.

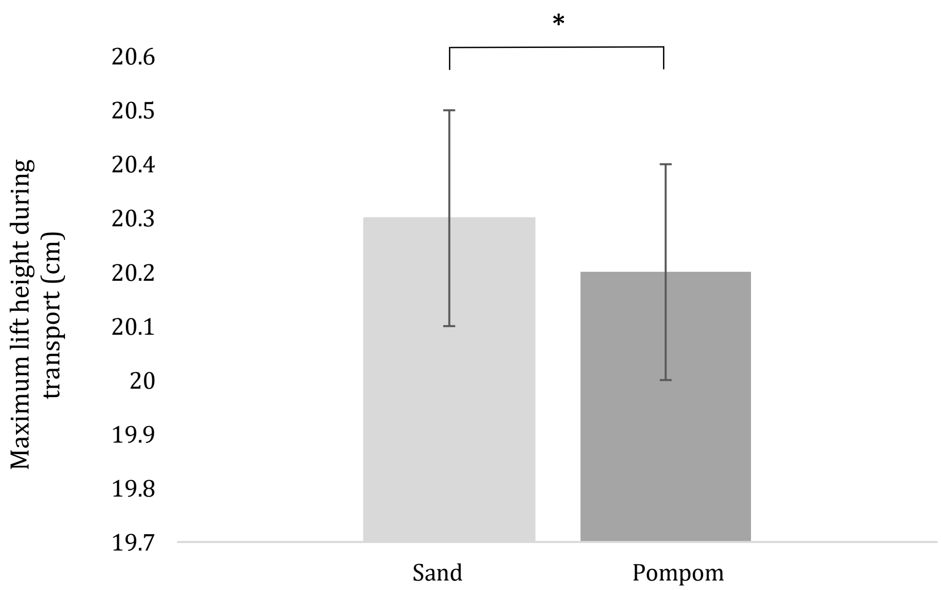


Figure 22. A graph demonstrating the significant difference in maximum lift height during the transport of sand and pompom blocks (p < .001 ***, p < .01 **, p < .05 *).

5.1.3.3 Trial Effects

In the brightness and material trials, there was a significant and marginally significant linear effect of trial on grasp height, F (1, 13) = 8.728, p = .011, $\eta_p{}^2$ = .402 and F (1, 12) = 3.853, p = .073, $\eta_p{}^2$ = .243. The height of grasp became lower throughout the duration of the experiment, gradually becoming closer to the objects' COM.

In the material trials, there was also a significant linear effect of trial on maximum approach velocity, F (1, 15) = 11.921, p = .004, $\eta_p{}^2$ = .443. Post hoc comparisons reveal that velocity when approaching the blocks increases over the course of the experiment.

5.1.4 Discussion

5.1.4.1 Prior-to-contact

Previously, it has been suggested that the longer duration of the approach towards heavier objects reflects the more thorough planning of the movement as a slower approach will decrease the variability of grasp points (Fitts, 1954). Research suggests that individuals approach heavier objects more slowly with the intention of grasping more closely to the objects' centre of mass to ensure a secure grip which avoids rotation (Fleming, Klatzky, & Behrmann, 2002; Paulun et al., 2014; Paulun et al., 2016;). We argue that these findings do not necessarily apply to all types of grasp, nor do they apply to all types of object.

In this experiment, participants were asked to use a pincer grip to transport objects, however in Eastough and Edwards' (2007) study, participants grasped with an 'all-digit, precision grip.' They did not find evidence of differentiated peak velocity towards objects which vary in weight, however they did find evidence of closer grip to the objects' COM for heavier objects. This suggests that although participants grasp heavier objects more precisely, they do this at no cost to the time taken to approach the object. It could be suggested that using more digits for the grasp allows more room for error, as other fingers can be used to stabilise the object if it is grasped at inadequate distance from the COM. In contrast, when participants grasped with a two-digit pincer grip or three-digit pinch, there is evidence of longer movement durations for heavier objects, explained by the increased importance placed on a grip close to the COM (Fleming et al., 2002; Paulun et al., 2014; Paulun et al., 2016). We suggest that individuals who use all-digits might grasp heavy objects closely to the COM but are less cautious about this in the control of reach speed than those using a pincer grip, whereby more precision is required.

The question still remains; why in the current study are objects which are expected to be heavier (black), approached more quickly than those expected to be lighter (white)? One explanation lies in the variation of object weight differences across studies. Previous research uses objects which are substantially heavier than the stimuli used in our experiment. Our brightness stimuli weighed just 100g, in comparison to previous maximum object weight of 414g (Paulun et al., 2016) and 1318g (Eastough and Edwards, 2007).

We suggest that at these high weights, the placement of the digits close to the centre of mass would be prioritised more highly than it is in our study. It is proposed that the light weight of the stimuli in our study means that approaching 'heavier' objects slowly to secure a grasp close to the COM is not a necessity. Although a study using low-weight objects has found evidence that light objects are still approached with shorter reach durations than heavier objects, the relative contribution of friction and weight cannot be disentangled in this study (Paulun et al., 2014). In their study, the heavier object had a smooth surface, whereas the light object had a rough surface; a difference which is suggested to be more important than weight in choosing precision requirements.

Alongside object weight, we also propose that object size and shape might have a substantial bearing on whether the object is grasped at an optimum distance from the COM. Studies showing a closer central grip position for heavier objects, have often used larger, taller, cylindrical/upright cuboid, stimuli, (7.1cm, 8.7cm, and 11cm diameter - Eastough & Edwards, 2007; 10cm height - Paulun et al., 2014; Paulun et al., 2016), shapes for which grasping closer to the COM is arguably more necessary to avoid rotation.

Our finding that neither black blocks nor sand blocks are grasped lower (closer to the objects' COM) than the white blocks or pompom blocks supports our assertion that grasp placement is not necessarily important for these light objects, with low weight distribution, and relatively small overall size. As we suggest that grasping closer to the COM is not important for these stimuli, we propose that the opposite effect occurs. As the objects are relatively light, they need to be approached more cautiously to avoid knocking or displacing the object, particularly the objects which are intended to look lighter.

Previously research has shown that conditions which make a grasp more difficult, such as orientation, fragility, high weight, and low friction, lead to longer reach durations, which offer greater precision (Fikes, Klatzy, & Lederman, 1994; Flatters et al., 2012; Paulun et al., 2014; Paulun et al., 2016). We propose that whilst heavier weight has previously been thought of as a difficult grasp condition, equally a very light object might be even more difficult to grasp precisely. Therefore, the black (heavy) objects are approached more quickly than the white (light) objects as care is taken to avoid displacing the 'lighter,' white cube.

Alongside the overall weight of stimuli, the anticipated difference in weight between our stimuli and that used in previous experiments, also makes direct comparison of findings difficult. It has been suggested that a larger maximum grip aperture (MGA) can lead to higher accuracy (Smeets & Brenner, 1999). However, Weir et al. (1991) and Paulun et al. (2016) did not find a difference in MGA for differently weighted objects, a finding which Eastough and Edwards (2007) attribute to the smaller weight difference between objects. In their study the maximum weight difference was ~1kg, in comparison to ~ 400g in the Weir et al. (1991) and Paulun et al. (2016) studies. There is also evidence of larger MGA for the lighter of two objects when both objects are light (0.8g and 42.3g), but with a large difference in weight (light object is ~2% of weight of heavier object), (Paulun et al., 2014). These findings suggest that at the very light end of the scale, the lighter object requires greater precision (Paulun et al., 2014), whereas at the heavy end of the scale, the heavier object requires greater precision (Eastough & Edwards, 2007). This assumption corresponds with our ideas regarding the precision required in the approach speed towards very light or very heavy objects.

Our stimuli have a smaller weight difference with a naturally filled version of the pompom block weighing 36g and the sand block weighing 208g. Though difficult to quantify, the anticipated difference in weight for the black and white cubes was expected to be smaller. It is suggested that for weight to affect the MGA, it might be that differences between objects must be larger, either in terms of % of overall weight or in terms of grams difference. Although a difference in MGA has already been suggested to be dependent on the size of the expected weight difference, we argue that other measures might also only be revealed with sizeable weight differences.

Our conclusion for the prior-to-contact kinematics is that several factors might have bearing on whether differences in the approach and grasp are observed, explaining what so far appears to be much conflicting research. It is suggested that if precision is not a requirement, there might not be a difference observed in the approach speed towards objects. Furthermore, we suggest that the weight of the object can impact on what is considered to be a difficult lifting condition which subsequently requires high-levels of precision. At the lightest end of the scale, we propose that lighter objects are more difficult to grasp as excessive speed might cause displacement. At the heavier end of the scale, heavier objects might be more difficult to grasp as grasping close to the centre of the block is important to avoid rotation. This explains why evidence of a faster maximum approach speed towards black objects compared to white objects was shown. We also propose that when expected weight differences are small, or lifting conditions are considered to be relatively easy, some effects might not be evidenced.

Whilst this result suggests a possible difference in weight expectation based on brightness, it is also possible that other factors, aside from expected weight, may cause participants to reach more slowly for the white block. It is possible for example that participants expect the white block to be more fragile or compressible. Both of these material properties might warrant extra caution, and therefore less velocity, when approaching the object.

5.1.4.2 Transport

After contact with the object, a different story is revealed. Whilst prior to contact, darker objects were approached with greater speed but sand blocks were not; after contact with the object, evidence suggests that the sand block was expected to be heavier.

Whilst preliminary analysis revealed no significant difference in the number of trials whereby the sand block was lifted higher than the pompom block, the ANOVA of the maximum lift height values revealed a significant difference across the two materials. It is suggested that this difference implies that whilst there is not a difference in lift height across an extensive number of trials, on the trials where there is a difference, the difference is substantial. The largest difference in the expected direction is 3.98cm; meaning that the sand block was lifted almost 4cm higher than the pompom block. This difference is not an outlier (difference in lift height ≥ 2cm – 8 pairs; difference in lift height of ≥ 3cm – 4 pairs). These considerable difference scores demonstrate how such a result emerges, despite the null preliminary result.

Research has shown that when an object is lighter than expected, the lift is higher and faster than intended (Vollmer & Forssberg, 2009). The finding that sand blocks were lifted higher than pompom blocks is suggested to be evidence that greater force was applied during lifting as it was expected to be heavier. In contrast, the pompom block was expected to be light, and was therefore lifted with less initial force and subsequently lifted to a lower height. This finding is similar to results showing that larger objects are lifted higher than identically weighted smaller objects and that objects which weigh less than expected are lifted to a greater maximum height during transport (Davis & Roberts, 1976; Johansson & Flanagan, 2009).

5.1.4.3 Trial Effects

Alongside the main effect measures that were demonstrated, there were a couple of trial effects which are worth discussing as they add to our understanding of what kinematic adjustments are made. Grasp height for the brightness and material stimuli was shown to become gradually closer to the objects' centre of mass as the trials progressed. Additionally, approach velocity became faster over the duration of the experiment for the material stimuli. These linear trial effects might be attributed to one of two causes. It could be that there is a gradual revision of reaching kinematics whilst adjusting to the true weight of the object, explaining why participants grasp the blocks more optimally as time progresses. Previous research suggests that participants reach more slowly for objects which require greater precision (Fikes, Klatzy, & Lederman, 1994; Flatters et al., 2012; Paulun et al., 2014; Paulun et al., 2016). The faster approach towards objects as the experiment progresses, could be attributed to the initial precision taken with unfamiliar objects, which gradually reduces as more information about the objects is gained. Alternatively, as there is no evidence of an increase in maximum velocity across trials for the brightness blocks which are earlier in the experiment, $F(1, 15) = 1.716$, $p = .210$, it might be that the faster approach could be attributed to participant fatigue. We suggest it is likely that the linear effects are a result of the combination of both factors.

5.1.4.4 Time before sensory-based adjustments

It was hoped that by looking at both the first 100ms and the first 500ms of transport, it would become evident when corrections to the lift begin to be made. As there were no significant differences in the velocity or acceleration measures within either 100ms or 500ms from lift onset, it is difficult to conclude which the most accurate time frame is for examining the time before sensory-based adjustments occur.

5.1.4.5 Concluding Remarks

It would have been interesting to have looked in more depth at the first pair of trials to examine what happens on participants' first interaction with the objects. Unfortunately, there were strong order effects on these trials making it difficult to disentangle the effects of trial order from the effects of material and brightness. This was especially true for the material stimuli which did not have a comparison object. In hind-sight, it would have been beneficial to have a familiarisation object for the material section of the experiment. Although by this point in the experiment participants were familiar with the procedure, the change in object type was substantial and participants might have struggled to predict the weight of the first object of this type.

Nevertheless, this research has shed light on some of the kinematic differences that emerge when expectations of weight vary. Findings have demonstrated evidence of differentiated action for a correspondence between material and weight and also what we believe to be the first evidence of the brightness-weight correspondence, using kinematic measures. It has been demonstrated that individuals reach more slowly for white blocks than black blocks. It is suggested that in reaching more slowly for white blocks, participants might be demonstrating the need to be cautious with objects of such a light weight. Other potential reasons for a slower approach have also been discussed. Similar results were obtained with objects varying in material, showing that blocks filled with sand are expected to be heavier and are therefore lifted higher than blocks filled with pompoms.

CHAPTER 6

Infants' Appreciation of Crossmodal Correspondences

6.1 Introduction

In this chapter, research into infants' detection of crossmodal correspondences will be discussed. As proposed in the literature review, there are many benefits of studying crossmodal correspondences in infants. The potential gains are to understand more about the nature and origin of correspondences, alongside the potential to understand more about infant perception.

As discussed in greater detail in the literature review, the brightness-weight correspondence is a particularly interesting correspondence as it does not fit clearly into any of Spence's (2011) proposed correspondence categories. There is very limited evidence of a consistent statistical co-occurrence and semantic explanations are refuted by cross-cultural studies. Suggestions that crossmodal correspondences might have been learnt during the early days through infants' sensitivity to statistical regularities in the environment, or through caregivers' crossmodal biases during speech are therefore difficult to accept for the brightness-weight correspondence (Aslin, Saffran, & Newport, 1998; Nygaard, Herold, & Namy, 2009; Shintel, Nusbaum, & Okrent, 2006; Spence, 2011).

It has been suggested that by looking more closely at structural explanations, and specifically considering the neonatal synaesthesia hypothesis, there may be an explanation for the source of the correspondence. The hypothesis suggests that crossmodal correspondences might be innate in young infants, as they experience a form of synaesthesia that dissipates over the course of development (Maurer & Mondloch, 2005; Wagner & Dobkins, 2011). It has been suggested that crossmodal correspondences observed in children and adults are the remnants of neonatal synaesthesia (Maurer & Mondloch, 2005). If the neonatal synaesthesia hypothesis is thought to be the source of the correspondence between brightness and weight, the suggestion is that the qualities of brightness and weight are matched in infants from birth. This would suggest that before experience of any potential co-occurrences between brightness and weight, the two sensory features are associated, potentially due to transient connectivity or lack of speciality of brain areas. Experience of the brightness-weight correspondence in adults would therefore be suggested to be a remnant of this early experience of synaesthesia. As discussed previously, it is thought to be unlikely that crossmodal correspondences would all have the same origins (Spence, 2011). Therefore, if a structural account were thought to underly the brightness-weight correspondence, it is entirely plausible that other correspondences would have different origins.

It is proposed that by examining the presence of the brightness-weight correspondence in infancy it is possible to narrow-down the potential origins of the specific correspondence. It is also hoped that Experiments 5 and 6, presented in Chapters 6 and 7, will add to the literature detailing which correspondences young infants appreciate.

6.1.1 Crossmodal Correspondence Appreciation During Infancy

Four-month-old infants have been shown to appreciate correspondences between pitch and visual sharpness, and pitch and vertical location (Walker et al., 2010). More recently, newborn infants have also been shown to appreciate the correspondence between pitch and vertical location (Walker, Bremner, Lunghi, Dolscheid, Barba, & Simion, 2018). Ten-month-old infants have also been shown to appreciate the correspondence between pitch and brightness (Haryu & Kajikawa, 2012). To our knowledge, there is no evidence yet of an appreciation for the brightness-weight correspondence in young infants, and only questionable evidence in children. Plack and Shick (1976) demonstrated some evidence of a potential correspondence between brightness and weight in 5-year-old children, however the results cannot be directly interpreted as evidence of the correspondence. As discussed earlier, this research focusses more broadly on the effect of hue and value upon weight perception, rather than focussing in specifically on the correspondence between brightness and weight. The presence of the brightness-weight correspondence in young infants, who have limited experience with different objects, and who also have not yet developed complex language, was therefore the focus of the current study.

6.1.2 Linguistic Knowledge

We can be reassured that infants at 12-14 months will not be familiar with the linguistic term which overlaps between the description of brightness and weight. As discussed previously, in the English language, the term 'light' can be used to describe both brightness and weight. According to age of acquisition ratings, the word 'light' is not comprehended until 4.7 years of age. This age of acquisition is the same for both meanings of the word; 'not heavy' and 'pale in colour.' Associated words including 'lightness' and 'lightweight' are not understood fully until 9 and 8 years respectively (Brysbaert & Biemiller, 2017; Kuperman, Stadthagen-Gonzalez, & Brysbaert, 2012). It was to be expected that infants just beginning to make their first utterances would be unlikely to have acquired knowledge of these word meanings; particularly because previous research has shown that referential words such as nouns tend to be produced before relational terms, such as adjectives (Gasser & Smith, 2010).

Though less relevant to the linguistic argument, but for reference, the terms 'bright' and 'brightness' are acquired at 6.6 and 7.2 years respectively. Words associated with the other end of the brightness scale are learnt marginally earlier, with 'dark' and 'darkness' learnt at 3.8 and 4.9 years respectively. Although learnt slightly earlier, these terms are still acquired several years after the age at which infants are tested in the following studies (Brysbaert & Biemiller, 2017; Kuperman et al., 2012).

6.1.3 Understanding of Weight

Prior to thinking about whether infants will appreciate the brightness-weight correspondence, we must consider their understanding of weight more generally. Before their first birthday, infants have been shown to perceive and distinguish properties of weight. Using a preferential reaching task, research has shown that 11-month-old infants will choose the lighter object after experiencing both a lighter and heavier object (Hauf, Paulus, & Baillargeon, 2012; Paulus & Hauf, 2011). After being habituated to a light test object, a heavier test object also induces an increased holding time, for 12-month-old infants (Molina & Jouen, 2003).

In terms of eliciting different actions upon the object, haptic perception of weight has been suggested to emerge later in development than perception of other features, such as size and texture (Bushnell & Boudreau, 1991). Smaller objects are picked up and released, switched from one hand to another, and touched unimanually, more often than larger objects. Similarly, squeezing actions are demonstrated on spongy objects, whilst harder objects are more frequently banged (Palmer, 1989). These differentiated actions demonstrate an ability to haptically perceive a difference in features. Whilst there is evidence of such discrimination based on weight, the research is more limited. Changes in weight have been shown to elicit more banging than changes in colour or texture in 12-month-old infants, with a lighter object being waved more frequently than a heavier object. At 12-months, lighter objects are also manipulated more often with one hand, and heavier objects are manipulated more often with two hands (Palmer, 1989; Ruff, 1984). Evidence that infants make distinctions between weights from an early age, and before the end of the first year are able to respond differently to these weights, is encouraging evidence that infants have a relatively good understanding, or at least, a perception of weight. It is important to note however, that these studies generally demonstrate direct haptic perception as opposed to perception of weight based upon visual cues, with the exception of the studies by Hauf, Paulus, and Baillargeon (2012) and Paulus and Hauf (2011).

Considering the current research on infants' understanding of weight, it is noted that many of these studies have a physical element whereby infants manipulate objects. This contrasts with crossmodal studies which tend to have relied on looking-time or eye-tracking measures. Looking-time has previously been a sufficient measure for examining the appreciation of a variety of crossmodal correspondences, showing that infants distinguish congruency by looking longer towards either congruent or incongruent correspondence displays. Whilst this has been informative for the previous studies, we suggest that it might not be the most valuable way to assess a correspondence with weight. Presentation of weight on a visual display relies on the assumption that infants understand a range of complex physical phenomena, including causality.

Visual displays of collision events whereby one object collides with another object and displaces it to a set distance, have often been used to examine understanding of causality. Whilst it has been shown that infants understand simple causality from 6.5

months, it has been suggested that the development of knowledge about collision events is complex and involves the combination of many other developmental processes (Wang, Kaufman, & Baillargeon, 2003). At 6.5 and 11 months, infants realise that the distance an object is moved depends on the size of a ball which collides with it (Kotovsky & Baillargeon, 1994; Kotovsky & Baillargeon, 1998). However, it is not until 9 months that they attend to the size of the stationary object in a collision event (Wang et al., 2003). To our knowledge, the earliest evidence that infants attend to weight in collision events is at 10 months (Wang, 2001; Wang & Baillargeon, 2003). In these studies, weight was cued by allowing infants to feel the weight of the objects. When infants knew that both objects weighed the same, they were surprised that both objects did not displace the stationary object in a collision event. It is suggested that although weight is attended to when weight is made to be a salient feature of the objects (through touch); when a less salient feature (brightness) is used to cue weight, it might not be attended to until a substantially later age. It is suggested that the complex nature of collision events makes them a problematic method for examining the appreciation of the brightness-weight correspondence.

When considering other ways that as adults we depict weight in a visual display, a series of problems are raised as often these displays rely on the assumption that infants understand the particular casual event. Balance scales and floatation can be used as examples to illustrate this point. To most adults it is clear that a heavier weight causes the balance scale to tip that way. A complete understanding of balance scales however, is not thought to emerge until relatively late in development, with children demonstrating a comprehensive understanding by 12-13 years (Inhelder & Piaget, 1958). Visual demonstrations of floatation which can also be used to illustrate weight for adults are not fully understood until late childhood. Young children aged 4-5 make contradictory predictions about floating, and it is not until 11-12 years that children systematically determine conservation of volume and density which are essential for understanding of floatation (Inhelder & Piaget, 1958). Understanding of both of these causal events is therefore typically developed much later than the infant age groups which are of interest for this particular study.

We propose that an alternative method for testing appreciation of weight correspondences in infants is to use preferential reaching/lifting paradigms as in the studies by Hauf et al. (2012) and Paulus & Hauf (2011).

6.2 Experiment 5: Examining the Brightness-Weight Correspondence in Infants Using Preferential Lifting

6.2.1 Introduction

6.2.1.1 Lighter Preference

As discussed, previous research has demonstrated that 12-month-old infants reach preferentially for the object which they expect to be lighter, due to the object's reduced motor demands. Infants were first given a demonstration of a compressible, cotton wool, surface and were then presented with two objects placed onto this surface. One of the objects caused a visibly larger degree of compression than the other. Infants reached preferentially for the object which compressed the surface less, with researchers concluding that they used the visual information to infer weight, and subsequently select the lighter one (Hauf, Paulus & Baillargeon, 2012). Similarly, research has shown that after playing with a lighter and a heavier object, 11-month-old infants will subsequently choose the object which they know to be lighter, using the objects' material as a cue. By 13-months-old, infants will generalise the information about the correspondence between material and weight to novel objects, selecting the object made from the material thought to be lighter (Paulus & Hauf, 2011).

6.2.1.2 The Current Experiment

The current study will examine whether infants display a preference to lift black or white objects, because of their expected weight. To determine that the preference was made on the basis of weight, it is important to consider alternative reasons why infants might choose to reach preferentially for a particular object. Commonly cited reasons for preferences include: complexity, novelty, and salience (Franklin, Gibbons, Chittenden, Alvarez, & Taylor, 2012). As the objects in our study will differ only in terms of brightness, and will not have been lifted previously, it is not anticipated that any of these features will differ across objects.

Another explanation why infants might preferentially lift one block over the other is simply that they have a preference for that colour, regardless of its weight. As object choice has been suggested to be a measure of what people like (Savani, Markus, & Conner, 2008), it is important to consider whether infants show a preference for darker or brighter colours. Though adults have been shown to have a preference for lighter colours; infants do not consistently show preferential looking towards either lighter or darker chromatic colours. Research has found no difference in looking towards objects of different lightness at 1 – 6 months (Taylor, Schloss, Palmer, & Franklin, 2013), a preference for less brightness at birth (Adams, 1987), and also a preference for isochromatic stimuli of higher white luminance than lower white luminance at 3 months (Teller, Civan, & Bronson-Castain, 2004). As most of the research focuses on chromatic colours, research cannot provide conclusive evidence of a preference for black or white specifically. Additionally, the more general consensus across studies appears to be that dimensions of hue and saturation dominate brightness in terms of preference.

There is difficulty in generalising preferences revealed from looking measures to preferences in other situations. For example, preferential looking towards a stimulus does not necessarily indicate that there is an overall preference for this stimulus in all situations. Attention in the Teller et al. (2004) study might naturally be directed more automatically towards bright colours due to their intensity. This does not necessarily mean however than under different conditions, objects of this colour are preferred. Similarly, the newborns preference for less brightness might be due to avoidance of luminance (Adams, 1987).

It is also difficult to establish causality in the relationship between brightness and object preference. Hypothetically, looking preferences for lighter colours displayed in adults (Taylor et al., 2013) could be the result of the correspondence between brightness and weight rather than due to qualities of the colour. The suggestion is that believing objects of a darker colour are heavier in weight might lead to less fondness for these colours.

A further advantage of using preferential reaching measures is that it enables the presentation of black and white blocks together. We suggest that simultaneous presentation of objects which vary in brightness might enhance the focus on brightness, making any potential differences in weight expectation more prominent.

6.2.2 Method

6.2.2.1 Participants

The final sample for this study included 33, 13-14-month-old infants (M_{age} = 408 days, *Range* = 397 days – 402 days, 18 boys and 15 girls). Four more infants were excluded as they did not reach for either block, after the maximum of three presentations.

This research gained approval from Lancaster University Ethics Committee and all infants were recruited from the Lancaster Infant-Lab Database. Parents were given information and consent forms upon arrival which they were asked to sign. At the end of the study, parents were given a verbal and paper debrief and were reminded of their right to withdraw their infant from the study for up to one month after the study. Travel costs were reimbursed to parents and infants were also given a book to take home.

6.2.2.2 Stimuli

There were 4 PLA, test, blocks which consisted of 2 black blocks and 2 white blocks, (see Figure 23). The smaller blocks measured 3.5cm x 3.5cm x 3.5cm, and the larger blocks were matched in size to stimuli used in studies which have previously shown that infants reach for lighter objects (Hauf et al., 2012; 10cm x 10cm x 10cm). It was expected that the smaller blocks would be lifted unimanually as piloting revealed that blocks of this size could generally be lifted in one hand at 13-14 months. This allows for the analysis of unimanual vs. bimanual reaching for white and black cubes. When presented with two of the small blocks at the same time, we considered the possibility that infants might either reach towards both blocks or reach towards one block bimanually. The larger blocks were expected to require a bimanual lift, regardless of brightness.

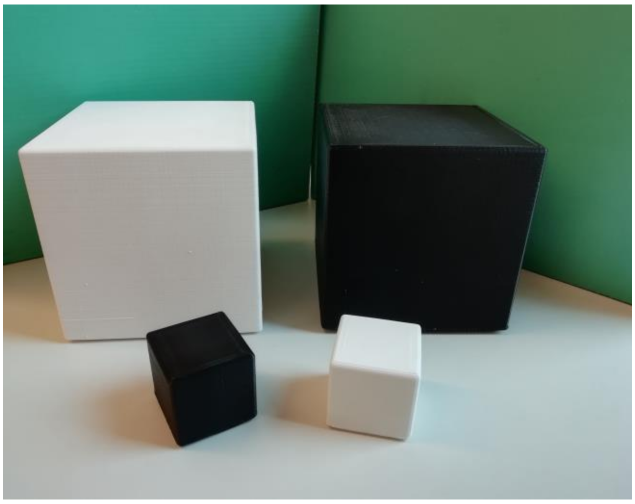


Figure 23. Large and small test blocks used in Experiment 5.

Blocks were presented in same-size, black and white pairs, for example a 3.5cm black cube would only be presented with a 3.5cm white cube. The pairs of cubes therefore varied only in terms of surface brightness (large black 10.67 cd/m^2; large white 196.88 cd/m^2; small black 7.20 cd/m^2; small white 207.73 cd/m^2).

6.2.2.3 Apparatus

Five, Flex 3 OptiTrack Motion Capture cameras, set to greyscale mode, recorded infants' interactions with objects. Although motion capture data was not gathered, the same camera set-up from previous experiments was utilised. Cameras were situated so that data regarding infants' lifting preference could be coded after data collection. Blocks were evenly spaced on a wooden grey board (40cm width x 20cm depth x 1 cm height).

A screen, which measured 47cm in length and 16.5cm in height, was created to hide the blocks from infants' view until the trial begun. The screen was made from a metal frame and a grey cloth which was lifted to reveal the objects, that were subsequently pushed forwards.

6.2.2.4 Design

The primary dependent variable in this study was which object infants preferentially lifted. We were also interested in looking at the number of bimanual reaches to black and white cubes.

Initially, each infant completed only one trial, with half of infants being presented with the small blocks (3.5cm x 3.5cm x 3.5cm) and half of infants presented with the large blocks (10cm x 10cm x 10cm). Testing the initial participants (13 infants), it became apparent that infants were reluctant to lift the larger blocks with only 50% of the 6 infants successfully lifting a large block. This was compared with 100% of the infants successfully lifting the smaller blocks. The decision was therefore made to stop the larger block trials as exclusion rates were very high.

Infants lifting the small blocks were therefore assigned to one of two counterbalancing conditions, those presented with the black cube on the left and the white cube on the right (16 infants), and those presented with the white cube on the left and the black cube on the right (17 infants).

6.2.2.5 Procedure

Infants were seated either in a highchair or on a parent's lap and were positioned centrally to the table. Behind a screen, the experimenter set up the appropriate blocks. When it was time to begin the trial, the screen was removed; this process also helped to draw the infants' attention to the stimuli.

The wooden board with the small black and white blocks on was then pushed forwards. The experimenter encouraged the infant to lift a block saying 'What's this? Can you lift one up?' As the experimenter was aware of the hypothesis, they looked towards the centre of the board to avoid inadvertently cueing infants which block to lift.

If infants pushed the objects out of the way without lifting, or demonstrated loss of interest, the objects were removed, re-centred, and re-presented for a maximum of 3 attempts. Although there was a maximum of 3 presentations, once a lift had been completed, the experiment ended. The average number of presentations before a lift occurred was 1.3 presentations. The experimenter then praised and thanked the infant.

6.2.2.6 Data coding

The researcher first coded trials for lifting preference. Lifting preference was defined as the first object which the infant lifted off the board. Any subsequent lifts were not coded or included in analysis as they were subsequent to the lift of the 'preferred object.' Lifting of subsequent objects might therefore be based on the experience of the weight of the first preferred object.

The researcher also coded the number of hands used to lift the object (unimanual vs. bimanual) and the number of presentations before a lift occurred. All lifts of the small cubes were unimanual and therefore an analysis of unimanual/bimanual lifting for white and black objects is unfortunately not possible.

An independent rater who did not know the aims of the experiment second-coded 24% of trials This coder reported which object the infant lifted preferentially. Once any disagreements were resolved, 100% agreement was obtained.

6.2.3 Results

A two-tailed binomial test was conducted to examine whether brighter objects were lifted preferentially. The test revealed no significant difference in the number of times that the black and white cubes were preferentially lifted (p = .597), (see Figure 24).

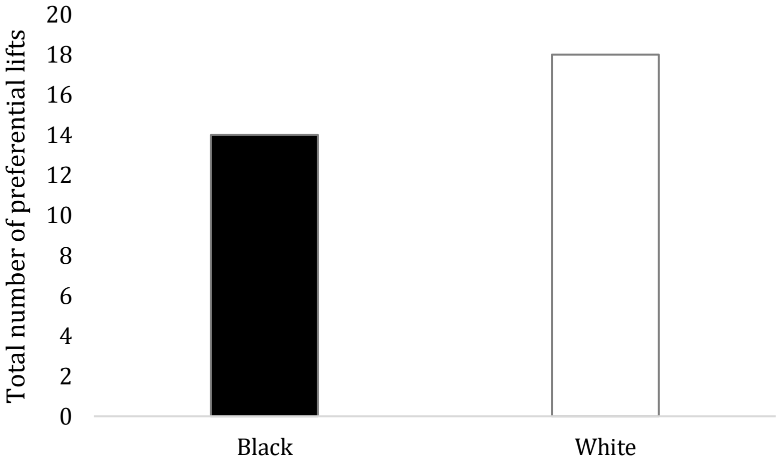


Figure 24. A graph demonstrating no significant difference in the number of times that black and white cubes were preferentially lifted.

Although the side of cube presentation varied across infants, it is still possible that infants lifted preferentially on one side over the other, for example if the infants had begun to develop a right-hand dominance. Therefore, another two-tailed binomial test was conducted to examine whether one hand was used preferentially. The test revealed no significant difference in the number of times that the left and right hands were used (p = .487), (see Figure 25).

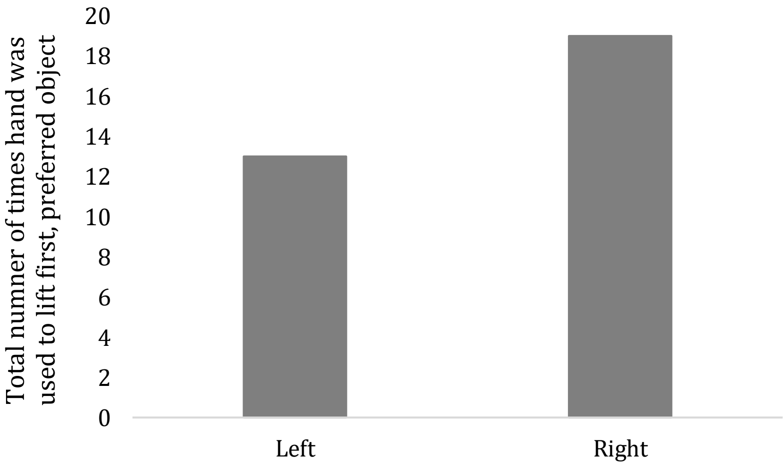


Figure 25. A graph demonstrating no significant difference in the number of times that the left and right hands were used to reach for the first preferred object.

6.2.4 Discussion

As previous research suggested that 13 to 14-month-old infants reach preferentially for objects which they expect to be lighter (Hauf, Paulus & Baillargeon, 2012; Paulus & Hauf, 2011), this study set out to examine whether infants reach preferentially on the basis of brightness as a cue to weight. Based on these findings, it was suggested that infants would preferentially lift the white cube over the black cube if they appreciate the correspondence between brightness and weight, as they would expect this object to be lighter in weight.

The results of this study demonstrate no evidence of preferential lifting of either white or black cubes. Whilst evidence of preferential lifting of the white cube might have indicated that infants thought this object was lighter in weight, absence of preferential lifting does not necessarily indicate that the infants do not make the correspondence between brightness and weight.

It is possible that preferential lifting of the 'lighter' object was not observed because the objects were small and therefore light enough that infants felt confident to lift either object comfortably. If infants did not expect either object to be especially heavy, then their choice of object will likely have been based on a range of other factors aside from weight, such as their personal general preference or which was easiest to grasp from their current position. The suggestion that both objects were expected to be relatively light is supported by the finding that 100% of the small object lifts were unimanual.

Despite this finding in the current study, the measure of unimanual vs. bimanual lifting as a measure of expected weight remains an interesting area of study. It is unfortunate that in the current study the lifting requirements were such that bimanual reaches were not necessitated. To examine this in future studies it would be important to use black and white stimuli of an intermediate size and weight that could plausibly be lifted with one hand but might also more easily be lifted with two hands. This would enable the analysis of the potential differences in weight expectation through the number of hands, and therefore the required force, used to lift black and white objects. Using objects with more challenging lift requirements would also make the consideration of weight more salient. Using such stimuli, it is possible that infants might demonstrate a preference for lifting the 'lighter' object.

Whilst the current study is limited in the information it provides on the brightness-weight correspondence, it is still considered to be an important area of research. The experiment in the following chapter uses similar methods to those used in adult Experiments 2 and 4 to examine infants' selective preparation when reaching for black and white objects. It is possible that although they do not demonstrate a preference for the 'lighter' objects, infants might still selectively prepare their actions across objects, taking into account any expected weight differences.

CHAPTER 7

Infants' Selective Preparation for the Brightness-Weight and Material-Weight Correspondences

7.1 Experiment 6: Examining the Brightness-Weight and Material-Weight Correspondence in Infants Using Kinematic Measures

7.1.1 Introduction

As the preferential lifting study did not reach a clear conclusion regarding infants' appreciation of the brightness-weight correspondence, an alternative method is proposed. Experiment 6 examines how infants reach for and transport objects, as in the adult studies. Playing a give-and-take game will most likely be a familiar experience for infants by one year and would therefore give relatively naturalistic results.

With established evidence that infants can make distinctions on the basis of weight, we consider infants' ability to form expectations about weight. One way to examine this is by considering prospective motor control. Generally, prospective motor control is the ability to adjust actions with respect to future task demands, goals, or more specifically in this case, with respect to weight.

There are conflicting findings regarding the demonstration of anticipatory control of force for weight in young infants. Early research by Forssberg, Kinoshita, Eliasson, Johansson, Westling and Gordon (1992) found that before 18 months, anticipatory control for different weights is rarely exhibited. Rate of change of grip and load force during lifting is not scaled to previously felt weights at this age. Only by the second year do children use information about object weight for prospective control. They argue that differentiating reach speed for size, which is demonstrated in the first year, is fundamentally different from differentiating on the basis of weight. They suggest that size provides continuous visual information which weight does not (Carrico & Berthier, 2008; von Hofsten & Rönnqvist, 1988; Zaal & Thelen, 2005).

Since then, Mash (2007) has proposed that although anticipatory fingertip control for object weight might not emerge until later in development, as in the study by Forssberg et al. (1992), prospective control of the palmar grasp for object weight might emerge sooner, as this type of grasp generally develops earlier (Bertenthal & Clifton, 1998). Studies are now consistently finding that young infants make selective preparations based on expected weight; these preparations have been examined by looking at the reach and lift components of the action.

7.1.1.1 Weight Expectation and Approach

Mash (2007) examined whether 9, 12, and 15-month-old infants adjust manipulative force in object-directed actions, based on previous exposure to object weight. During familiarisation infants were presented with two objects that varied in terms of colour and weight. Colour was used to identify and distinguish objects rather than as a correspondence that directly cued weight. Infants were then presented with test objects, whose colour-weight correspondences were reversed. Analysis of reach kinematics showed that the approach towards objects which were previously heavier, was significantly faster, than towards objects expected to be lighter. Despite positive findings of differential peak reach velocity, infants do not demonstrate evidence of changed reach duration, average reach velocity, peak acceleration, distance of reach, and straightness of reach for objects of different weights, measures which have previously been shown to vary as a result of weight in adults (Claxton, Keen, & McCarty, 2003; Mash, 2007). Similarly, when precision requirements vary, infants do not demonstrate all reach differences which are observed in adults, such as the hallmark longer deceleration phase used for greater precision (Claxton et al., 2003). Peak reach velocity appears to be the most sensitive measure for revealing differences in prospective control; showing that infants can consider the necessary requirements to succeed at lifting an object, based on the objects' weight.

7.1.1.2 Weight Expectation and Object Transport

Though differences in the approach to differently weighted objects have been shown, the transport of objects appears to be more fruitful in revealing infants' prospective control. It has been suggested that inadequate adaptation to an object's weight might yield erratic control during transport (Jenmalm, Schmitz, Forssberg, Ehrsson, 2006). Methods whereby an expectation of weight is purposefully created and then reversed or violated are frequently utilised in this area of research. When set the task of retrieving an object placed on top of a cloth, 12-month-old infants fail to retrieve the object more often if previously established colour-weight pairings are reversed, than when they remain consistent. This is thought to be due to the inadequate force generation which is applied based on previously learnt weight predictions (Upshaw & Sommerville, 2015).

It has been shown that when a lifted test object was lighter than expected (based on prior experience), 12-month-olds transported the object with significantly greater average and peak speed, and greater acceleration, than a standard object of the expected weight (Mash, 2007). Similarly, when presentation of solid brass rods is followed by visually identical hollow rods, the hollow rods are lifted with an overshoot (Mounoud & Bower, 1974). Furthermore, at this age infants generalise their actions, not only to seen objects, but also to unseen objects of the same category, suggesting an expectation of the same object-weight pairing across members of the same category.

When object-weight test trials were inconsistent with those previously experienced, movement jerk was greater than on consistent trials in which the weight was as expected (Mash, Bornstein, & Banerjee, 2014). These studies demonstrate how by the first year infants selectively scale forces for objects which they expected to have different control requirements, relying upon their internal representations of the objects.

Alongside the speed measures during object transport, research has also identified that the lift trajectory of objects varies depending on the prior visual-weight information received. When prior visual information that distinguishes weight is available (e.g. colour), 14-month-old infants lift lighter objects higher than heavier objects, suggesting they are able to apply different amount of force to objects which vary in weight (Gottwald & Gredebäck, 2015). Different results have been obtained when objects are a different weight than expected. Objects which were lighter than expected were lifted for a greater distance, and objects that were heavier than expected were lifted with less straight trajectory than the same-weight standard objects (Mash, 2007).

Despite a general interest in the speed of infants' reach and transport of objects as a measure of prospective control, the more precise details regarding what time point to take this measure has varied across experiments (Gottwald, 2018). Studies have used entire movement durations such as the reaching time (Zaal & Thelen, 2005) and the peak velocity of the full movement duration (Claxton et al., 2003; Mash, 2007).

Studies have also looked at pre-defined, partial segments of the movement. Of particular interest is the time period after attainment of peak velocity, which is also known as the deceleration duration. This time frame has been considered to be useful when looking at prospective motor control as an early peak velocity, and therefore a longer deceleration duration has been thought to provide greater precision (Chen, Keen, Rosander, & von Hofsten, 2010). Pre-defined periods have also been used to look at the initial section of the lift, with 500ms thought to be the window in which sensory based adjustments could not have substantially rescaled the movement in infants (Mash, 2007; Mash et al., 2014). A novel approach whereby periods are defined based on individual movement profiles has also been introduced by Gottwald and Gredebäck (2015), which will be discussed in greater detail in the discussion section.

7.1.1.3 The Current Experiment

The current study will examine whether infants' prospective motor control differs for equally weighted objects which vary in terms of brightness and material. As infants have been shown to plan their actions based on the expected weight of objects, if infants appreciate the correspondences between brightness and weight, and material and weight, we might expect to see differential reaching and lifting kinematics for objects which vary by these properties.

Potential selective preparation is expected to be revealed through differentiated approach and transport of blocks. Selective preparation for weight on the basis of brightness (black vs. white) and material (sand vs. fluff) could result in greater acceleration, velocity, and height during the transport of the black cube and the sand block. These measures would suggest that excessive levels of force were used to lift the equally weighted, dark and sand blocks. Similarly, we expect the brighter object and the fluff block will be transported to a lesser height, with less velocity and acceleration during transport.

When considering whether infants will reach quickly or slowly towards objects which they expect to be heavy, it remains difficult to form specific predictions. In most instances, it can be said that reaches are slower for objects and tasks which require a greater deal of precision (Carrico & Berthier, 2008; Claxton et al., 2003; Gottwald et al., 2017; Zaal & Thelen, 2005). As discussed in previous chapters, it is proposed that whether heavier or lighter objects are considered to require a greater level of precision is largely dependent on the features of the object. It is proposed that at the heaviest end of the scale, heavier objects require more precision to ensure a secure grasp; whereas at the lighter end of the scale, lighter objects require a more precise approach to avoid displacing the object. In the adult experiments, we found evidence of faster reaches towards objects which participants expected to be heavier, similarly to the infant observation by Mash (2007). However, it is equally plausible that if infants consider the stimuli to be relatively heavy, they might approach the 'heavier' blocks with more precision. If infants do not reach and transport objects differently, we cannot exclude the possibility that the expected weight differences are not great enough to elicit differences in action.

As in the adult experiments, material stimuli are included to compare any differences in kinematics between arguably a more obvious cue to weight (material), and a less obvious cue to weight (brightness). The findings from our adult study indicate that the differences in prospective control for material-weight and brightness-weight correspondences are revealed through different measures. Including both sets of stimuli will allow comparison of which measures, if any, reveal evidence of weight correspondences in infant participants.

The age of infants for the current study was decided upon considering the youngest age at which we could attempt to see evidence of the correspondence whilst also testing infants with the necessary motor skills to execute a relatively clear reach-grasp-lift motion, ideally in a manner that was comparable to adults.

By 12-months, infants already have a relatively sophisticated reach-to-grasp motion established. Assessment using the skilled reaching rating scale (SRRS) showed that 12-month-olds' execution of a reach-to-eat action was comparable to the adults' performance in terms of orientation, pronation, release, and evidence of the pincer grip, amongst other measures (Sacrey, Karl, & Whishaw, 2012). The pincer grip emerges between 8 and 11-months of age (Meyer, Braukmann, Stapel, Bekkering, & Hunnius, 2016) and biomechanically possible grips can be distinguished from impossible grips as infants' own experience with the sensorimotor experience develops from around 9 months (Senna, Addabbo, Bolognini, Longhi, Cassia, & Turati, 2016).

Additionally, infants at this age also begin to use unimanual lifts more often, a capability which makes the examination of measures clearer. Whilst at 5 months infants tend to use a bimanual reach, regardless of object properties, by 11-12 months, infants' reaches reflect the objects' diameter, using a bimanual reach for objects of a wider diameter (Fagard, 2000). By one year, there is also evidence that infants demonstrate a hand preference, predominantly the right hand (62.6%), with the number demonstrating this preference increasing over the following years (81.9% at 2 years), (Sacrey, Arnold, Whishaw, & Gonzalez, 2013; Sacrey et al., 2012). Demonstration of the right-hand preference varies substantially along with the task, with other research showing only a slight right-hand preference in 18-month-olds (Fagard & Marks, 2000). We anticipate that by 12-months, infants will have the necessary skills to make clean lifts of the blocks, primarily using a unimanual, pincer grip. This gives the valuable opportunity to make relatively close comparisons with the adult data.

As discussed in Chapter 6, research has shown that infants shake a lighter object more often than a heavier one. Evidence also shows that lighter objects are more often manipulated with one hand and heavier objects more often manipulated with two hands (Palmer, 1989; Ruff, 1984). Whilst the current study primarily focusses on selective preparation on the basis of weight, there is also the opportunity to examine these other weight-related behaviours. The study will therefore examine the presence of these behaviours across objects which vary in brightness and material to examine expectation and perception of weight.

The study in this chapter is very similar to the adult studies but with infant participants. There are a few changes that were necessary to make the study appropriate for infant participants. Firstly, to maintain infants' levels of attention, we chose to separate the brightness and material aspects of the experiment. Most infants completed both parts of the experiment with a short break in between. One group of infants completed the brightness experiment first (24 infants), and another group completed the material experiment first (21 infants).

7.1.2 Method - Experiment 6: Brightness

7.1.2.1 Participants

Forty-five infants were initially tested, however, the final sample for the gross behavioural data included 38, 12-month-old infants (M_{age} = 362 days, *Range* = 348 days – 379 days, 22 boys and 16 girls). Reasons for exclusion included infant fussiness (n = 4), poor video quality (n = 2), and incorrect age (n = 1).

The criteria for motion capture data inclusion was more stringent than for gross behavioural data inclusion (more details in 'Data Inclusion'), meaning that the final sample for this part of the analysis included 27, 12-month-old infants (M_{age} = 361 days, *Range* = 349 days – 379 days, 15 boys and 12 girls). Alongside those exclusions already mentioned, 11 infants were excluded because although they reached the criteria for the minimum number of trials, there was not a full pair of trials which contained adequate motion capture data for analysis. Of the 27 infants included in the kinematic analysis, 15 completed the brightness study first, 9 completed the material study first, and 3 completed only the brightness study.

The research gained approval from Lancaster University Ethics Committee and all infants were recruited from the Lancaster Psychology Department Infant-Lab Database. On arrival, parents were given information and consent forms which they were asked to sign if they agreed for their infant to take part in the experiment. When the study had ended, parents were given a debrief sheet and reminded of their right to withdraw their infant's data from the study up to one month after the study takes place. Parents travel costs were reimbursed and infants were given a book for participating.

7.1.2.2 Stimuli

Infants were presented with a grey, PLA, cube (41.73cd/m^2) to familiarise them with the procedure of the experiment. The cube measured 3.5cm x 3.5cm x 3.5cm and weighed 33.4g. The test objects included two PLA cubes which also measured 3.5cm x 3.5cm x 3.5cm, and both weighed 33.4g. The cubes varied only in terms of brightness, one cube was white (97.80cd/m^2) and the other was black (6.52cd/m^2), (see Figure 26).

Figure 26. The white and black test blocks and the grey familiarisation block used in Experiment 6.

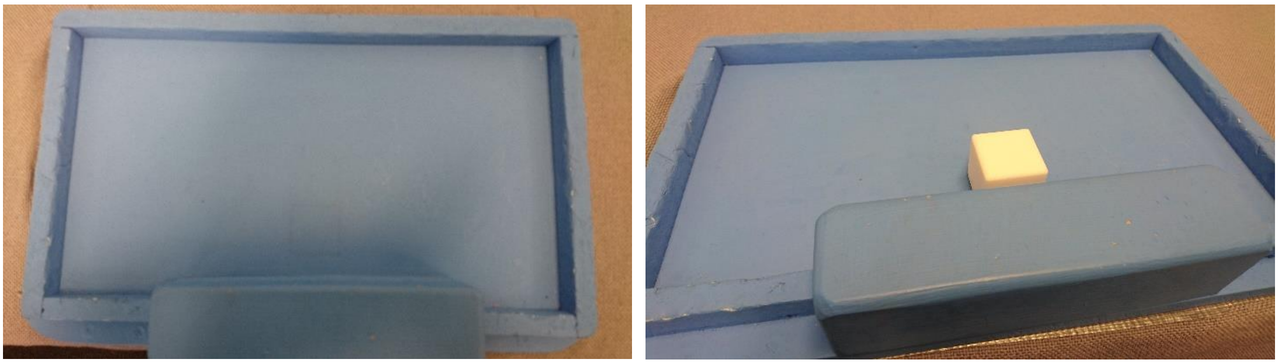


Figure 27. Table-top board on which objects were presented. From above (left) and from front (right).

Objects were presented on a table top board. As illustrated in Figure 27, this featured a barrier for infants to reach over, encouraging infants to add a vertical element to their lift and preventing them from simply sliding the cube towards themselves. The barrier dimensions were: 20cm width, 5cm height, and 5cm depth. The overall dimensions of the board were: 41cm width x 1cm height x 25cm depth. The board also had a low border (2cm high) around the edge, this was to prevent infants from swiping objects off the side of the board, without lifting. The closest side of the object was placed 1.5cm from the barrier.

7.1.2.3 Apparatus

As in the adult studies, a Flex 3, OptiTrack Motion Capture System was used in the present study to measure infants' hand movements. Four cameras recorded position data, and an additional camera was also used as a video camera. This addition was thought to be necessary for infant studies as the phases of movement were anticipated to be more difficult to identify. The cameras were all mounted on the wall, out of reach of infants.

Infants wore a wristband on each wrist. Each wristband was composed of a velcro strap, which had a 6mm reflective marker placed onto it.

7.1.2.4 Design

The dependent variables in this study were the kinematics of the infant's reach towards and transport of objects. The specific measures included: peak velocity towards the object, maximum height of lift during transport, and peak and average acceleration and velocity whilst transporting the object. All of these measures could be collected by the markers on both wrists. These measures were examined to see whether kinematics of reach and transport vary depending on the brightness of objects.

All infants were initially presented with two grey cubes to familiarise them with the experiment and the procedure. After the two familiarisation trials, infants were presented with the test objects. Approximately half of the infants (25 infants) were presented with the black cube first, and then the white cube; the other infants (20 infants) were presented with the white cube first, and then the black cube. Of those infants included in the motion capture analysis, 18 were presented with the black cube first, and 9 were presented with the white cube first. It is unfortunate there were unequal participants from each group included in the final analysis, however counterbalancing was included as a between factor to observe whether there was an effect of group. It is in the nature of motion capture that the number of exclusions is not clear until the very final stage of data editing and coding.

The test objects were then each presented five times more, carrying on with the alternation assigned at the start of test. This creates a total of 2 familiarisation trials and 12 test trials (6 with each object). It was hoped that for each infant, satisfactory data could be collected from at least one pair of trials. Exclusion criteria will be discussed in the following section.

7.1.2.5 Procedure

Infants were seated in a highchair and were strapped in comfortably. The highchair was positioned in front of a sturdy desk. Secured onto the desk, was the table top board.

On each trial, the infant was presented with one of the cubes, positioned behind the barrier. During placement of cubes, the experimenter rotated the object to draw the infant's attention to the cube. Once the object was placed, the experimenter said 'What's this? Can you lift this one up?' Infants were praised for lifting the object and the experimenter said 'Thank you! Well done!' These verbal cues were necessary to encourage the infant to continue to lift the same objects multiple times.

If infants did not lift the object, the experimenter encouraged them, saying 'Can you lift that one up?' If the infant still did not lift the object, the object was removed and the next in the series was presented.

The first two trials were the familiarisation trials with the grey cube. The grey cube was presented to familiarise infants with the procedure and to set a baseline expectation of how heavy these cubes are likely to be. The infants were then presented with the test objects, either the black cube followed by the white cube, or the white cube followed by the black cube. They were then presented with each cube five times more.

7.1.3 Method - Experiment 6: Material

7.1.3.1 Participants

Forty-two infants were initially tested, however, the final sample for the gross behavioural data included 37, 12-month-old infants (M_{age} = 363 days, *Range* = 348 days – 379 days, 20 boys and 17 girls). Reasons for exclusion included infant fussiness (n = 1), poor video quality (n = 2), incorrect age (n = 1), and stimuli issues (n = 1).

The criteria for inclusion of motion capture study was more stringent than for the gross behavioural data (more details in 'Data Inclusion'), meaning that the final sample for this part of the analysis included 27, 12-month-old infants (M_{age} = 364 days, *Range* = 348 days – 379 days, 17 boys and 10 girls). Alongside those exclusions already mentioned, 10 infants were excluded because although they reached the criteria for the minimum number of trials, there was not a full pair of trials which included adequate motion capture data which could be analysed. Of the 27 infants included in the kinematic analysis, 14 completed the material study first, and 13 completed the brightness study first.

This research also gained approval from Lancaster University Ethics Committee and all infants were recruited from the Lancaster Infant-Lab Database. The information, consent, and debrief procedures were identical to the previous study.

7.1.3.2 Stimuli

The test objects were two clear Perspex cubes (3.8cm x 3.8cm x 4cm), one was filled with red fluff and the other filled with red sand, (see Figure 28). Naturally, the fluff cube (19.4g) weighed substantially less than the sand cube (72.5g), therefore the weight of these cubes was manipulated; in this case by adding steel bolts to a central pillar in the fluff cube and plastic to the centre of the sand cube. After this manipulation both cubes weighed 65.5g.

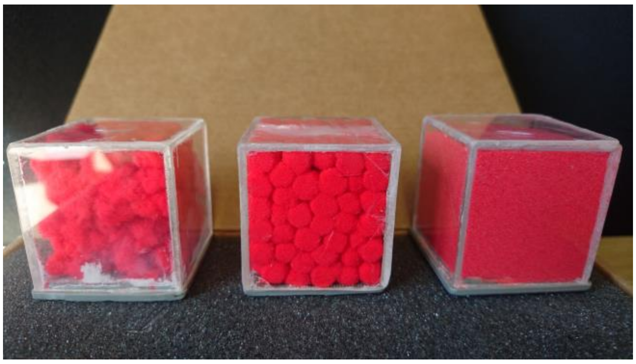


Figure 28. The fluff and sand test blocks and the pompom familiarisation block used in Experiment 6.

In the adult and infant brightness-weight studies, a grey cube was presented initially as a mid-brightness comparison, however as discussed, a familiarisation object was not presented for the adult aspect of the material-weight study. For the infant, material-weight study a familiarisation object was required as infants might not be familiar with the procedure if they completed the material experiment first. In the adult experiments, the 'lighter' object was a transparent block filled with red pompoms and the 'heavier' object was a block filled with red sand. Through extensive piloting, we attempted to find a material which adults consistently rated as lighter than sand but heavier than pompoms, however this was problematic as the pompoms were packed in densely which made them appear heavier than they were. Consequently, we introduced fluff as the 'lightest' material. Piloting with 24 adults revealed that 20 out of 24 participants expected the fluff to be the lightest, the pompoms to be mid-weight, and the sand to be the heaviest. A one sample t-test revealed that rating in this order was significantly greater than chance ($t(23) = 12.43$, $p < .001$, $d = 2.54$). Therefore, the decision to use these materials was made.

7.1.3.3 Apparatus

The same camera set-up was used as in the previous infant study (Flex 3, Optitrack Motion Capture System). Infants also wore the same wristbands, one on each wrist.

7.1.3.4 Design

The dependent variables were the same as in the infant brightness study and included: peak velocity towards the object, maximum height of lift during transport, and peak and average acceleration and velocity whilst transporting the object. These measures were collected to examine whether kinematics of reach and transport vary depending on the perceived material of objects.

Approximately half of infants were presented with the fluff-filled cube first, and then the sand-filled cube (22 infants). The others (20 infants) were presented with the sand-filled cube first and then the fluff-filled cube. Of those infants included in the motion capture analysis, 17 were presented with the fluff cube first, and 10 were presented with the sand cube first. It is unfortunate that again there were unequal participants from each group included in the final analysis, however counterbalancing was included as a between factor to observe whether there was an effect of group.

Both test objects were then presented five times more each, continuing with the alternation assigned at the start of the experiment; creating a total of 12 test trials (6 with each object).

7.1.3.5 Procedure

As in the brightness-weight study, the first two trials were the presentation of the familiarisation object, which in this experiment was the pompom cube. This was to familiarise infants with the procedure and to set a baseline expectation of object weight. The rest of the procedure was identical to the first study, with the alternation of sand and fluff cubes instead of black and white cubes.

7.1.3.6 Data Editing

Labelling

Markers were labelled by an independent coder who manually labelled each marker as either the 'left hand' or the 'right hand.' Though attempts were made to use rigid bodies, single markers were less problematic with infants, meaning that labelling of markers had to be done post-processing.

Fill gaps

Only small gaps in the data (≤10 frames) were interpolated using the built-in function in Motive, to avoid the inaccurate reconstruction of data. Markers occasionally became occluded due to the experimenter's hand moving in front, or due to the infant lifting their palms up. Trials in which the marker from the moving hand was occluded during an important time point in the reach or lift were excluded from analysis.

Filtering

In Experiment 4, the adult data were manually inspected to examine the effect of different filtering cut-offs and 14Hz was selected as the most appropriate filter. The most appropriate cut-off differs across experiments and so therefore the infant data was also visually inspected.

As in the adult data, most sections were relatively smooth, suggesting that a high cut-off frequency should be used, keeping as much of the original data as possible. However, some sections of the data do contain considerable noise as can be seen in Figure 29, supporting the use of data filtering. In both segments displayed, it is evident that filtering at 14Hz reduces the noise and sharp movements, whilst also maintaining a true representation of the shape of the data. Filtering at lower cut-offs increasingly changes the data, making it farther away from the original shape. A cut-off of 14Hz was therefore applied when editing the data.

7.1.3.7 Data Coding

There were three time phases during each trial which were manually coded: reach, grasp, and transport. The reach phase began when infants start reaching for the target object. The grasp phase began when infants first made contact with the object. The transport phase began when the object first lifted off the surface. This was coded manually as in Experiment 2. In Experiment 4, it was possible to additionally examine the point at which the velocity of the object reached 50mm/s, this was a measure used in previous studies to mark lift-off. Unfortunately, in the current study, it was not possible to include a marker on the object (due to occlusion by the infant), and therefore the 50mm/s threshold for object lift-off was not used. It was also concluded that manual coding of the data would account for any unexpected actions by the infants. Within the transport phase we were interested in looking at the first 500ms of movement, after lift-off.

In addition to coding of time phases, the gross behavioural aspect of this experiment also required coding of actions which followed lifting. The action succeeding the lift was coded into one of seven categories including: lifting the object up high or passing it back to the parent or researcher, holding the object to self, lifting with a wrist twist, lifting to the mouth, lifting and then throwing, lifting and then shaking or banging, lifting and then dropping the object. It was important to code the subsequent behaviour in this infant study. In the previous adult study, there was an intended action with the object, which was to place it onto a platform. In this study, the action possibilities are more varied. Research has shown that the way objects are grasped is influenced by the intended action. Ten-month-olds reach for a ball faster if they plan to throw it (Claxton et al., 2003), 14-month-olds reached more slowly when a subsequent target goal was smaller and further away (Gottwald et al., 2017), 18-21-month-olds demonstrated an earlier peak velocity when the intention was to build a tower than when it was to put it into a container (Chen et al., 2010).

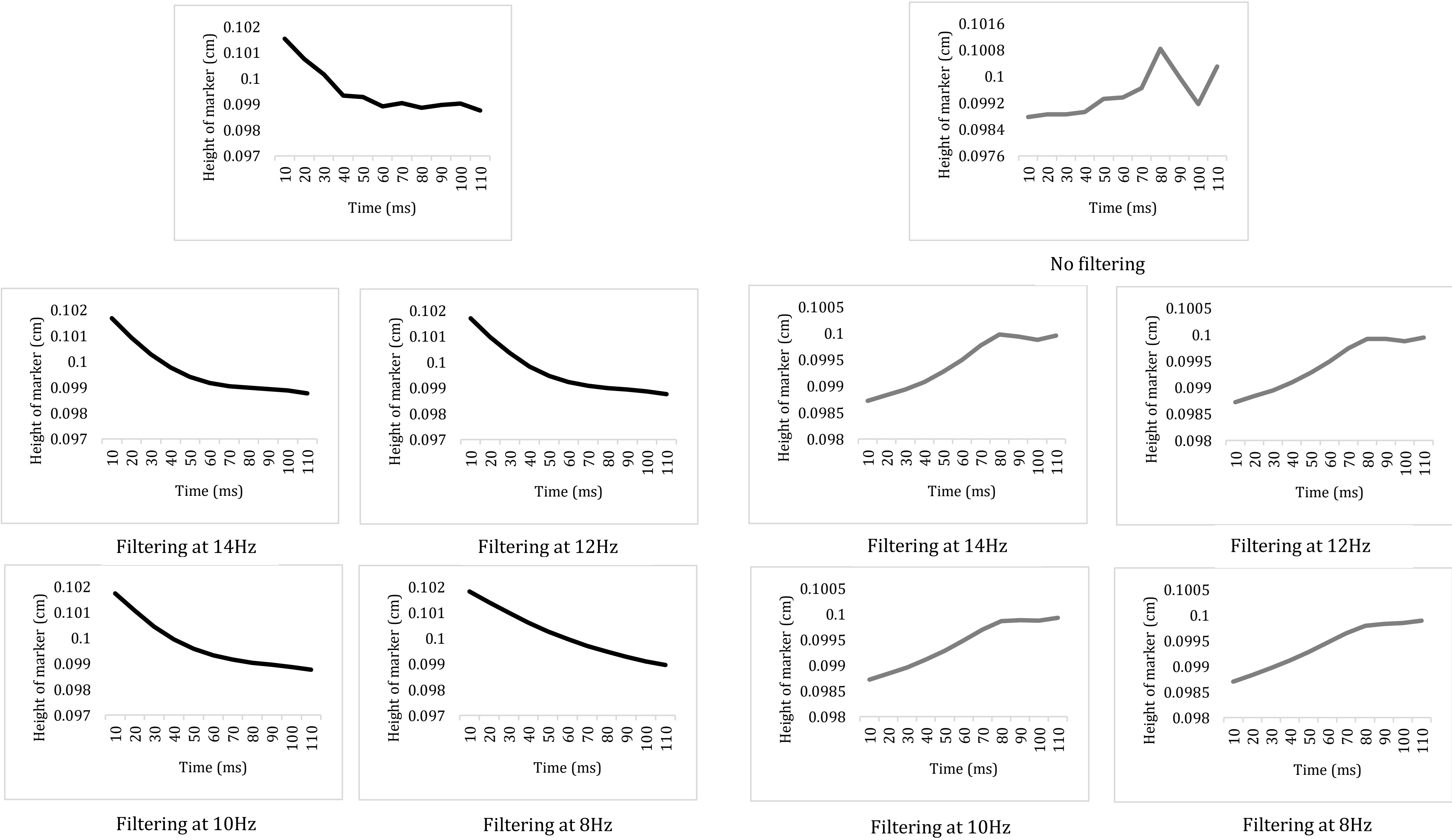


Figure 29. These graphs demonstrate the effect of filtering on a portion of one infants' reach in the Y axis, whereby there is relatively little noise (black lines), and a relatively large amount of noise (grey lines).

7.1.3.8 Data Inclusion

Gross Behavioural

There were a series of criteria that had to be met for inclusion at each stage of the analysis. Firstly, any infants who did not lift the blocks on at least 50% (3 pairs) of trials were excluded from the analysis. By pairs of trials we refer to two trials, including a black and a white cube; for a pair of trials to be included, infants must have reached on both trials. The specifics of how objects were lifted does not matter at this stage of exclusion, infants might later have trials excluded meaning that only one pair of trials can be included, but this is considered adequate. Reasons for not meeting the minimum criteria included lack of engagement or infant fussiness (1 material; 4 brightness), and broken stimuli (1 material). Infants were also excluded at this stage for technical issues with the camera (2 material; 2 brightness), and incorrect infant age (1 material; 1 brightness). After these exclusions there were 37 participants (518 trials) included in the material trials and 38 participants (532 trials) included in the brightness trials. Within the 518 material trials, there were 24 trials where no lift occurred, resulting in 494 trials. Within the 532 brightness trials, there were 31 trials where no lift occurred, resulting in 501 trials.

Although not all of the motion capture data for these trials could be analysed, we decided to look at the behavioural data collected within these 995 trials. The rationale for consideration of these trials is discussed later in detail.

Motion Capture

The exclusions detailed in the gross behavioural section also apply to the motion capture data, however there were also additional criteria that needed to be met. Only unimanual lifts were analysed in the motion capture part of this study. During piloting, it was evident that 12-month-old infants are generally comfortable lifting these cubes with one hand and previous research has shown that by this age they are more selective in when to use a bimanual reach (Fagard, 2000). Although in previous research with 14-month-olds, only data from the dominant hand has been analysed (Gottwald & Gredebäck, 2015), we chose to use data from both hands. This decision was made as many infants did not demonstrate hand dominance, despite an overall preference across babies for the right hand.

Trials were also excluded from motion capture analysis if there was a substantial amount of difficulty lifting the block or there was not one distinct lift. Occasionally, the object would be moved around or tapped on the board before being successfully lifted; these trials were excluded as the object would be lifted from a different location, potentially requiring different lift forces. Another reason for trial exclusion was if the object was lifted by leaning on the block and twisting the wrist. In this type of lift, the infant does not bring the object closer to themselves and the wrist marker appears to remain almost stationary, meaning that no lift data are available for analysis.

The final reason for exclusion was when the quality of the motion capture tracking was poor, with occlusions during important time points. If one of the lifts in a pair was excluded due to any of these reasons, the other was also excluded from analysis. This was to ensure that there were equal numbers of black and white trials to analyse.

After all exclusions were completed, infants were included if they had at least one pair of trials which could be used in the motion capture analysis. Whereas in the adult studies, each participant contributed a set number of trials, infants contributed a varied number of trials, from various points in the experiment. This meant that we could not easily analyse the effect of trial on lifting, and therefore had to average the measures across all contributed trials. Although there were some overall differences in the measures across trials, e.g. increasing velocity over trials, Experiments 2 and 4 demonstrated that there were no significant changes in adults' erroneous lifts throughout the duration of 16 trials. For example, adults continued to lift sand blocks higher than pompom blocks for the duration of the experiment (Experiment 4). The infant study had only 12 trials, and it is therefore suggested that substantial difference across trials is unlikely. This adaptation is therefore thought to be a sufficient way to include the largest amount of reliable data.

For the brightness study, infants contributed a total of 73 pairs of trials, with an average of 2.7 pairs of trials per participant (ranging between 1 pair and 6 pairs). For the material study, infants contributed a total of 66 pairs of trials, with an average of 2.4 pairs of trials per participant (ranging between 1 pair and 5 pairs).

7.1.4 Results: Motion Capture

In the results section, the brightness and material results will be discussed separately. Results will then be compared in a detailed discussion. Brightness and material experiments are both analysed using two tests; first a preliminary analysis and then a more detailed analysis.

Preliminary analyses were conducted using a binomial test to look at the percentage of outcomes in the expected direction. There was one outcome, per measure, per participant as values across trials were averaged, e.g. recorded approach velocities for all white blocks for participant 1 were averaged. As there were 27 infants included in both the brightness and material aspects of the study, the maximum number of results in the expected direction was 27. Out of the 27 participants, the total number of participants whose averaged measures were in the expected direction (e.g. sand lifted higher than fluff), were labelled as 'successes.'

A thorough analysis then looked at whether brightness and material had an overall effect on each measure (e.g. lift height, approach velocity). Whereas the preliminary analysis looked only at the direction of the result, this analysis involved looking at the specific measurements (e.g. cm, mm/s), and whether this varied across objects of different material and brightness.

7.1.6.1 Material

Approach velocity

Both the preliminary and ANOVA analyses revealed no significant difference in the approach velocity towards blocks filled with sand and fluff, (see Table 4).

Transport velocity

Preliminary analyses showed that there was a marginally significant effect of material on the average velocity of transport (p = .052, on a two tailed binomial test), with 70% of participants demonstrating a faster transport for the sand block compared to the fluff block.

The more in-depth ANOVA analysis revealed a significant effect of material upon average velocity during transport, F (1, 25) = 8.096, p = .009, $\eta_p{}^2$ = .245. Analysis of means revealed that the sand block (M = 237mm/s) was transported with a greater average velocity than the fluff block (M = 184mm/s), (see Figure 30).

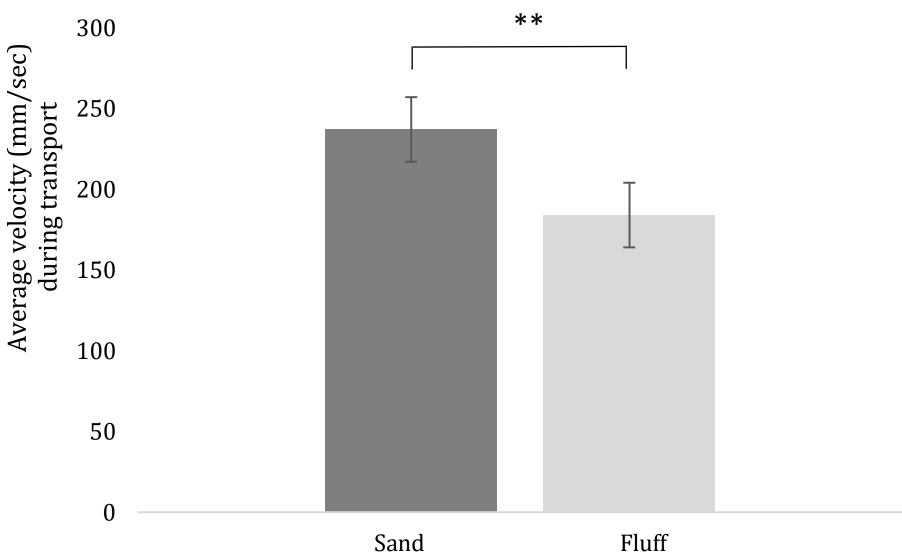


Figure 30. A graph showing the significant difference in average transport velocity for sand and fluff blocks (p < .001 ***, p < .01 **, p < .05 *).

Although the preliminary test revealed that there was no significant effect of material upon the total number of participants that lifted the sand block with a greater maximum velocity (see Table 4), the ANOVA revealed there was a significant effect, F (1, 25) = 8.065, p = .009, $\eta_p{}^2$ = .244. Analysis of means revealed that the sand block (M = 410mm/s) was lifted with a greater maximum velocity than the fluff block (M = 320mm/s), (see Figure 31).

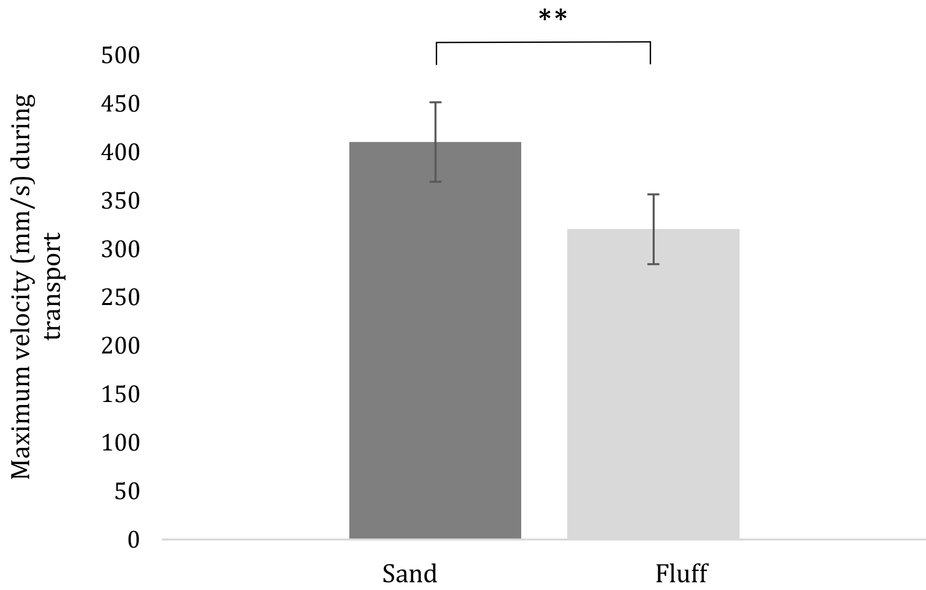


Figure 31. A graph showing the significant difference in maximum transport velocity for sand and fluff blocks ($p < .001$ ***, $p < .01$ **, $p < .05$ *).

Transport acceleration

Preliminary analysis also revealed a marginally significant effect of material on average acceleration during transport ($p = .052$, on a two tailed binomial test), with 70% of participants showing a greater acceleration with the sand block.

Detailed analysis revealed a marginally significant effect of material upon average acceleration during transport, $F\ (1, 25) = 3.975$, $p = .057$, $\eta_p{}^2 = .137$. Analysis of means revealed that the sand block ($M = 2.098\text{m/sec}^2$) was transported with greater average acceleration than the fluff block ($M = 1.699\text{m/sec}^2$), (see Figure 32).

Both the preliminary analysis and the ANOVA revealed no significant effect of material upon the maximum acceleration during transport.

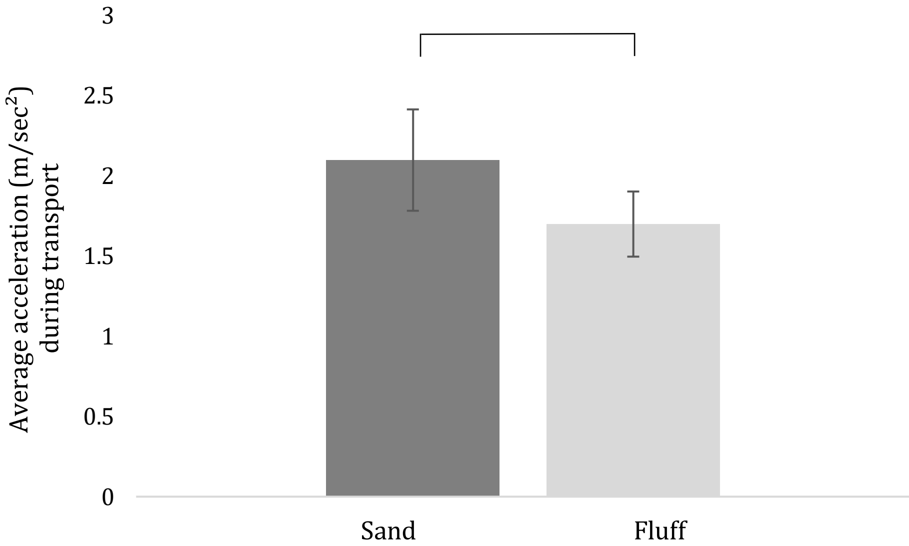


Figure 32. A graph showing the marginally significant difference in the average transport acceleration for sand and fluff blocks.

Maximum lift height during transport

There was also a marginally significant effect of material on maximum lift height (p = .052, on a two tailed binomial test), with 70% of participants lifting the sand block to a greater maximum height than the fluff block.

The ANOVA also revealed a significant effect of material upon maximum lift height during transport, F (1, 25) = 9.630, p = .005, $\eta_p{}^2$ = .278. Analysis of means revealed that the sand block (M = 13.7cm) was lifted higher during transport than the fluff block (M = 12.4cm), (see Figure 33).

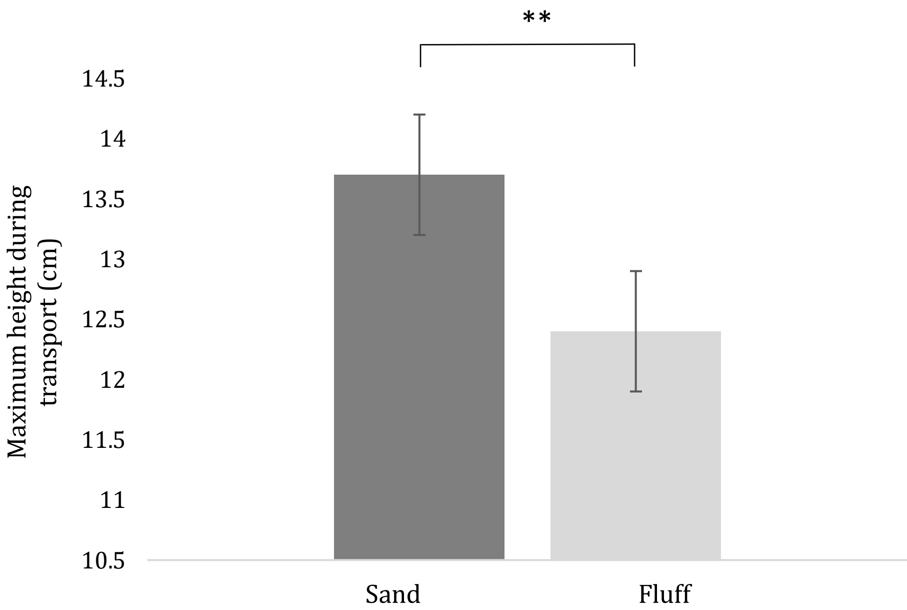


Figure 33. A graph showing the significant difference in the maximum lift height of sand and fluff blocks (*p* < .001 ***, *p* < .01 **, *p* < .05 *).

Table 4.

Mean values and p values for each kinematic measure during the approach and transport of objects which vary in material.

	Preliminary	ANOVA		
	p	Sand	Fluff	*p*
Max velocity approach (mm/s)	1.00	425	463	.292
Max velocity transport (mm/s)	.122	410	320	****.009**
Average velocity transport (mm/s)	**.052**	237	184	****.009**
Max acceleration transport (m/sec^2)	.248	5.996	5.166	.661
Average acceleration transport (m/sec^2)	**.052**	2.098	1.699	**.057**
Max height of wrist (cm)	**.052**	13.7	12.4	****.005**

Note: Bold entries are significant or marginally significant results ($p < .001$ ***, $p < .01$ **, $p < .05$ *).

7.1.6.2 Brightness

The preliminary analysis revealed no significant effects of brightness on any of the kinematic measures, as can be seen in Table 5.

The ANOVA analyses also showed that there was no significant difference in the kinematic measures on the basis of brightness. Neither the approach (velocity), nor the transport measures (velocity, acceleration, and lift height) were significantly different across black and white cubes, (see Table 5).

Table 5.

Mean values and p values for each kinematic measure during the approach and transport of objects which vary in brightness.

	Preliminary	ANOVA		
	p	Black	White	*p*
Max velocity approach (mm/s)	1.00	437	425	.763
Max velocity transport (mm/s)	.442	465	510	.610
Average velocity transport (mm/s)	1.00	260	274	.664
Max acceleration transport (m/sec^2)	.248	6.233	7.748	.596
Average acceleration transport (m/sec^2)	1.00	2.551	2.758	.780
Max height of wrist (cm)	.701	14.1	14.0	.931

Condition

As discussed in the methods section, the number of infants included in each counterbalancing condition was unequal following application of the exclusion criteria. It was therefore especially important to check whether condition assignment influenced the measures, or whether there was an interaction between condition and material/brightness.

Condition assignment (e.g. black>white, white>black, fluff>sand, sand>fluff), did not have a significant effect on any of the measures, meaning that which object is presented first does not significantly affect the outcome. There was an interaction between condition and brightness for only one measure, maximum velocity of the approach, F (1, 25) = 8.749, p = .007, $\eta_p{}^2$ = .259. It was revealed that those presented with the black block first, approached the white block (M = 480mm/s) significantly more quickly (p = .023) than the black block (M = 376mm/s). However, those presented with the white block first did not show a significant difference in reach velocity towards the blocks, (p = .122). The reason for this interaction is not immediately clear, but possible explanations will be discussed below.

7.1.5 Discussion: Motion Capture

Previously, research has demonstrated that infants selectively scale forces for objects which are expected to have different control requirements, relying upon infants' internal representations of the objects (Mash, 2007). In the current experiment, the aim was to examine whether infants selectively prepare for objects which are expected to vary in weight. Stimuli were identical in weight but were intended to appear differently weighted. One set of stimuli had a more obvious cue to weight, material; and the other set of stimuli were considered to feature perhaps a less obvious cue to weight, brightness.

7.1.5.1 Material

Infants differentiate materials from a young age (Bourgeois, Khawar, Neal, & Lockman, 2005; Striano & Bushnell, 2005), however less research has examined the age at which infants use material to guide their actions (Berger, Adolph, & Lobo, 2005; Paulus & Hauf, 2011).

As discussed in relation to Experiment 5, previous research demonstrated that after experiencing two objects which are made from different materials, 11-month-old infants reach preferentially for the same object which they know to be lighter, using material as a cue to object identity. By 13-months, infants reach preferentially for a novel object made from a material which had previously been experienced and found to be lighter (Paulus & Hauf, 2011). These findings demonstrated a developmental trajectory for the ability to use material as a cue to weight. Paulus and Hauf (2011) suggest that it indicates that 'from 11 months on infants use information about an object's material to remember its affordances and use this material information to guide their actions.'

The findings from the current study provide further evidence that 12-month-olds used material to guide their actions. Whereas in the Paulus and Hauf (2011) study material was used to guide *which* object to lift, in the current study the material guided *how* to lift each object. There were a variety of significant differences in the transport of objects which varied in material. Blocks filled with sand were transport with a greater average acceleration, greater average velocity, greater maximum velocity, and also to a greater maximum height, than equally weighted blocks filled with fluff. It is suggested that these findings demonstrate that 12-month-old infants selectively prepared for objects on the basis of their expected weight, which was cued by material. It is proposed that infants lifted the sand block with an excessive amount of force meaning that it was lifted with more acceleration, velocity, and height. On the other hand, infants lifted the fluff block with less force meaning that it was lifted with less acceleration, velocity, and height.

An important difference between the current study and the one by Paulus and Hauf (2011) is that in their study, infants were given prior experience of the particular material. In the current study, the examination of material as a cue to weight was upon the initial presentation. It is not clear whether infants will have experienced these specific materials before, although it is proposed that they will most likely have had experience with similar materials. Infants might have had experience with sand either on a beach or in a sandpit, and material similar to the fluff might have been felt on teddies or soft toys. It is therefore possible that infants have used weight knowledge gained from such material experiences to make predictions about the weight of the sand and fluff blocks. Generalising to novel objects of a *similar* material in this way would be an even more advanced ability than the generalisation to novel objects of the *same* material which Paulus and Hauf (2011) observed at 13 months.

Alternatively, it is possible that infants might not have experienced materials which are sufficiently similar to the test stimuli to use the material to cue weight. In this case, it is possible that infants might have used another cue to predict weight, such as density. To adults, the sand block would appear distinctly denser than the fluff block, which has more gaps in the material. However, infants understanding of density at this age is not fully understood. It seems intuitive that understanding of material is less complex than understanding of density; and it is therefore suggested that previous experience with similar materials are most likely to have been used to make weight predictions. It is however important to consider the possibility that infants might have used either material or density cues to form predictions about weight.

In conclusion, it is proposed that 12-month-old infants can make selective preparations on the basis of object weight. Infants are able to use visual information, most likely in the form of material, to create predictions about weight and consequently act upon these expectations.

7.1.5.2 Brightness

The findings of this experiment do not provide evidence that infants use brightness as a cue to weight in this same way. This conclusion is based on the observation that the selected measures did not reveal any systematic differences in the ways that black and white objects were approached or transported differently.

It is proposed that there are three primary explanations of why no differences were observed in the measures of selective preparation based on brightness. The first proposal is simply that infants do not make the correspondence and therefore do not act upon brightness as a cue to weight. The second suggestion is that infants might make the correspondence but do not act upon it. The third idea is that issues with the measures taken during the approach towards objects explain the absence of an effect of brightness. Each of these ideas will now be discussed in greater detail.

Infants do not appreciate the brightness-weight correspondence

Firstly, it is possible that infants simply do not make the correspondence between brightness and weight. Research has so far has demonstrated evidence of the correspondence in adults and children as young as 5 years (Plack & Shick, 1976; Walker et al., 2010), but no studies to date have demonstrated that younger children or infants appreciate the brightness-weight correspondence. Although there is evidence that newborn infants and 3-4-month-old infants appreciate correspondences between pitch and height, and visual sharpness (Walker, Bremner, Lunghi, Dolscheid, Barba & Simion, 2018; Walker et al., 2010); it is entirely plausible that correspondences emerge at different points. It might be the case that 12-month-old infants do not appreciate the correspondence between brightness and weight.

It is suggested that because the brightness-weight correspondence composes a physical element, it might be later to develop than other correspondences. The correspondences which have previously been observed in infancy are suggested to be between less interactive stimulus features than weight (Haryu & Kajikawa, 2012; Walker et al., 2010; Walker et al., 2018). For example, infants can passively observe the shape, brightness, and height of an object, alongside the sound that it produces. However, to begin to experience weight, infants must have had more active engagements with objects. The ability to grasp objects develops gradually and very young infants will have had limited experience holding objects. When infants first begin to grasp objects, the objects are likely to be items approved by the caregiver, such as baby toys or food, which are all relatively light in weight. It is only when infants become more mobile that they are likely to come into contact with heavier objects as they begin to walk and grasp a wider variety of objects. Even at this age, caregivers are likely to remove especially heavy objects from infants' reach to avoid injury. If exposed only to very light objects, it is possible that when interacting with objects, weight might be a less relevant feature than visual or auditory features which are more readily noticeable (e.g. pitch, height). It is suggested therefore that experience with a wider range of differently weighted objects might be necessary for the establishment of the brightness-weight correspondence. Infants' limited experience with weight as a concept might explain why weight correspondences could develop later than other crossmodal correspondences.

Leading on from this is the consideration that if infants have not experienced especially high weight, they might not feel the need to use cues to predict weight in the same way that adults do. However, evidence of selective preparation on based on material in the current experiment suggests that infants are able to utilise weight expectations when lifting objects.

Appreciation of the correspondence, without acting upon it

It is also possible that brightness is expected to cue weight in certain circumstances, but is not necessarily considered a reliable cue. It is suggested that whilst material is a relatively consistent cue to weight in the real-world, brightness is less likely to be consistent. Whilst it is reasonable to adjust preparation on the basis of material, it might be considered riskier to adjust on the basis of brightness as it could be misleading.

Another suggestion is that whilst brightness is used as a cue to weight, the expected difference in weight is not large enough to warrant changes in kinematics. Findings from the adult studies showed that although consistently reporting brightness-weight correspondences, participants did not consistently demonstrate selective preparation for object weight using the cue of brightness across all measures. In the case of the infant studies it might be that although the black block is expected to be marginally heavier, the kinematic demand of making precise alterations to the lift between objects is great, particularly at 12-months when infants' grasping skills are already fairly restricted. If the lift used for a white block is expected to be sufficient to lift the black block too (even if it is marginally heavier), then the same lift might be used. A similar explanation may also explain the absence of differences across a variety of the measures in the adult studies.

In contrast to this, it is suggested that the material blocks were expected to differ substantially in weight and therefore different selective preparation was made. If the blocks were not manipulated to weigh the same amount, the fluff block would weigh substantially less than the sand block, with a total weight of only 27% (19.4g) of the total weight of the sand block (72.5g). It is therefore proposed that infants lifted the blocks based on the assumption that sand would be substantially heavier, subsequently resulting in the different acceleration, velocity, and height values during transport. Any expected difference in weight of the black and white blocks is anticipated to be substantially less than this, although the specific difference is unknown. In the previous adult experiments, it is difficult to know how much lighter, brighter objects were expected to be; this is addressed in further detail in the final discussion section.

Measurement issue

In Experiment 4 there was a significant different in adults' peak velocity on approach towards the cubes which varied in brightness; black blocks were approached with a significantly greater peak velocity than white blocks. It is suggested therefore that for objects which vary in brightness, the approach might be where the differences are expected to lie.

In the current experiment, there was no significant difference in the peak reach velocity towards the black and white blocks. It is suggested that selective preparation might simply not be made on the basis of brightness; alternatively it might be that no differences were obtained because of the differences in the procedures between adult and infant studies. It is proposed that the measures obtained during the infants' reach are substantially less controlled than in the adult study. Whereas the adults were instructed to begin from a set marker and reach for the object; infants' reach could have begun from any location. Although exceptionally short reach distances were excluded, there is still likely to be a large variation in infants' reaches. Factors which might have affected the speed of the approach include the distance of reach and the location where their reach began.

In the current experiment, it is difficult to identify whether the large variation in reach distance and location are responsible for the absence of a difference between peak reach velocity. It is suggested that in future studies, more focus should be placed upon controlling the start position of infants' hands.

One suggestion for encouraging a consistent position is asking parents to gently hold their infants' hands at the start of each trial.

Another concern with the measure of reach velocity in the current study is that there was a significant interaction between condition and brightness. The result showed that infants presented with the black block first approached the white block significantly more quickly than the black block. However, infants presented with the white block first did not show any difference in approach velocity to black and white blocks. As discussed previously, there was unfortunately a substantial difference in sample size between infants presented with the white block first and infants presented with the black block first. Although initial group assignment was close to equal, the exclusion of 22 infants meant that final group sizes were not equal. Eighteen infants were presented with the black block first and 9 were presented with the white block first. As the significant difference in reach velocity is shown only in the larger group, it is difficult to interpret the interaction. It is possible that infants reached more quickly towards the white block in the black>white condition because of its expected weight. However, it is also possible that the faster reach towards the white block in the black>white condition is the result of it being the second object to be presented. It seems reasonable to suggest that infants may be more hesitant in the approach towards the first object and therefore demonstrate a slower reach velocity for the black object when presented with it first. With only 9 participants in the white>black condition, we can only speculate upon the explanation for the difference between these two groups. It is important to note that there were no other interactions between condition and brightness for any of the other measures.

Origins of the correspondence

What the current study tells us about the potential origins of the brightness-weight correspondence is limited. If future work reveals evidence of the correspondence at 12-months, it would cast doubt on the assertion that statistical origins are responsible for the correspondence. As discussed in detail in the literature review, correspondences with statistical origins are those whereby there is an identified co-occurrence of its dimensions within the natural environment. For example, the correspondence between size and pitch is reinforced through observation that larger instruments and animals tend to produce lower pitch sounds than smaller ones (Coward & Stevens, 2004; Rogowska, 2015; Smith, Patterson, Turner, Kawahara & Irino, 2004). As discussed previously, infants will have had limited experience with heavy objects, which would make it unlikely that a correspondence could be formed based on statistical co-occurrence of brightness and weight. Most objects which they encounter regularly are light toys or food. Similarly, the co-occurrences which have been observed in natural materials (e.g. sand, soil, wood) (Walker et al., 2010), are unlikely to have been observed by 12-month-olds.

Observation of the correspondence in 12-month-old infants would also cast doubt on the suggestion that a semantic basis is responsible. As discussed, semantic correspondences are those whereby there is a verbal overlap in terms used to describe two dimensions. For example, the term 'high' is used to refer to both pitch and vertical placement, which can partially explain evidence of the pitch-height correspondence in English speaking participants (Dolscheid, Shayan, Majid, & Casasanto, 2013; Evans & Treisman, 2010). As infants have limited experience with language and have not yet acquired the overlapping term of 'light' to refer to brightness or weight (Brysbaert & Biemiller, 2017; Kuperman, Stadthagen-Gonzalez, & Brysbaert, 2012), it is therefore unlikely that this common term would be responsible for the formation of the correspondence.

As the correspondence between brightness and weight was not observed in infants however, it is difficult to reach any conclusions regarding the potential origins of the correspondence.

7.1.6 Results: Gross Behavioural

In addition to the motion capture data, the frequency of pre-defined kinematic actions were also examined. This analysis was purely exploratory. The frequency of left and right-handed lifts, reaching type, and actions after a successful lift were examined, across all trial types. On both the brightness and material trials, infants used the right hand (257 trials - brightness; 255 trials - material) significantly more often than the left hand (206 trials – brightness; 180 trials - material), $p = .020$ and $p < .001$, respectively on two-tailed binomial tests. Unimanual reaches (463 trials – brightness, 435 trials - material) were also more common than bimanual reaches (38 trials – brightness; 59 trials material), $p < .001$ and $p < .001$ on two-tailed binomial tests. The most common post-lift actions were for the infant to hold the object to themselves (197 trials – brightness; 227 trials - material), or to lift high/pass back to the parent or researcher (114 trials – brightness; 110 trials - material).

Next, the frequency of the coded actions across different object types was examined. As 12-month-old infants have been shown to manipulate heavier objects bimanually (Palmer, 1989), we propose that infants who expect particular objects to be heavier might approach them with two hands, instead of one. Similarly, infants have been shown to wave a lighter object more often than a heavier one (Palmer, 1989); a behaviour comparable to actions which we coded as shaking/banging. Therefore, we predicted that infants might shake the object which they expect to be lighter more frequently. Alternatively, if they lifted a particular object by twisting their wrist, it might be an indication that they felt the support from the block was needed to lift the 'heavier' block. Such analysis is predominately exploratory and as such, we have no specific expectations.

Binomial tests were conducted to examine whether there were any additional differences in the lift of black and white blocks, or sand and fluff blocks, that was not due to chance. As can be seen in Figure 34, although the total number of bimanual lifts was greater for the black cube as opposed to the white cube, this difference was not significant, $p = .108$ (on a one-tailed binomial test). Similarly, there was no significant difference in the number of wrist twists or shaking actions with black or white objects ($p = .724$, and $p = .728$, respectively on two-tailed binomial tests). There was also no difference in the number of bimanual, wrist twists and shaking actions for sand and fluff objects, ($p = .892$, $p = .542$, and $p = .749$, respectively).

The trials in which no lift occurred were also examined to see whether no lift occurred more frequently for one type of object, as opposed to another. There were 26 brightness trials in which no lift occurred, but the experiment continued as infants regained interest in subsequent trials. There was no significant difference in the occurrence of no lifts for black and white objects, p = .541 (on a two-tailed binomial test).

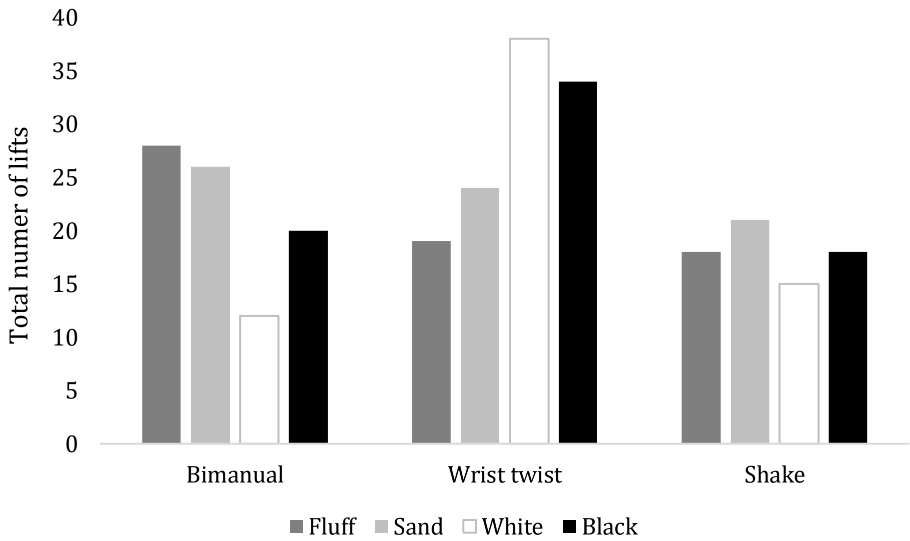


Figure 34. The total number of bimanual, wrist twist lifts, and shaking actions demonstrated for fluff, sand, white, and black blocks.

7.1.7 Discussion: Gross Behavioural

The analysis of this behavioural data was purely exploratory and therefore it might not be particularly surprising that the results did not reveal differences across objects. This is made more likely by the fact that in the previous research, the 'lighter' objects which were shaken more, were truly lighter, not just perceived as lighter (Palmer, 1989). It might therefore be that the lighter objects were simply easier to wave than the heavier objects. In the current study, although we proposed they might expect one type of block to be heavier, the objects were identically weighted; meaning that the true control requirements were the same.

Although it is suggested that analysis of waving frequency might not be the appropriate measure of anticipated weight because it occurs after the lift, it is thought that the measure of unimanual vs. bimanual could be utilised successfully in similar future studies. To make the motion capture data most similar to the adult data, the infants' cubes were designed so as to be lifted comfortably with one hand. This meant that there was a relatively small number of lifts which were bimanual (97 lifts) as opposed to unimanual (898 lifts). We propose that it would be interesting to look at this measure again with larger objects for which the consideration of a bimanual reach would be more frequent. Under such circumstances the consideration of the control requirements, and hence the need for a bimanual reach, might be greater.

7.1.8 Evaluation of Infant Studies

Whilst the exploratory, gross behavioural data provided little insight into infants' appreciation of the material-weight and brightness-weight correspondences; the motion capture data provided a wealth of information evidencing infants' appreciation of the material-weight correspondence and raised a variety of questions about their appreciation of the brightness-weight correspondence.

Using motion capture to study the appreciation of crossmodal correspondences in infant participants is a novel approach and therefore it was important to carry out an evaluation of the viability of this method, focussing on areas for improvement. The following section will discuss the issues which were encountered specifically in the infant studies and how these could be rectified in future studies.

Time before sensory based adjustments are made

In the current study, transport measures were taken for the first 500ms of transport. As discussed previously, this has been suggested to be the time period before sensory based adjustments to erroneous lifts can be made (Mash, 2007; Mash, Bornstein, & Banerjee, 2014). An alternative action-based method for examining prospective control was later proposed by Gottwald & Gredebäck (2015). This is based on the idea that data within the first movement unit is most important for the examination of prospective control (von Hofsten, 1979, 1991). Using this method usually covers the first 200ms-600ms of an infants' reach, or the appropriate portion of the lift. The benefit of this method is that it avoids the involvement of corrective behaviours based on sensory feedback by looking at each individual movement. For example, the acceleration phase is the initial acceleration only, and not any subsequent accelerations resulting from adjustments.

The way that we choose to measure prospective motor control is of upmost importance for infant studies. In adults, target-orientated reaches often consist of only one movement unit and have straight trajectories with one velocity peak (Jeannerod, 1988). To reach this level of precision however, the number of movement units steadily decreases through development, with infants' reaches often containing multiple movement units (von Hofsten, 1979). Similarly, the grip and load forces in an adult grip have been shown to increase in parallel with single peaked force-rate profiles. In contrast, children under two years tend to display increased grip force, followed by increased load force, resulting in force patterns with multiple peaks (Forssberg, Eliasson, Kinoshita, Johansson, & Westling, 1991). Both measures are evidence of how infants and young children use feedback to continuously inform the reach and lift. The skill of the adult reach means that peak measures taken over the duration of the reach usually provide an accurate reflection of the initial movement (as demonstrated in Experiment 2). To do so with an infants' reach however, would likely include multiple movement units, reflecting both their initial movement and corrective actions.

As it has been suggested that within the first 500ms of the movement infants will not yet have been able to make sensory-based adjustments, it is expected that the measured actions within this time frame will reflect initial selective preparation (Mash, 2007; Mash et al., 2014). However, we acknowledge that examining the first movement unit (Gottwald & Gredebäck, 2015) is a more accurate way of ensuring that corrective action is not included in measures of selective preparation.

Whilst it is possible to look at the measures within the first movement unit using a Matlab script, the data for the current study were edited and coded within Excel, making it considerably more difficult to examine the first movement unit. The decision to use Excel was made to overcome the absence of a time-phase tagging system within the OptiTrack Motive set-up. Time phases were therefore added manually into Excel. Despite the impracticalities of looking at first movement units within the set-up of this particular study, it is suggested that this is likely to be the optimum method for examining prospective control as it guarantees on a trial-by-trial basis that no sensory-based adjustments have been made.

Averaging across trials

As discussed in the method section, the averaging of measures across trials means that it is not possible to examine whether these errors are made in earlier lifts and corrected as the experiment progresses. The experiments presented in Chapters 3 and 5 demonstrated that adults showed no evidence of corrections to erroneous lifts within the duration of the experiment. Looking at the effect of trial was therefore not considered a priority within this experiment, however enabling the examination of this in future studies would be beneficial.

To avoid the averaging of trials, it would be necessary to obtain a higher retention rate of usable motion capture data. In the issues and recommendations section of Chapter 8, suggestions for how to increase the quality of motion capture data in infants and adults is provided. The number and placement of cameras are thought to be the key factors in improving the data quality.

Chapter 8

Summary

8.1 Introduction

The aim of the thesis was to shed more light on the brightness-weight correspondence, focussing specifically on the origins of the correspondence and the situations in which it is revealed. This chapter gives an overview of the key findings of the adult and infant experiments and what the implications are in relation to the wider literature. The chapter also discusses recommendations for future research, in particular with the use of motion capture.

8.2 Overview of Studies and Key Findings

Experiment 1 demonstrated further evidence of adults' appreciation of a correspondence between brightness and weight. When asked to order wooden blocks in terms of expected weight, participants reported that the darker block was heavier than the brighter block. Further evidence of the brightness-weight illusion was also shown as participants reported a reversal in judgements of weight after lifting, stating that the brighter block was heavier than the darker block. These findings added to the current literature showing an appreciation of the correspondence between brightness and weight (Walker et al., 2010).

In Experiment 2, the aim was to examine the situations in which the brightness-weight correspondence is revealed. Previous research, including Experiment 1, focussed primarily upon asking participants to make weight judgements of blocks which vary in terms of surface brightness (Payne, 1958; Plack & Shick, 1976; Walker, Francis & Walker, 2010; Wright 1962). By examining appreciation of the correspondence through other methods and measures, it was thought that more information could be revealed about whether the brightness-weight correspondence was revealed only when asked to rate objects with different brightness levels in terms of weight, or whether it was a more general experience which was not only experienced frequently but also acted upon spontaneously.

Experiment 2 therefore applied a more discrete and less explicit measure of appreciation of the correspondence. In this study, participants lifted onto a platform equally weighted, wooden blocks which varied in brightness. Selective preparation for weight using the cue of brightness was examined using motion capture. It was proposed that if participants expected darker blocks to be heavier than brighter blocks, they might show differentiated kinematics during the approach and lift of the object. A thorough review of the literature suggested that measures previously shown to vary alongside expected weight included: maximum grip aperture, approach velocity, transport acceleration, transport velocity, maximum lift height (Buckingham, Byrne, Paciocco, van Eimeran, & Goodale, 2014; Eastough & Edwards, 2007; Fleming, Klatzky, Behrmann, 2002; Johansson & Flanagan, 2009; Johansson & Westling, 1988; Paulun et al., 2014; Paulun et al., 2016; Vollmer & Forssberg, 2009; Weir et al., 1991).

The key finding of Experiment 2 was that black blocks were transported more quickly than white blocks. One interpretation of this finding is that black blocks were lifted with more force, suggesting that they were expected to be heavier. Although previous research had demonstrated evidence of selective preparation on the basis of size-weight and material-weight correspondences (Baugh et al., 2012; Buckingham et al., 2009; Davis & Roberts, 1976; Flanagan &

Beltzner, 2000; Grandy & Westwood, 2006; Paulun et al., 2014; Paulun et al., 2016), this study provided the earliest indication to-date that selective preparation is made for the, perhaps, less salient brightness-weight correspondence, even when a focus upon weight is not made explicit. However, a minor weight difference (white weighed more than black), was suggested to potentially explain this effect and so further studies were required.

It had previously been suggested that in natural materials, there is some evidence of a natural co-occurrence between brightness and weight. For example, darker woods are heavier, and some materials become darker and heavier when wet (Edlin, 1969; Walker et al., 2010). If this were the case, the brightness-weight correspondence observed with wooden stimuli in Experiments 1 and 2 could be attributed purely to statistical origins in the observation of darker woods being heavier. To examine the contribution of such a potential co-occurrence, Experiment 3 replicated Experiment 1 with plastic blocks, a material for which a brightness-weight co-occurrence is not known to exist. Results again showed evidence of a brightness-weight correspondence, with darker blocks rated as heavier than brighter blocks. Alongside adding to the existing literature which demonstrates evidence of a brightness-weight correspondence (Payne, 1958; Plack & Shick, 1976; Walker, Francis & Walker, 2010; Wright 1962), this result also contributes to the literature regarding the potential origins of the brightness-weight correspondence. In this experiment the correspondence was observed with stimuli made from material for which there is no known co-occurrence of brightness and weight. This suggests that if a statistical origin is responsible for the emergence of the brightness-weight correspondence, it can be largely generalised across materials and objects. For example, it is likely that a possible co-occurrence of brightness and weight within certain types of materials (e.g. soil and wood) can be generalised to objects formed from a material which has no observable co-occurrence (e.g. plastic). The conclusion of Experiment 3 is not that statistical origins are responsible for the emergence of the brightness-weight correspondence, rather that *if* they are responsible, generalisation of co-occurrence observation across objects and materials is thought to be likely.

Interestingly, although Experiment 1 demonstrated evidence of the brightness-weight illusion; Experiment 3 did not provide any evidence that participants experienced an illusion of weight. It is possible that the absence of a brightness-weight illusion in this experiment is due to the material of the stimuli as this was the only factor to change in the brightness element of this study. It is suggested that the brightness-weight correspondence might have been more robustly experienced with the wooden stimuli, for which there is a natural co-occurrence, than for the plastic stimuli, for which there is no natural co-occurrence. Although participants reported expecting darker blocks to be heavier than brighter ones, the absence of an illusion raises questions about how strong this expectation was. This proposal is at variance with the results of previous work which demonstrated evidence of the brightness-weight illusion with stimuli made from synthetic polymer, phenolic resin; another material for which there is anticipated to be no observable co-occurrence between brightness and weight (Walker et al., 2010). Another possible explanation therefore is that the material-weight stimuli which were also presented in Experiment 3 might have resulted in the absence of participants' experience of a brightness-weight illusion. It is proposed that after the experience of a stronger illusion between material and weight, the brightness-weight illusion could have become lost in comparison.

The material-weight correspondence and illusion demonstrated in Experiment 3 showed that sand was rated as heavier than pompoms before lifting; but after lifting, pompoms were rated as heavier than sand. This finding adds to the previous literature which demonstrates evidence of a material-weight correspondence before lifting and a material-weight illusion after lifting (Buckingham, Cant & Goodale, 2009; Buckingham, Ranger & Goodale, 2011; Harshfield & DeHardt, 1970; Wolfe, 1898).

Building on the findings of Experiment 2, the aim of Experiment 4 was to examine whether there was evidence of selective preparation for weight on the basis of brightness and material. It was suggested that the correspondence between material and weight was perhaps more regularly reinforced than the correspondence between brightness and weight. It was therefore decided that an interesting comparison of any kinematic differences across the two object types could be made. This experiment used the black and white, plastic, blocks and the sand and pompom blocks from Experiment 3. A few minor adjustments were made to the procedure from Experiment 2, alongside absolute equalisation of weights to ensure a clear interpretation of findings.

Early evidence of selective preparation for both brightness and material was observed in Experiment 4. Black blocks were approached with a greater peak velocity than white blocks. It is suggested that this could be due to avoidance of displacement of the lighter, or more fragile, white block. Material was also shown to be selectively prepared for as sand blocks were lifted to a greater maximum height than pompom blocks. This corresponds with previous research which indicated that objects which are lighter than expected are lifted higher than intended (Vollmer & Forssberg, 2009). It is suggested that this demonstrates evidence of the additional force which was used to lift the sand block, due to its anticipated greater weight.

The findings of this experiment alongside the findings from Experiment 2 appear to demonstrate that the presence of a correspondence between brightness and weight is not simply the result of being asked to rate objects of different brightness levels in terms of expected weight. Instead, it is suggested that adults use the brightness and material of objects as cues to selectively prepare their lift on the basis of object weight. The implication of this finding is that it is possible that brightness is utilised in everyday lifting situations to cue weight.

The second half of the thesis focussed on examining the appreciation of the brightness-weight correspondence in infants. The decision to study infants' appreciation of the correspondence was made with the aim of understanding more about the possible origins of the brightness-weight correspondence. Previous research demonstrated evidence of correspondences between pitch and height in newborn and 4-month-old infants (Walker et al., 2010; Walker et al., 2018) and evidence of a pitch-sharpness correspondence in 4-month-old infants (Walker et al., 2010). However, to-date there had been no known research examining the correspondence between brightness and weight in infants, with 5-year-old participants being the youngest yet to show evidence of the correspondence (Plack & Shick, 1976).

Experiment 5 therefore aimed to examine infants' appreciation of the brightness-weight correspondence through preferential lifting measures. Infants had previously been shown to reach preferentially for objects known to be lighter (Hauf et al., 2012; Paulus & Hauf, 2011). Therefore, it was suggested that if presented with two blocks simultaneously, preferential lifting of a white block could suggest that infants expected it to be lighter than an otherwise identical black block. However, results demonstrated no evidence of preferential lifting of either block. It was suggested that there are two possible explanations for this finding.

The first explanation is that both blocks were expected to be a comfortable weight and therefore individual preference choices were not made based on weight. Rather, it could have been made based on other factors, such as ease of reachability from starting position for each individual infant, or individual colour preference which might not be consistent across infants. Considering this explanation, it is still possible that infants expected one block to be heavier than the other, however the weight of neither stimuli was thought to restrict lifting. With different circumstances and different objects, it is possible that infants demonstrate appreciation of the correspondence between brightness and weight. The alternative explanation is that neither block was thought to be lighter than the other, and therefore there was no evidence of preferential lifting for either object. This explanation suggests that infants at 13-14 months do not appreciate a correspondence between brightness and weight.

The first explanation suggests that there is the possibility of a small difference in weight expectation which does not affect behaviour. The second explanation suggests that there is no difference in weight expectation, resulting in no difference in behaviour. As there were no significant differences in reach towards either object, it was difficult to reach any conclusions regarding infants' appreciation of the brightness-weight correspondence from Experiment 5.

Experiment 6 therefore focussed on the finer details of infants' interactions with objects to see whether more sensitive measures might reveal evidence of the correspondence between brightness and weight in 12-month-old infants. In an experiment similar to adult Experiments 2 and 4, infants were presented with a series of blocks which varied in terms of brightness or material. Motion capture cameras recorded position data for the approach towards objects, and the transport of objects. Previous research demonstrated that infants selectively prepare for objects on the basis of expected weight (Gottwald & Gredebäck, 2015; Mash 2007; Mash 2014; Mounoud & Bower, 1974). Experiment 6 therefore sought to examine whether brightness and material were used as cues to selectively prepare for object weight.

Results demonstrated substantial evidence that infants selectively prepared for object weight on the basis of object material. Infants lifted the sand block with significantly greater acceleration, velocity, and height, than the fluff block. These measures were taken as evidence that they expected the sand block to be heavier and subsequently lifted it with more force, resulting in an excessive lift. Previous research demonstrated that infants reached preferentially for a material known to be lighter in weight, demonstrating that infants use material as a cue to weight when deciding *which* object to lift (Paulus & Hauf, 2011). The current research adds to this literature by suggesting that not only is material used to cue *which* object to lift but it is also used as a cue to weight which helps to inform *how* to lift the object.

Despite this, there was no evidence of selective preparation based on brightness, with no significant differences in either the reach towards or transport of objects. However, results should not be taken as evidence that infants do not appreciate the brightness-weight correspondence. It is suggested that the differentiation of reach speed on the basis of brightness, which was observed in adults, might have been more difficult to identify in infants due to the larger variation in actions preceding the lift. It is also possible, as suggested with the adult studies, that other measures did not reveal evidence of a brightness-weight correspondence as the effects were too subtle to alter action. In other words, it is possible that a small difference in weight expectation based on brightness is not substantial enough to require differentiated action which is selectively prepared for weight. This is in contrast to material for which the difference in weight expectation was large enough to affect selective preparation.

Alternatively, taken alongside evidence of an appreciation of the pitch-visual elevation correspondence in newborn and 4-month-old infants and appreciation of the pitch-sharpness correspondence in 4-month-old infants (Walker et al., 2010; Walker et al., 2018), it is suggested that the correspondence between brightness and weight might be later to develop than other correspondences because it composes a physical element. The suggestion is that pitch, height, and sharpness are all features of stimuli which can be observed passively. In contrast, weight must be experienced actively as infants can only experience weight by interacting with objects. It is suggested that interactions with a wide range of weights, especially heavy objects, is unlikely to occur during the first months and that weight might subsequently be a less salient feature of objects for young infants.

Whilst Experiment 6 provided further evidence that infants selectively prepare for objects on the basis of expected weight (Gottwald & Gredebäck, 2015; Mash 2007; Mash 2014; Mounoud & Bower, 1974), specifically using the cue of material; conclusions regarding whether infants appreciate the brightness-weight correspondence are limited. This means that conclusions on the possible origins of the correspondence are also limited. As discussed, it is possible that evidence of correspondence appreciation is not revealed through this particular method as the effects are too small to affect action; alternatively, it is possible that the correspondence is not present at 12-14 months and that it emerges alongside experience with differently weighted objects.

8.3 Issues and Recommendations for Motion Capture

Though motion capture has proved to be an interesting way to study the application of crossmodal correspondences in a more natural setting, there have been a variety of hurdles to overcome along the way. Whilst some might expect motion capture to produce information on a variety of different kinematic measures, the system used in the current experiments did not produce such measures. The motion capture cameras and software enable the tracking of sensors in 3D space, however, the only information they provide is the position data for each sensor with regards to each axis. A variety of skills therefore need to be established before data collection and analysis can begin.

The editing of data was especially time consuming as each trial needed to be individually filtered, labelled, and filled (discussed more in Experiments 2, 4, and 6). Though this became more effective and efficient as the studies progressed, the lengthy process must not be underestimated. The coding of data was also substantially time consuming as each trial needed to be coded at each significant time point. As the time frames cannot be added into the software, this creates an additional step when it comes to data extraction.

Though these processes are simply a requirement of the kit, alternative ways of designing the methodology have since been considered to reduce the time load during data extraction. In the adult studies (Experiment 2 and 4), the procedure was a simple reach-grasp-lift task whereby participants were asked to lift the object onto a platform. This action was thought to simulate a frequent movement which would most likely be performed daily, e.g. lifting an item onto a shelf. In hind-sight, an even simpler procedure would have been optimum.

One of the primary obstacles in the analysis of the data collected in the kinematic studies was the collation of individual axes to form 3D data. This was a difficult process due to the requirement for user knowledge of complex formulas and physics principles. If users are already knowledgeable in this area, the analysis of 3D data might be optimum. However, for researchers wishing to use motion capture who do not have a background in this area, several recommendations would be made. In Experiments 2 and 4, restricting the movement to primarily one dimension would be hugely beneficial. Using the method presented previously, participants moved the object in a multitude of directions (up, back, and across), meaning that information from the x, y, and z axis are all relevant. However, if participants were instructed to lift the object vertically, only information from the y axis would be important. The proposed experiment would involve asking participants to lift a cube from a starting position to a given height. Analysis could then examine the acceleration and velocity in the y axis, and also the maximum height that the object was lifted to. If the brightness-weight correspondence was observed using such a procedure, we might expect to see that the black cube is transported with more velocity and acceleration in the y axis, and also to a greater height than the equally weighted white cube.

Another issue which was experienced during this project was an insufficient number of cameras. When set up optimally, more motion capture cameras in a set-up generally results in better quality tracking. This is because the cameras can cover a greater space from a variety of different angles, subsequently meaning that tracking is less likely to be lost. For the adult studies, 4 cameras were used. As there was an intended action to be made by the participant, and a researcher ensuring that this was the case, a video camera was not required. In the infant studies however, there were no specific instructions given to the infant, meaning that the approach might not be immediate, and any subsequent action might follow the lift of the object. It was therefore decided that it was necessary to have an additional camera which recorded actual video footage from the trial. Subsequently, an additional camera was purchased. It is important to note that this was a small-scale movement involving only a reach and lift task; motion capture over larger scenes with a greater number of markers would most likely require substantially more cameras. Even with the additional camera, a large amount of data was lost during the transport phase. Although the positioning of cameras was piloted, during data editing it became evident that infants often lifted their palm during lifting in such a way that it resulted in marker loss. An additional camera placed behind the infant would have avoided or substantially reduced this data loss.

8.4 Ideas for Future Research

It is suggested that future research in this area should aim to focus on understanding more about the brightness-weight correspondence. Key areas of study are: the potential source of the brightness-weight correspondence, as well as the scale of the correspondence, and the situations in which it is utilised.

Field review of natural co-occurrence

This thesis attempted to reveal more information about the potential origins of the brightness-weight correspondence by studying its presence in infants. This enabled assessment of the contribution of statistical co-occurrence and semantic overlap in the formation of the brightness-weight correspondence.

With this in mind, an important area to be addressed in future studies is the potential source of an association between brightness and weight. Though there is evidence that there are some natural co-occurrences in which darker materials are heavier than brighter ones, the evidence is very much incomplete. Current evidence suggests that darker woods tend to be heavier and that sand and soil tend to become simultaneously heavier and darker when wet (Edlin, 1969; Walker et al., 2010). A thorough study of many natural materials should be conducted to examine the consistency of this correspondence in the natural environment. Similarly, it would be interesting to look at the weight of more manufactured objects as it is equally plausible that a co-occurrence between brightness and weight might occur in manufactured objects. For example: Does an identical cup made from black plastic or white plastic weigh a different amount? Is there something in the pigment meaning that the same amount of black paint could weigh more than the identical volume of white paint? Do dyes used to colour material darker use heavier components than dyes used to colour material brighter? These are all questions which it would be interesting to address in a review of brightness-weight co-occurrences observed with natural materials and manufactured items. Undoubtedly such an extensive study would require exceptional levels of control to ensure that comparable objects are identical other than in terms of brightness. When looking at tins of paint for example, it is plausible that more paint might be contained in one tin than another to equalise the weights.

A field study of this nature would help to address the underlying question of whether darker objects really are heavier than brighter ones. This would enable a deeper understanding of the origins of the brightness-weight correspondence by examining the potential role of statistical observation of a co-occurrence between brightness and weight. Understanding the origins of the correspondence can help to understand whether infants would be expected to appreciate the correspondence, and equally evidence of whether infants appreciate the correspondence can help to understand more about the origins of the correspondence.

Qualitative data

It is also proposed that the collection of qualitative data with regards to why people expect darker objects to be heavier would also be very informative. During Experiment 1 of the current thesis, one participant reported unprompted that the black block looked 'more full.' Most probably, qualitative responses would be difficult to obtain as it is expected that many participants would not be able to provide an explanation for perceiving darker as heavier. However, such reports are thought to be key in providing new lines of enquiry into where the correspondence stems from. For example, though we cite language as a potential explanation for the correspondence between brightness and weight, whether participants would typically make a connection between 'light' brightness and 'light' weight is yet unclear. Qualitative data would help to understand more about what other people perceive the origins of the correspondence to be.

Adaptations to the current studies

It would be beneficial to repeat kinematic Experiments 2, 4, and 6 with stimuli that have more difficult lifting requirements. The results from these studies demonstrate some evidence (although not consistently), that participants selectively prepare for object weight, based on brightness. As discussed, we propose that the objects used in our experiment had relatively easy lifting requirements which might not have revealed the extent of differentiated lifting across material and brightness. If objects have a more difficult lifting requirement, such as they were heavier, larger, or taller, it is expected that participants would be required to put more focus on how to lift the objects to avoid rotation. It was proposed in Chapter 5 that white objects were approached more slowly than black objects as the focus was on avoiding displacement of the lighter or more fragile block. It is proposed that under a condition with more difficult lifting requirements such as greater overall weight, the heavier black block might be approached more slowly as the focus might be shifted to ensuring a more secure grip placement. As discussed previously, it is possible that the difference in expected weight between black and white cubes is not great enough to elicit differences during the transport of objects. If this were the case, increasing the weight of the objects would not be expected to change the relative difference in expected weight. Instead, the proposed benefit of using heavier stimuli is that participants might be more likely to consider the more challenging control requirements.

Scale of the expected difference

Although participants consistently report that they expect darker objects to be heavier than brighter objects, a recurring theme of the thesis has been that it is not clear *how much* heavier darker objects are thought to be. Instructions in Experiment 1 and 3 specified that participants order blocks in terms of expected weight, from least to most heavy. The outcome is a clear order of weight expectation, however what is not clear is whether the black block was expected to be a lot heavier, or just a little heavier than the white block.

Understanding of the scale of the difference is important for the study of the brightness-weight correspondence. If the white block was expected to be only marginally lighter than the black block then it follows that selective preparation might not be adapted for the objects based on brightness in the kinematic studies.

Research has begun to look at the strength of the brightness-weight illusion specifically. By comparing the perceived matching of differently weighted grey balls to equally weighted white and black balls after lifting, Walker et al. (2010) were able to establish the combined perceived weight difference between black and white balls. The difference between the balls perceived weight was 7.97g, equivalent to 6.2% of their actual weight. Walker et al. (2010) suggest that brightness would be likely to have a larger impact on perceived weight before lifting, and that subsequently differences would be expected to be larger.

To understand more about the scale of the correspondence, experiments could focus on ratings of weight which use scale rather than categorical ratings. Rather than reporting which is the heaviest, participants could be asked to provide individual judgements of weight. An example of a method for this study would be to individually and repeatedly present objects which vary in brightness and ask for expectations of weight in grams. Rating black objects as 1% heavier than white objects might suggest that kinematic adaptation is unlikely, however if ratings are 10% greater for black, kinematic studies could be expected to reveal differences in selective preparation. The scale of the expected difference would help to provide information on whether the continuation of the study of the brightness-weight correspondence through kinematic measures is appropriate.

Alongside gathering more information on the scale of expected weight differences, it is suggested that research should also focus on participants' confidence in their ratings of expected weight differences. It might be, for example, that although rating black as heavier than white, participants are not completely sure that they expect this block to be heavier. Current methods do not take into account this level of doubt. This area is beginning to attract more attention with a recent study asking participants to rate their confidence in sound-shape matching in the Bouba/Kiki effect (Chen, Huang, Woods, & Spence, 2018).

Alternative methods

Though motion capture has proved to be an informative measure of expected weight, future research should also remain open to alternative methods for examining the brightness-weight correspondence in infants. Infants' EEG responses have shown sensitivity to expected object weight when infants observe an experimenter reach for objects which they know to be heavier or lighter, based on prior experience (Marshall, Saby, & Meltzoff, 2013). A potential future study could be to measure EEG responses when an infant observes an adult lifting darker and brighter blocks to see whether there is different sensitivity to expected object weight across the different levels of surface brightness.

8.5 Concluding Remarks

This research has provided further evidence of the brightness-weight correspondence, revealed by asking participants for judgements on expected weight of objects. We cautiously suggest the experiments have also provided early evidence that adults selectively prepare for object brightness, a distinction which is thought to be due to expected weight differences. This is the first evidence suggesting that the brightness-weight correspondence is not simply an artefact of the experimental situations utilised in previous research. Previously, it was possible to suggest that participants might make a correspondence between brightness and weight just when asked to rate objects which vary only in terms of brightness, in terms of weight. It is possible that in this situation, participants might have deduced that the only variable to change (brightness), should be used to cue weight. However, evidence presented in this thesis showing that the correspondence is revealed spontaneously through actions, suggests that the correspondence influences our choices and actions when completing day-to-day tasks.

These findings have implications in multiple areas of product design. The finding that brighter objects appear lighter may be of interest to those companies designing products for which weight is a salient and desirable feature. For example, within the technology sector the ability to make products such as phones and laptops appear lighter than they are is likely to be highly sought after; especially when the solution relates only to the colour of the product. Furthermore, the finding that people act upon these expectations of weight has implications in the design of equipment for safety. An idea which could be presented to this sector is to utilise darker boxes to signify heavier weight and brighter boxes to signify lighter weight. Individuals lifting heavy boxes with a congruent surface brightness, which is darker, are expected to be more likely to lift the box with adequate force, reducing the risk of injury.

It is not only the brightness-weight correspondence which has such applications. There are other examples of potential uses of crossmodal correspondences and also specific examples of where they are already being utilised in the real world. This highlights the importance of studying crossmodal correspondences more generally. Similarly to the brightness-weight correspondence, the brightness-visual height correspondence has been suggested to have potential applications in retail. As brighter colours are associated with higher visual space, it has been suggested that placing brighter objects in a congruent visual space (high) facilitates shoppers' visual search. Shoppers' decisions about which product to buy has also been shown to be affected, with light products more likely to be chosen over dark ones when they are located high in visual space (Sunaga, Park, & Spence, 2016). The placement of products affecting the consumer's decision in this way is likely to be of high interest to the retail market.

There are also instances where associations are already been utilised. For example, associations between sound and taste have been used to create a 'tasting concert' whereby the matching of sensory modalities is used to create a unique symphonic experience. At these concerts, an audience are invited to eat different flavoured chocolates alongside music which is suggested to correspond to each flavour. Ideas such as this are the result of acknowledging that the senses interact in different ways.

Research into crossmodal correspondences enables us to understand more about which sensory modalities are associated, and also what situations evoke these associations. The examples provided demonstrate how these findings can be utilised in the real world.

Alongside the adult work, the thesis also involved important studies into the appreciation of the brightness-weight correspondences in infants. Whilst the studies presented in the thesis do not provide any evidence that infants appreciate the correspondence between brightness and weight, there is strong evidence that infants do selectively prepare their actions on the basis of expected weight, using cues such as material.

Infants demonstrated selective preparation on the basis of material through a variety of different measures, including: transport lift height, velocity, and acceleration. However, adults demonstrated selective preparation only through the measure of lift height. These findings demonstrate that both adults and infants use material as a cue to weight when lifting an object. The larger body of evidence from infant participants is thought to suggest that the measures are more sensitive for these participants who are unaware of the experimental setting. We speculate that whilst adults may attempt to second-guess the aims of the study and act accordingly, infants might act more naturally as they simply see the lifting task as a game.

Evidence of selective preparation on the basis of material confirms the viability of the kinematic method used. The implications of an absence of selective preparation on the basis of brightness can therefore only be speculated upon. The notion of an absence of an appreciation of the brightness-weight correspondence during infancy is possible. It is proposed that the correspondence between brightness and weight might develop at a later stage than other correspondences, due to the involvement of physical experience with weight. Appreciation of the correspondence, without acting upon the correspondence is also equally plausible.

As discussed earlier, it is advocated that motion capture should continue to be used to examine the presence of weight correspondences in adult and especially infant participants. We suggest that the methods which can be used to test infants' appreciation of crossmodal correspondences, weight correspondences particularly, is limited and that motion capture provides a practical solution for wider study of this area.

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