Reviewing Evidence for Perception-Action Dissociations

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Contents

Abstract

The Perception-Action Model, proposed by Goodale and Milner (1992), is an influential model about the functional organisation of the human visual system. The core tenet of this model is that visual information is processed in anatomically and functionally separate pathways depending on the output requirements. Object identification and recognition, or broadly visual perception, presumably relies on representations based on allocentric coordinates, relative metrics and holistic processing of the ventral cortical stream. Conversely, visuomotor actions are assumed to rely on egocentric coordinates, absolute metrics and analytic processing of the dorsal cortical stream. Neuropsychological patient studies and studies on the behaviour of healthy participants were initially cited as converging evidence for this model. Subsequent research has shown that inferences from patient data were not as clear-cut as originally reported. Therefore, recent research has focused on demonstrating perception-action dissociations, or differences in performance in perception and action, in the behaviour of neurologically intact individuals.

This dissertation contributes to the work on perception-action dissociations by evaluating the evidence from three different behavioural paradigms. We first examined the claim that grasping violates a fundamental psychophysical principle, Weber's law (Ganel et al., 2008), demonstrated in several sensory domains including visual perception. We demonstrated that a mathematical flaw in the calculation of the just-noticeable-differences (JNDs), that are used to assess Weber's law, resulted in an apparent violation of Weber's law in grasping. We proposed an improved method to estimate JNDs in grasping. Applying this method to our own data and reanalysing the data from three representative studies, we showed that grasping does follow Weber's law, as does perception. We therefore found no evidence for a perception-action dissociation in Weber's law.

Next, we looked at the prominent claim that grasping evades Garner interference while speeded-classification and manual size estimation (perception) suffer this interference (Ganel & Goodale, 2003). We reviewed the literature on this and found an empirical inconsistency: there were only two studies that actually demonstrated Garner interference in manual estimation. We thus performed four replications and a quantitative review of fifteen studies on this topic. Our results suggest that Garner interference in grasping and manual estimation are quite similar, although smaller than in speeded-classification. Again, we found no evidence for a perception-action dissociation in Garner interference.

Finally, we investigated the report that grasping is more accurate at discriminating object sizes than perception (Ganel et al., 2012). This conclusion was based on a significant difference between participants' grip apertures to a small and large object, but a low perceptual judgement accuracy – an unequal comparison of different measures in perception and action. But, when calculating the corresponding classification accuracies in two experiments, we found that grasping has a close-to-chance accuracy and that perceptual judgement accuracies are considerably higher. Manual size estimation accuracy was also close-to-chance and similar to grasping. A meta-analysis of the different studies revealed a similar pattern. Here too, we found no evidence for a perception-action dissociation in size resolution.

Based on our comprehensive investigations including replications, meta-analyses and improved methods, we conclude that neither of the three paradigms under scrutiny here provide evidence for perception-action dissociations, and consequently, the Perception-Action Model. Instead, when task requirements are controlled for, we find similar behavioural performance in perception and action, suggesting that they are based on a common representation of object features in the visual system.

Zusammenfassung

Das von Goodale and Milner (1992) aufgestellte Perception-Action Model (Wahrnehmung-Handlung-Modell), ist ein einflussreiches Modell der funktionellen Organisation des menschlichen visuellen Systems. Der Hauptaspekt dieses Modells ist die Teilung der visuellen Informationsverarbeitung in anatomisch und funktionell separate Pfade je nach Anforderung. Objekterkennung, oder allgemeiner visuelle Wahrnehmung, hängt vermeintlich von Repräsentationen ab, die auf allozentrischen Koordinatensystemen, relativen Maßstäben und holistischen Verarbeitungsmodi des ventralen kortikalen Pfades basieren. Auf der anderen Seite hängen visuell-motorische Handlungen vermeintlich von Repräsentationen ab, die auf egozentrischen Koordinatensystemen, absoluten Maßstäben und analytischen Verarbeitungsmodi des dorsalen kortikalen Pfades basieren. Neuropsychologische Patientenstudien und Studien mit gesunden Versuchspersonen galten zunächst als übereinstimmende Belege für dieses Modell. Nachfolgende Forschung wies jedoch darauf hin, dass die Schlussfolgerungen von Patientenstudien nicht so eindeutig waren wie berichtet. Deswegen konzentrierte jüngere Forschung sich darauf, Wahrnehmung-Handlung-Dissoziationen (Unterschiede in Wahrnehmung und Handlung) im Verhalten gesunder Individuen nachzuweisen.

Diese Dissertation trägt zu der Forschung über Wahrnehmung-Handlung-Dissoziationen durch die Neubewertung der Belege in drei verschiedenen Paradigmen von Verhaltensexperimenten bei. Erst haben wir die Behauptung untersucht, dass das Greifen ein fundamentales, psychophysikalisches Prinzip, Webers Gesetz, verletzt (Ganel et al., 2008), das sich in vielen sensorischen Bereichen, einschließlich visueller Wahrnehmung, bewiesen hat. Wir haben nachgewiesen, dass ein mathematischer Fehler in der Berechnung der just-noticeable-differences (JNDs), welche für die Beurteilung von Webers Gesetz verwendet werden, eine scheinbare Verletzung von Webers Gesetz im Greifen produziert. Wir schlugen eine bessere Methode vor, um JNDs beim Greifen zu schätzen. Wir haben diese Methode zur Analyse unserer Daten und den Daten von drei repräsentativen Studien eingesetzt. Dabei haben wir nachgewiesen, dass sowohl Greifen als auch Wahrnehmung Webers Gesetz unterliegen. Demzufolge fanden wir keine Evidenz für eine Wahrnehmung-Handlung-Dissoziation.

Dann haben wir die Behauptung geprüft, dass das Greifen nicht von Garner Interferenz betroffen ist obwohl Schnellklassifizierung und manueller Größeneinschätzung (Wahrnehmung) es sind (Ganel & Goodale, 2003). Wir haben die Garner-Interferenz-Literatur überprüft und fanden eine empirischen Unstimmigkeit: es gab nur zwei Studien, die Garner Interferenz bei manueller Größeneinschätzung gezeigt haben. Demnach haben wir vier Replikationen durchgeführt und eine quantitative Literaturübersicht mit 15 Studien zu Garner Interferenz zusammengestellt. Unsere Ergebnisse deuten auf einen vergleichbaren Garner-Interferenz-Effekt beim Greifen sowie bei manuellen Größeneinschätzungen hin, welcher aber kleiner als bei Schnellklassifizierung ist. Erneut fanden wir keine Evidenz für eine Wahrnehmung-Handlung-Dissoziation.

Abschließend haben wir einen Befund untersucht, nach dem das Greifen präziser Objektgrößen unterscheiden kann als die Wahrnehmung (Ganel et al., 2012). Dieser Schluss

basiert auf einem statistisch signifikanten Unterschied im Abstand der Finger beim Greifen von kleinen und großen Objekten trotz niedriger Genauigkeit bei wahrnehmungsbasierten Urteilen — ein unangemessener Vergleich zwischen Wahrnehmung und Handlung auf Basis von verschiedenen Maßen. Nachdem wir jedoch die jeweiligen Klassifikationsgenauigkeiten in zwei Experimenten berechnet haben, fanden wir eine Genauigkeit nahe Zufallsniveau für Greifbewegungen und eine beträchtlich höhere Genauigkeit bei wahrnehmungsbasierten Urteilen. Die Genauigkeit bei der manuellen Größeneinschätzung war ebenfalls nahe Zufallsniveau und ähnlich wie beim Greifen. Eine Meta-Analyse offenbart ein ähnliches Ergebnismuster in anderen Studien. Hier fanden wir demnach abermals keinen Nachweis für eine Wahrnehmung-Handlung-Dissoziation bei der Fähigkeit Objektgrößen zu unterscheiden.

Auf Grundlage unserer umfassenden Untersuchungen einschließlich Replikationen, Meta-Analysen und verbesserten Methoden können wir schließen, dass keines der drei hier betrachteten Paradigmen einen Nachweis für Wahrnehmung-Handlung-Dissoziationen und dementsprechend für das Perception-Action Model liefert. Stattdessen finden wir ähnliche Fähigkeiten in Wahrnehmung und Handlungen, solange die Beschaffenheiten der Aufgaben vergleichbar gehalten werden, was auf eine gemeinsame Repräsentation von Objekteigenschaften hindeutet.

List of Publications

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- **Bhatia*, K.**, Löwenkamp*, C., & Franz, V. H. (2022). Grasping follows Weber's law: How to use response variability as a proxy to JND. *Journal of Vision* 22(12), 13-13. (* equal contribution)
- **Bhatia, K.**, Osenberg, A., Janczyk, M., & Franz, V. H. (2025). Reviewing evidence for the perception–action model from Garner interference. *Journal of Experimental Psychology: Human Perception and Performance*, 51(2), 217–242.

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Status: Published

CL conceptualised the original idea, collected data, performed the initial analyses, and wrote the first draft of the manuscript. After CL left academia, KB joined the project, conducted additional analyses, created visualisations, rewrote and edited parts of the manuscript and handled the submission and reviews. VHF supervised and administered the project, contributing to resources, funding acquisition, conceptualisation and writing.

2. **Bhatia, K.**, Osenberg, A., Janczyk, M., & Franz, V. H. (2025). Reviewing evidence for the perception–action model from Garner interference. *Journal of Experimental Psychology: Human Perception and Performance*, 51(2), 217–242.
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KB conceptualised the original idea, collected some data, performed all analyses, created all visualisations, wrote the original draft and handled the submission and reviews. AO collected data and contributed to conceptualisation. MJ supervised and administered the project, and contributed to conceptualisation, funding acquisition and writing. VHF supervised and administered the project, and contributed to conceptualisation, resources, funding acquisition and writing.

3. **Bhatia, K.**, Huber, T., Osenberg, A., Göhringer, F., Schenk, T., Janczyk, M., & Franz, V. H. (2025). Is the size resolution of actions better than perception? *Manuscript in preparation*.
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KB conceptualised the original idea, performed all analyses, created all visualisations and wrote the original draft. TH collected data and contributed to conceptualisation. AO collected data. FG and TS supported the conceptualisation and provided data. MJ contributed to funding acquisition. VHF supervised and administered the project, contributed to conceptualisation, resources, funding acquisition and writing.

1. Introduction

> Mere predictability doesn't matter like it should (without a good story appended to it).
>
> Dawes (1999, p. 29)

Scientific progress often relies on a cyclic process of observation of natural phenomena, formulation of theories and models to explain them and tests of those theories in the form of experiments. Supporting evidence from experiments should then increase confidence in a theory, prompting further tests, and contradictory evidence should prompt revision or update of a theory. Repeated failures to find supporting evidence for a theory should then decrease confidence in that theory as a viable explanation of the natural world.

Here we evaluate the evidence for a prominent theory of the functional organisation of the human visual system, the Perception-Action Model (PAM, Goodale & Milner, 1992). We examine three different behavioural paradigms that have been cited as providing strong support for this model in healthy participants: Weber's law, Garner interference and size resolution. In each case, we applied improved analyses and experiment designs, accumulated evidence from replications and aggregated evidence from meta-analyses. Based on these comprehensive investigations, we conclude that there is no evidence for the PAM from these paradigms.

1.1 Perception-Action Model (PAM)

The PAM assumes that there are distinct representations of object features in the ventral and dorsal cortical streams (Milner & Goodale, 1995). The representations in the ventral stream, projecting from the striate cortex to the inferior temporal cortex, are involved in visual perception, that is, perceptual identification and recognition of objects. Meanwhile, the representations in the dorsal stream, projecting to the posterior parietal cortex, mediate visuomotor actions toward objects (Goodale & Milner, 1992). While the PAM is not the first theory to propose two visual systems (e.g., the 'what vs. where' distinction of Ungerleider & Mishkin, 1982), it is unique in its emphasis on the output requirements rather than the input distinctions of visual information. Milner and Goodale (1995) stress that while most accounts of vision have focused on visual perception, vertebrate vision evolved first and foremost to serve motor output, which would have required different computations than visual perception. Thus, Milner and Goodale (1995) argue for the functional separation of the two streams from an evolutionary point of view. Therefore, Milner and Goodale (1995) propose that the ventral and dorsal streams operate on different representations (instead of combined representations advocated by Ungerleider & Mishkin, 1982).

The influence of this proposed dorsal-ventral distinction has not been limited to the domain of perception and action. Beyond the claims of different representations for different purposes, Milner and Goodale (1995) also postulated that only the ventral stream has conscious access and not the dorsal stream. This resulted in some theories of consciousness proposing so-called

’zombie modes’ involving the dorsal stream - in other words, that rapid, stereotyped actions guided by the dorsal stream do not enter consciousness (Crick & Koch, 2003). Investigating the roles of the ventral and dorsal streams as suggested by the PAM thus has implications for our understanding of consciousness (e.g., O’Regan & Noë, 2001). Furthermore, some models of visual attention (Deco, 2005; Desimone & Duncan, 1995) relied on presumed features of the dorsal and ventral streams. Therefore, evaluating the PAM can improve our understanding of the architecture of the visual brain, which can improve our general understanding of human cognition. Importantly, understanding the normal functioning of the brain also sheds light on the abnormal functioning of the brain. Patients with disorders of perception (visual form agnosia) and action (optic ataxia) resulting from lesions to the ventral or dorsal stream provided initial insights that culminated into the PAM (Milner & Goodale, 1995), but there is also evidence that the dorsal and ventral streams may be involved in a range of disorders like autism (Dakin & Frith, 2005), aphantasia (Keogh & Pearson, 2018), dyslexia (Vidyasagar & Pammer, 2010) and apraxia (Martin et al., 2016). Thus, clarifying the contribution of the dorsal and ventral streams to vision has not only theoretical but also practical value.

The PAM was formulated as an integration of evidence from studies in monkeys and behavioural analyses of neuropsychological patients and healthy participants (Goodale & Milner, 1992). The core behavioural evidence from both lesion patients and healthy observers relies on perception-action dissociations, that is, different output behaviour from the two streams during perception and action. Goodale and Milner assume that these different output behaviour reflect distinct representations within the streams. The next section reviews the evidence for perception-action dissociations from lesion patients that built the foundation of the PAM, and the subsequent sections describe the behavioural paradigms that apparently demonstrated strong perception-action dissociations in neurologically intact participants, considered to provide converging evidence supporting the PAM.

1.2 Perception-Action Dissociations

If perception and action rely on distinct processing pathways, it is assumed that there will be observed differences in the performance and behaviour pertaining to perception and action. These will henceforth be referred to as perception-action dissociations.

1.2.1 Double Dissociations in Lesion Patients

Compelling double dissociations of perception and action in patients with lesions to the ventral and dorsal streams prompted the idea of two visual streams for perception and action. As described in Goodale and Milner (2013) and Milner and Goodale (1995), the story started when the authors met with D.F., a woman who had suffered carbon monoxide poisoning leading to brain damage. This had left her with a peculiar disorder in which her visuomotor abilities were preserved but she could not recognise or identify objects. Goodale and Milner (2013, p. 17) also describe a fascinating anecdote in which the authors held out a pencil to D.F., and while she could not recognise it (beyond that it was yellow) or judge the orientation of how the pencil was being held, when she reached out to grasp it, her hand shaped correctly and she was able to skilfully grasp it without problems. This inspired several experiments which demonstrated that D.F. could act on objects but not recognise or identify them: perception-action dissociations. For example, D.F. could not match the orientation of a card held in her hand to the orientation of a slot, but she could successfully 'post' it through the slot (like a letter through a mailbox, Milner & Goodale, 1995, Figure 5.3; but see Hesse et al., 2021). D.F. could also accurately draw objects from memory, but not copy images of those same objects (Goodale & Milner, 2013, Figure 1.2). Her visuomotor proficiency was also demonstrated by her ability to stably grasp objects that were irregularly shaped (Milner & Goodale, 1995, Figure 5.7). Her symptoms were therefore consistent with visual form agnosia, a disorder of visual recognition. Further, neuroimaging evidence (Milner et al., 1991) suggested that "D.F.'s ventral stream has been deprived of visual form information from all sources" (Milner & Goodale, 1995, p. 134). Thus, D.F.'s behaviour coupled with the characterisation of her brain lesions led Goodale and Milner to propose that the ventral stream is involved in perception but not action.

On the other side, Milner and Goodale (1995) describe experiments with patients suffering from optic ataxia, a visuomotor disorder characterised by misreaching occurring due to lesions to the dorsal stream. Here, observations from patients showed a complementary pattern to deficits of D.F.: they could not accurately post their hand through a slot (Milner & Goodale, 1995, Figure 4.2) or perform stable grasps on irregular objects (Milner & Goodale, 1995, Figure 5.7) but they could copy images well (Goodale & Milner, 2013, Figure 3.5). Many of the comparisons came from patient R.V., an optic ataxic whose lesions were localised to the dorsal stream (and complementary to the lesions of D.F., Goodale, Meenan, et al., 1994).

This pattern of complementary double dissociations from patients with visual form agnosia and optic ataxia formed the foundational basis of the PAM, and led Goodale and Milner (1992) to propose that "the ventral stream ... plays the major role in perceptual identification of objects, while the dorsal stream ... mediates the required sensorimotor transformations for visually guided actions directed at such objects" [p. 20].

1.2.2 Generalisation to Healthy Individuals

The PAM was mainly conceptualised based on studies with lesion patients, and heavily relied on dissociations observed in D.F. But, Milner and Goodale (1995) themselves conceded the importance of complementing neuropsychological evidence with evidence from healthy individuals, and there are a number of reasons why this is necessary to sustain the PAM as a reasonable model for the human visual brain.

First, if the dorsal and ventral pathways independently support action and perception in a neurologically intact brain, then perception-action dissociations should also be observed in healthy individuals. If not, the dissociations observed in patients might be better explained by other models (Schenk et al., 2011).

Second, despite Milner and Goodale (1995, p. 157) asserting that "evidence from a wide range of neuropsychological studies ... suggest that there is a clear dissociation between the visual pathways supporting perception and action in the cerebral cortex", recent research has shown that this is *clearly* not the case. Already early on, Goodale, Meenan, et al. (1994, p. 608) admitted that dissociations from D.F., although striking, can only support tentative functional mappings suggested by the PAM, because of the diffuse nature of her lesions. Nevertheless, the popular science book on the PAM, "Sight Unseen" (Goodale & Milner, 2013) focused almost exclusively on experiments with D.F. and this evidence continues to be cited (Ganel & Goodale, 2019) in favour of the PAM. Recently, there has been mounting evidence that decreased confidence in dissociations observed in D.F.: it was shown that D.F. also had deficits in her visuomotor abilities (Himmelbach et al., 2012), and they are also similar to those observed in optic ataxia (Rossit et al., 2018). Goodale, Meenan, et al. (1994) had suggested that complementary double dissociations in patients with optic ataxia like R.V., whose lesions can be confidently localised to the dorsal stream provide strong support for their proposal. McIntosh et al. (2011), however, demonstrated with more stringent tests of optic ataxia that it is not only a visuomotor disorder, and such patients also show several perceptual deficits. Taken together, the picture of double dissociations in patients with visual form agnosia and optic ataxia is not as clear as advocated recently by Ganel and Goodale (2019) and originally by Milner and Goodale (1995). Therefore, perception-action dissociations need to be reliably demonstrated in a neurologically intact population in order to substantiate a theory such as the PAM and generalise it to the human population as a whole.

Finally, behavioural perception-action dissociations in normal subjects would provide converging evidence for the PAM and strengthen its evidential foundations. Thus, in this thesis, we focus on evaluating the evidence for such perception-action dissociations from healthy observers. While perception-action dissociations could be demonstrated between lesion patients and healthy controls using tasks described above like card posting/orientation-matching, grasping irregularly shaped objects and copying/drawing objects from memory, it is not very informative to compare the performance of healthy individuals on these tasks because they typically make very few errors and are at ceiling-performance (Milner & Goodale, 1995, Figures 5.3 and 5.7). Thus, to investigate if processes mediating perception and action are different in healthy observers, new paradigms and tasks were needed.

1.2.3 Grasping versus Manual Estimation as Action versus Perception

Demonstrating perception-action dissociations in healthy observers would require appropriately matched perception and action tasks, that have similar requirements and demands on the participants. Only then would it be possible to conclude distinct representations and processing pathways for perception and action from perception-action dissociations. For example, if participants are asked to grasp objects (action) and their performance is compared to a situation where they are asked to press a button to make a category judgement (perception), then observed differences might not warrant strong conclusions about the neural basis of perception versus action – the observed difference might boil down to task differences (cf. Ganel & Goodale, 2003)

In these behavioural paradigms, two conditions/tasks are typically contrasted: precision grasping (grasping with tips of index finger and thumb) and a standard/classic perception task like category judgement, speeded-classification or adjustment (cf. Aglioti et al., 1995; Ganel & Goodale, 2003; Ganel et al., 2008, 2012). However, these tasks are often different in the requirements and cognitive demands on the participant (cf. Experiment 1 of Ganel & Goodale, 2003). Sometimes, the response format also differs, for example, dichotomous in one case and continuous in the other (Ganel et al., 2012; Haffenden & Goodale, 1998). Studies like Haffenden and Goodale (1998) therefore advocated for contrasting grasping with manual size estimation - here, participants indicate the size of a target object with the separation between their finger and thumb. It is assumed that the manual size estimate provides a "manual 'read-out' of what [participants] perceive" (Haffenden & Goodale, 1998, p. 125).

The obvious advantage is that the same "read-out" can be directly compared for perception and action. Coupling this with the observation that D.F.'s (who has impaired visual perception) finger separation in grasping correlates with object size, but not manual estimation (Goodale et al., 1991, Figure 2), results in a framework for testing the PAM that has been employed by several studies on the PAM in various behavioural paradigms: grasping versus manual estimation as proxies for action versus perception.

It is important to note here that manual estimation relying on perceptual representations and being guided by the ventral stream is an auxiliary assumption of the PAM (but lacks direct empirical evidence, see also Cesanek & Domini, 2018, and Section 5.1.1). But a comparison between grasping and manual estimation is an important condition, because it satisfies the requirement for adequately matched perception and action tasks, and allows inferences of representations in the ventral and dorsal streams. In evaluating the evidence for the PAM from different paradigms, we therefore emphasised the importance of the comparison between manual estimation and grasping for demonstrating perception-action dissociations (cf. Bhatia et al., 2025).

The next sections summarise the status of perception-action dissociations between grasping and manual estimation in different behavioural paradigms with healthy observers.

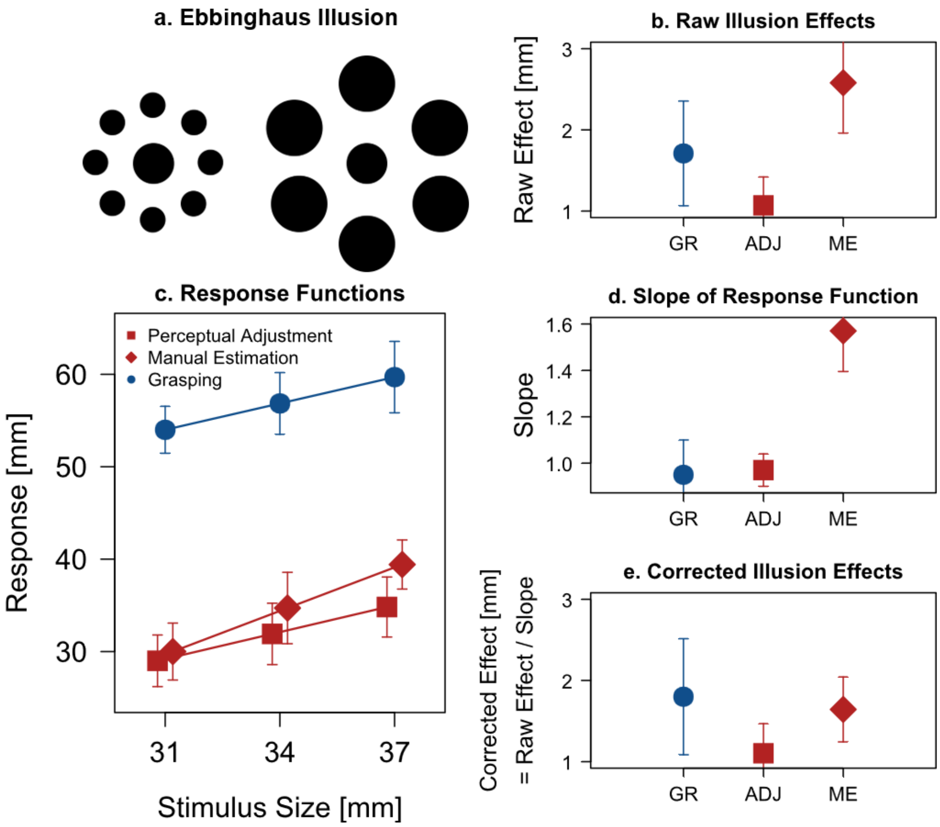
1.3 Visual Illusions: Are Actions Immune to Visual Illusions?

Aglioti et al. (1995) demonstrated one of the first perception-action dissociations using behavioural data in a neurologically intact population, paving the way to generalise the PAM beyond lesion patients. They investigated the influence of visual illusions on perception and action. Specifically, Aglioti et al. (1995) employed the Ebbinghaus illusion, a size contrast illusion (cf. Figure 1a), for their experiments. Even though the central discs are equal in size, most participants report that the disc surrounded by large context circles appears smaller (and the disc surrounded by small context circles appears larger). Quite surprisingly however, they reported that participants' grip apertures when they grasped the central discs scaled mainly to the true size of the target disc, and were not influenced by its illusory size. Based on this result, they concluded that "actions are mediated by visual processes that are separate from those mediating our conscious experiential perception" (p. 679).

Though this finding was quite influential and "captured most of the limelight" (Carey, 2001, p. 109), it was not uncontested (for reviews, see Franz & Gegenfurtner, 2008; Schenk et al., 2011; Westwood & Goodale, 2011). The major controversies in this discussion included the question of whether grasping is affected by illusions at all, the variation in illusion effects on different perceptual tasks and whether the context circles in the Ebbinghaus illusion behaved as obstacles and could explain why some studies found illusion effects on grasping. The core issue was a methodological confound in the determination of the illusion effects: a direct com-

Figure 1

Different Response Slopes Necessitate Correction of Raw Effects of Visual Illusions



Note. (a) The Ebbinghaus illusion: central discs are equal in size but are perceived as different due to the effect of the context circles. (b) A larger illusion effect was reported for manual estimation than grasping (Haffenden & Goodale, 1998), and interpreted as a perception-action dissociation. (c) However, the response slopes in these tasks are different, meaning that the same change in the stimulus (say 1 mm) does not result in the same change in the response. (d) Values of the response slopes for the different tasks. Manual estimation has the steepest slope, such that the manual estimation response increases more than the grasping response for the same change in the stimulus. (e) Due to this difference in slopes, illusion effects across tasks must be normalised by the slope. The corrected illusion effect can be calculated by dividing the raw effect by the response slope. The corrected illusion effects are similar for the tasks and do not support a perception-action dissociation. Data in panels b, d and e are taken from Table 2 of Franz (2003).

parison of the illusion effects measured in grasping, manual estimation and classic perception did not account for differences in the response slopes in these tasks (see Figure 1c-d). Different response slopes mean that these tasks differ in how much the respective response (MGA, manual estimate and perceptually adjusted size) increases for a corresponding increase in the stimulus size. Manual estimation was shown to have a steeper response slope than grasping or classic perception, therefore the measured illusion effect was exaggerated and much higher. A meaningful comparison of illusion effects across these tasks would require a normalisation (or calibration) of the illusion effects by the respective response slopes.

In 2016, a large scale multi-site replication was undertaken in the form of a registered report to conclusively resolve the empirical inconsistencies in studies on visual illusions in perception and action (Kopiske et al., 2016). Testing several configurations of the Ebbinghaus illusion and a total of 144 participants across four different labs, Kopiske et al. (2016) concluded that grasping is affected by the Ebbinghaus illusion (see Figure 1e), and that the illusion effect on grasping was correlated to the illusion effect on perceptual measures. This correlation could not be accommodated by the PAM, because it assumes that the ventral and dorsal streams rely on distinct representations of size for perception and action respectively – meaning that the illusions effects should be independent and not correlated. Furthermore, they found that the illusion effect on grasping was not simply an artefact of treating the context circles as obstacles during grasping.

Though this registered report attempted to provide some conclusive answers, discussions and disagreements remain (see Kopiske et al., 2017; Whitwell & Goodale, 2017). To this day, the debate about the effect of visual illusions on perception and action remains lively. Subsequently, some studies reported perception-action dissociations in illusions other than the Ebbinghaus illusion (Ozana & Ganel, 2020; Whitwell et al., 2018), while other studies demonstrated that perception-action dissociations in visual illusions might not provide evidence for distinct representations in the ventral and dorsal streams (Bruno & Uccelli, 2024; de la Malla et al., 2019), instead being dependent on experimental factors. Given the active controversy surrounding visual illusions, in this thesis, we decided to examine the other lines of evidence purported to provide support for perception-action dissociations and the PAM.

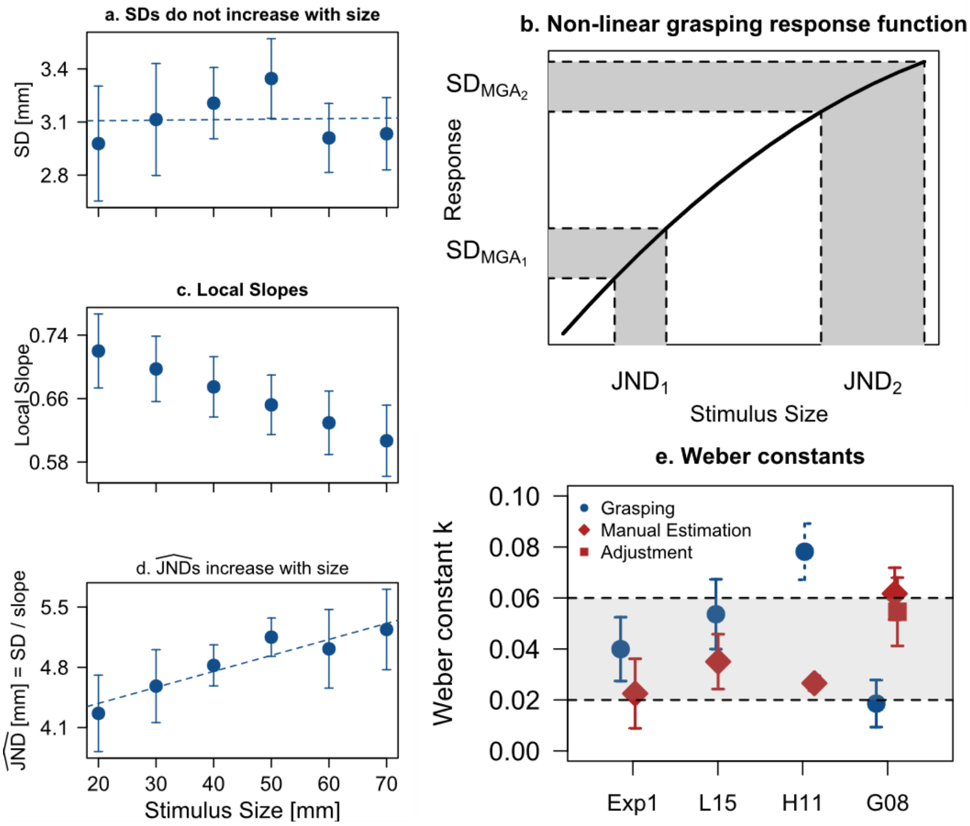
1.4 Weber's Law: Does Grasping Violate Weber's Law?

Another surprising result was that grasping did not obey Weber's law (Ganel et al., 2008), a fundamental psychophysical principle (Baird & Noma, 1978). According to Weber's law, as the stimulus magnitude increases, a larger difference in the stimuli is needed to distinguish between them. Formally, it is described as the 'just-noticeable-difference' (JND) between two stimuli being proportional to the stimulus magnitude. For grasping, it was observed that the standard deviation (SD) of the MGA (SD_{MGA}, measured as a proxy to the JND), did not increase as participants grasped larger objects (see Figure 2a). On the other hand, manual estimation and standard perception tasks like perceptual adjustment did show an increase of the JNDs with object size. This result was inferred as a perception-action dissociation and as evidence that "visual coding for action is based on absolute metrics" (Ganel et al., 2008, p. R599). A host of studies followed suit and were able to replicate these results (Ayala et al., 2018; Christiansen et al., 2014; Freud et al., 2019; Ganel et al., 2008; Hadad et al., 2012; Heath & Manzone, 2017; Heath et al., 2011, 2012; Heath et al., 2017; Holmes & Heath, 2013; Holmes et al., 2011; Jazi & Heath, 2017; Löwenkamp et al., 2015; Namdar et al., 2018; Ozana & Ganel, 2017, 2018; Ozana et al., 2018; Utz et al., 2015).

Thus, this result was ubiquitously reported. Subsequent studies then used the adherence to Weber's law "as a sensitive measure for the nature of the underlying visuomotor process" (Ozana et al., 2018, p. 1784). However, there was also mounting evidence that the violation of Weber's law in grasping might be a result of an overlooked feature of grasping that was irrelevant for perception: biomechanical constraints to the maximum opening of the hand

Figure 2

Non-linear Response Function Masks Weber's Law in Grasping



Note. (a) Weber's law was reported to be violated in grasping because the variability of the maximum grip aperture (SD_{MGA}) did not increase with stimulus size (Ganel et al., 2008). The dashed line is a regression line between SD and size. (b) However, the grasping response function is non-linear, and equal SD_{MGA} at different sizes could be compatible with increasing just-noticeable-differences (JNDs). (c) The non-linear response function means that the slope at each size is changing. Indeed, the local slopes decrease with object size. (d) Weber's law in grasping should be assessed by JNDs (change along stimulus) and not SDs (change along response), and the non-linearity in the response function means that JNDs at larger sizes are underestimated by SDs. JNDs can be estimated ($\widehat{JND}$) by dividing the SD by the local slope. Section 2 describes the details. When this is done, $\widehat{JNDs}$ in grasping do increase with size, such that Weber's law is followed. The dashed line is a regression line between $\widehat{JND}$ and size, and the slope of this line is the Weber constant *k*. (e) The Weber constants (slope of regression between JND and stimulus size) in the different tasks are within a range (0.02-0.06) expected from classical reviews (Teghtsoonian, 1971). Panels a, c, d depict a reanalysis data from Ganel et al. (2008), shared by Tzvi Ganel via personal communication (21 May, 2022).

(Bruno et al., 2016; Schenk et al., 2017; Uccelli et al., 2021; Utz et al., 2015). Importantly, all of these studies assessed Weber's law through the SD_{MGA} in place of the JND. In Section 2 (see also Bhatia et al., 2022), we argue that this is inappropriate and is the reason for an *apparent* violation of Weber's law in grasping. JND is a property of the stimulus, and it is the change at the level of the stimulus that is needed to detect a change in the magnitude of the stimulus. The MGA, however, is the response and SD_{MGA} reflects the change in the response not the stimulus.

Interestingly, Ganel (2015) makes this same argument in a critique of Heath et al. (2015), taking issue with them using the final grip aperture instead of MGA as the dependent variable. Ganel (2015) argued that "Heath et al. (2015) focus on the distance between the fingers - a response measure - rather than on the stimulus and noticed changes along the size of the stimulus, which is the subject of Weber's law." [p. 1]. The very same fallacy occurs when using the SD_{MGA}, as was used by all the studies following the initial study by Ganel et al. (2008). In classical psychophysics experiments, the JND was often measured as the SD of the responses in the method of adjustment (Stevens & Stone, 1959), which presumably inspired Ganel et al. (2008) to use SD_{MGA} as a proxy for the JND in grasping. However, this substitution of the JND with SD_{MGA} only works if there is a linear relationship between input (JND) and output (SD_{MGA}), which we show is *not* the case: changes in target object size in grasping do not linearly translate to changes in the MGA. Put differently, the MGA increases with size at smaller sizes more than at larger sizes (see Figure 2b). This means that even if Weber's law was truly followed in grasping and the JND increased with size, the SD_{MGA} would not increase with size due to the principle of propagation of uncertainty. Because of the non-linearity in the relation between MGA and size, the SD_{MGA} at larger sizes would be smaller than the true JND, resulting in no increase in SD_{MGA} with size and an apparent violation of Weber's law.

Therefore, due to this non-linearity, the SD_{MGA} cannot be directly used a proxy for the JND in grasping. In Section 2, we show that accounting for this non-linearity is straightforward. The JND is underestimated by the SD_{MGA} at larger sizes due to a shallower slope of the response function. Thus, dividing the SD_{MGA} by the slope corrects for this underestimation and results in appropriate JNDs ($J\widehat{ND}s$) that can be used to assess Weber's law in grasping. Doing this in a replication with grasping and manual estimation, we find that $J\widehat{ND}s$ in both grasping and manual estimation increase with object size, adhering to Weber's law (Figure 2d). Moreover, the Weber constants (slope of the regression between $J\widehat{ND}$ and object size) from our experiment, as well as of three representative studies from the literature were within a range expected for size perception (Teghtsoonian, 1971, and see Figure 2e). The apparent perception-action dissociation from Weber's law thus needs revision.

1.5 Garner Interference: Is There Garner Interference in Manual Size Estimation?

Another perception-action dissociation was claimed in the Garner interference paradigm by Ganel and Goodale (2003). Ganel and Goodale (2003) argued that visuomotor interactions with an object must require analytical processing so that irrelevant features of the object may be ignored. On the other hand, visual perception must rely on preserved relations between an object and its surrounding, thus requiring holistic processing. This entails that irrelevant features should influence perception.

Ganel and Goodale (2003) investigated this hypothesis using Garner's speeded-classification task (Garner, 1974) with rectangles as stimuli. Such a Garner task is typically used to demonstrate whether certain stimulus dimensions can be processed independently of each other (i.e., analytically), also called integral dimensions. An example of such integral dimensions is the length and width of rectangles (Felfoldy, 1974). The idea in a Garner task is to test how fast participants can classify the stimuli when only one dimension is changing trial-to-trial (baseline condition), compared to when both dimensions are changing (filtering condition). For integral dimensions, it is typically observed that participants are faster at classification in the baseline condition than the filtering condition, and this reaction time difference is called Garner interference (Pomerantz, 1986).

Ganel and Goodale (2003) thus expected Garner interference in perception but not action. In their first experiment, they contrasted a perceptual speeded-classification, where participants responded with a button press, to a speeded grasping task, where participants grasped rectangles along the relevant dimension. As predicted, they observed larger Garner interference in perception than grasping. However, they conceded that the perception and action tasks were not appropriately matched, and differing task demands might explain their results. They remedied this shortcoming in a second experiment where participants performed the Garner task and indicated manual estimates of the relevant dimension of rectangles with their finger and thumb. Such a manual estimation task is considered within the PAM framework to be based on perceptual representations. Here, they again found a large Garner interference effect (see Figure 3), concluding that action versus perception relying on analytical versus holistic processing respectively, "helps to explain why separate cortical pathways have evolved for these different kinds of visual processing" (Ganel & Goodale, 2003, p. 667).

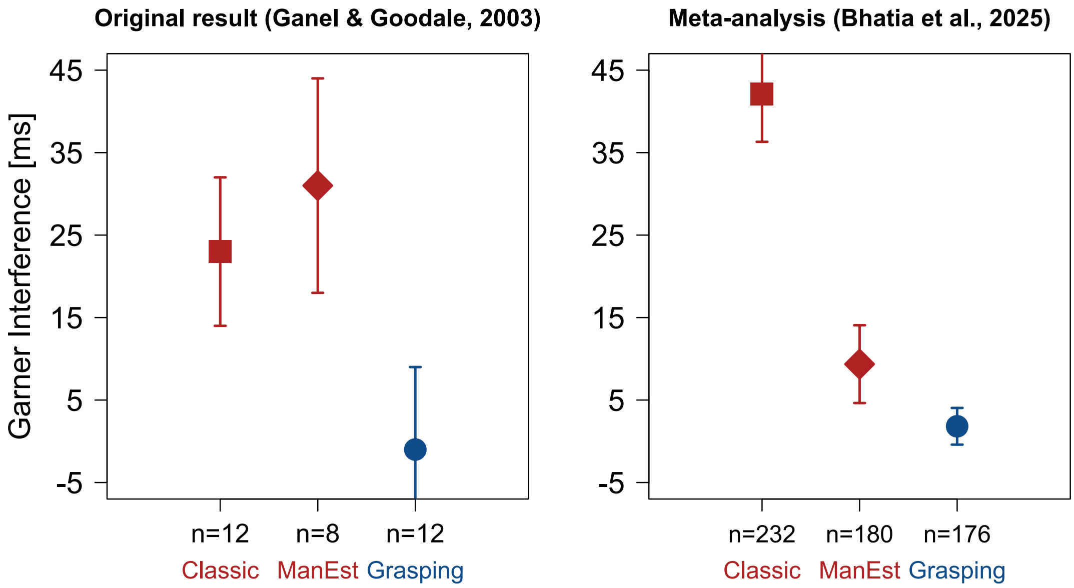
This result was taken as strong evidence in favour of the PAM (Westwood & Goodale, 2011), and inspired several studies that also reported a dissociation between grasping and perceptual speeded-classification (Eloka et al., 2015; Hesse & Schenk, 2013; Janczyk & Kunde, 2010; Janczyk et al., 2010; Kunde et al., 2007; Löhr-Limpens et al., 2020). As noted by Ganel and Goodale (2003), the critical comparison between perception and action with comparable task demands is grasping and manual estimation. But Garner interference in manual estimation was surprisingly only investigated by two other studies (Ganel & Goodale, 2014; Schum et al., 2012), with Schum et al. (2012) failing to replicate Garner interference in manual estimation (see their footnote 2).

In Section 3 (see also Bhatia et al., 2025), we investigated whether there is evidence for a perception-action dissociation in Garner interference. We started by replicating Ganel and Goodale (2003), and when we failed to replicate larger Garner interference in manual estimation than grasping, we focused exclusively on this task in subsequent experiments. Across four high-powered replications with a total sample size of 110 participants, we observed an average Garner interference effect in manual estimation that was comparable to the effect we observed in grasping (see Figure 3). We therefore consistently found evidence that Garner interference in manual estimation is more similar to grasping than speeded-classification.

Furthermore, Hesse and Schenk (2013) convincingly demonstrated that the difference in Garner interference between perception and action may result from methodological differences in how the reaction time is calculated. Specifically, they argued that in perceptual speeded-classification, the reaction time is measured at the time of button press and the decision time is fully captured by the reaction time. In contrast, reaction time in grasping is measured at movement onset, but the grip aperture can still change until the object is reached. These corrections or updates will not be reflected in the reaction time, and the full decision time

Figure 3

An Empirical Inconsistency in Garner Interference



Note. Ganel and Goodale (2003) was the original study that reported a perception-action dissociation in Garner interference: large effects in classic speeded-classification and manual estimation (both considered to be perceptual tasks by the PAM) and almost zero effect in grasping. However, a meta-analysis based on 15 studies with n = 232, 180 and 176 participants for speeded-classification, manual estimation and grasping shows surprisingly comparable effects in grasping and manual estimation. Specifically, manual estimation shows a much smaller effect than initially reported, weakening support for a perception-action dissociation in Garner interference. A detailed analysis is described in Section 3. Data from Ganel and Goodale (2003) were obtained via personal communication from Tzvi Ganel (4 April, 2024).

will not necessarily be captured by the reaction time. To demonstrate this, they conducted variants of a speeded-classification task varying distances between the start and response buttons, that is, varying decision amplitudes. They found that Garner interference differed as a function of the decision amplitude in the same speeded-classification task. Crucially, this task is assumed by the PAM to be processed in the ventral stream. Thus, they demonstrated how the decision amplitude can influence Garner interference, and further showed that it is possible to eliminate Garner interference in perception tasks, weakening support for the idea that Garner interference occurs in tasks processed in the ventral stream.

In our experiments, we considered whether decision amplitude could also influence Garner interference in manual estimation. Ganel and Goodale (2003) did not report the distance between the start position and manual estimation location, thus we could not ensure that our replication matched their experiment in this regard. We hypothesised that perhaps the different decision amplitudes between different studies might explain the inconsistent results. However, the decision amplitude did not substantially affect the Garner interference in our experiments, leaving open the question of whether decision amplitude can affect Garner interference in manual estimation, like Hesse and Schenk (2013) demonstrated for speeded-classification.

In response to Hesse and Schenk (2013), Ganel and Goodale (2014) argued that Garner interference can not only be observed in the reaction times, but also the accuracy of the responses, that is, MGAs in grasping and manual estimates in manual estimation. The logic relies on the irrelevant dimension ”interfering” and increasing the variability of the response to the relevant dimension of the same object size across trials. Thus, they demonstrated that the variability of the MGAs in grasping did not significantly differ between baseline and filtering conditions, and that this difference was much smaller than in the size estimates in manual estimation. Therefore, they again demonstrated a seeming perception-action dissociation between grasping and manual estimation, this time in terms of response variability and not just reaction time. Unfortunately, because this method was only proposed later (11 years after the initial study in 2003), few subsequent studies performed this analysis. In Section 3, we reanalysed the data of other studies that measured kinematic data and reported the Garner interference results for the grip apertures for the first time. A meta-analysis of 15 studies also showed similar values of Garner interference in the variability, and no evidence for a perception-action dissociation. A recent study, Warnecke (2024), focused on Garner interference in grasping and even found a modest Garner interference effect in the MGAs.

In addition to the initial claim of a perception-action dissociation, Garner interference was also used to examine other auxiliary assumptions of the PAM, namely, concerning cases of unusual grasping and dual tasking situations. The PAM assumes that left-handed grasping (even in left-handed individuals), grasping with a tool, grasping using fingers other than the index finger and grasping two-dimensional (2D) objects are cases of awkward or unskilled grasping (Freud & Ganel, 2015; Gonzalez et al., 2006, 2008) that lead to partial processing in the ventral stream. This means that the processing in these tasks should be more holistic and should show Garner interference. In a quantitative review of studies investigating these tasks (e.g., Eloka et al., 2015; Janczyk et al., 2010), we found that all these types of grasping show Garner interference that is comparable to right-handed, skilled grasping assumed to be processed in the dorsal stream. Thus, we also found no evidence for these auxiliary claims of the PAM from Garner interference.

Moreover, the PAM also assumes that dorsal processing is automatic, with a further assumption that it should not suffer interference from dual-tasking (Kunde et al., 2007). To the contrary, Janczyk and Kunde (2010), Kunde et al. (2007), and Löhr-Limpens et al. (2020) all reported dual-tasking costs in grasping, a dorsally processed task, and Löhr-Limpens et al. (2020) even found a modest Garner interference effect in grasping, presumably due to amplification by synchrony with the second task at hand (a shape discrimination task).

All of these results taken together show that neither the core predictions nor the auxiliary assumptions of the PAM have held up to scrutiny. While the Garner interference paradigm was initially deemed to be strong evidence for the PAM, mounting contradictory evidence and failed replications suggest that these claims should be interpreted cautiously. The current status of Garner interference research in perception and action suggests only a weak dissociation, if it is present at all.

1.6 Size Resolution: Is the Resolution of Size in Grasping Better Than Perception?

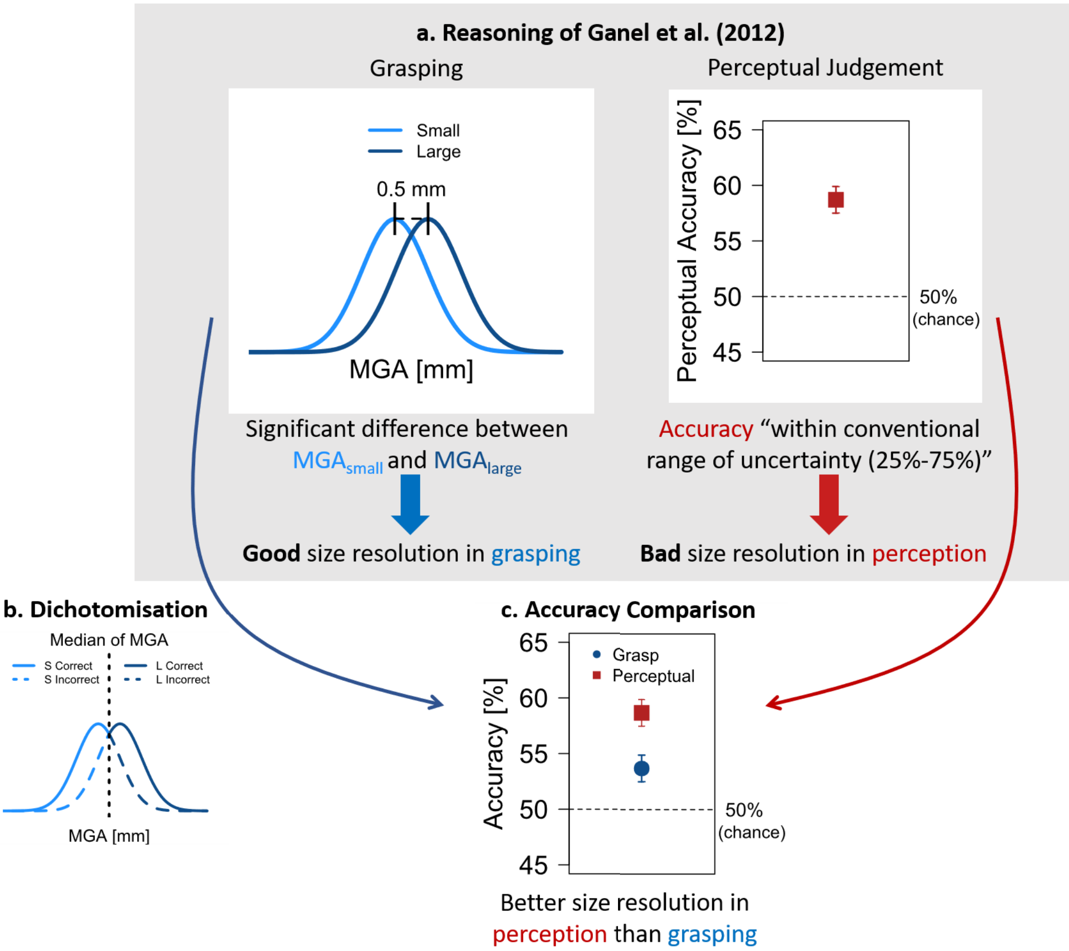
The third and final perception-action dissociation we investigated was from size resolution. Ganel et al. (2012) showed that grasping is apparently able to discriminate between small object sizes more accurately than visual perception. They conducted two experiments with participants performing two tasks sequentially (order was counterbalanced) within the same trial. The stimuli used were discs of diameters 40 mm and 40.5 mm. In one trial, participants judged whether one of the two discs (target) was smaller or larger, and then grasped it. Accuracy in perceptual judgement was measured as %-correct, and grip apertures (MGA) were measured in mm in grasping. While participants had poor accuracy of about 59% in perception, their MGAs to the small and large objects differed significantly by about 0.5 mm, the true size difference (see Figure 4a). This was the case even on those trials where the perceptual judgement was incorrect. Ganel et al. (2012) thus concluded that grasping is more accurate than perception. However, they conceded that the two measures (%-correct and grip apertures) were not comparable: one was dichotomous and one was continuous. To rule out that their results depended on this dissimilarity, they conducted a second experiment, where participants made manual estimates of the size of the target disc, along with perceptual judgements. Again, manual estimates are assumed to rely on perceptual representations and provide a continuous output measure comparable to MGA. Here they found a slightly higher accuracy in perceptual judgement, about 63%, but importantly, the manual estimates to the small and large discs differed significantly only for those trials where the perceptual judgement was correct, but not for those where it was incorrect. Thus, they concluded that even a continuous measure of perception shows poor resolution of size. Again, this pattern of results was inferred as providing support for the PAM.

Stating the conclusions differently, Ganel et al. (2012) inferred from the perceptual judgement accuracy ”within an unconventional range of uncertainty” [p. 4] that there is poor resolution of size. For grasping, they concluded that there is good resolution of size because of a significant 0.5 mm difference in the MGAs for the small and large discs. Such a conclusion runs into a well-known statistical fallacy, that of inferring sensitivity (or discrimination power) based on significant mean differences. Franz and von Luxburg (2015) have convincingly demonstrated for lie-detection studies using masked priming, that a significant difference between reaction times to congruent and incongruent trials actually resulted in a poor sensitivity, with close-to-chance discrimination. Briefly, this means that using a single value of MGA from one trial to predict whether the to-be-grasped object was small or large, would result in poor performance even though the mean differences between MGAs are significantly different. Therefore, it cannot be concluded from a significant difference between MGAs to small and large discs that there was good sensitivity to object size. Meyen et al. (2022, 2024) have made similar arguments in studies on unconscious processing and implicit learning, and showed for a number of studies that significant differences (in reaction times) correspond to poor sensitivities.

Therefore, the size resolution of grasping cannot simply be evaluated on the basis of a significant difference between the grip apertures. The classification accuracy, that is, how well the grip apertures can predict the object size, must be calculated. This idea was implemented

Figure 4

Comparing Different Metrics in Size Resolution



Note. Ganel et al. (2012) claimed to demonstrate a perception-action dissociation in size resolution. (a) They inferred that a significant difference in maximum grip apertures (MGA) of small and large discs meant that grasping had good size resolution. On the other hand, they inferred poor size resolution in perceptual judgement (visually judging which disc is smaller or larger) because of the relatively low accuracy that was "within the conventional range of uncertainty" (Ganel et al., 2012, p.4). Thus, different metrics were used for the two tasks. (b) By dichotomising the continuous grip apertures using the statistically-optimal median split method (Meyen et al., 2022, 2024) an accuracy value can be calculated for grasping. (c) Comparing the accuracies from perceptual judgement and grasping, we find that grasping is even less accurate than perceptual judgement - the opposite of what was suggested by Ganel et al. (2012). In Section 4, we also show that accuracies from manual estimation are quite similar to grasping. Again, we find no evidence to support a perception-action dissociation, when controlling for differing task demands by comparing manual estimation. Data were reanalysed from Ganel et al. (2012), see Section 4 for details.

by Göhringer et al. (2019), who conducted three experiments replicating Ganel et al. (2012). They calculated classification accuracies by dichotomising grip apertures at every possible value, and then chose the maximum accuracy achieved. In all three experiments, Göhringer et al. (2019) reported that the maximum-possible classification accuracy in grasping was *worse* than perceptual judgement. But these values were overestimated and not realistic estimates of grasping accuracy, as we show next.

Typically, a criterion is determined and then the classification accuracy is computed based on that. Göhringer et al. (2019) turned this around and chose the criterion resulting in the best accuracy. This gives an advantage to grasping and does not provide a realistic value for grasping size resolution. A similar overestimation was present in the analysis of a recent paper by Gunderson et al. (2023), who concluded that physiological body responses like vasoconstriction could result in better lie detection accuracy than explicit judgements with the maximum-possible classification accuracy, not the to-be-expected accuracy (see also Franz et al., 2024). Göhringer et al. (2019) however reasoned that if grasping performs worse than perception even after this big advantage, then the to-be-expected accuracy in grasping must be even worse.

The original question of the size resolution in grasping remained unanswered. To calculate the to-be-expected classification accuracy in grasping, Franz and von Luxburg (2015) suggest dichotomisation using the median of the data as the criterion, which has been shown to be the statistically-optimal classifier for the given data (see Figure 4b). In Section 4, we investigated the size resolution of perception and action by comparing classification accuracies in the different tasks calculated using the median-split dichotomisation. While this method has been successfully used for reaction times (Meyen et al., 2022, 2024), no other study applied it to grasping data. We conducted two experiments and measured data from perceptual judgements, grasping and manual estimation. In both experiments, classification accuracies in grasping were worse than perceptual judgement (see also Figure 4c), but comparable to manual estimation. We also performed a meta-analysis comparing the results of the other studies on this topic (Ganel et al., 2012; Göhringer et al., 2019; Heath et al., 2022). For this, we reanalysed their data to convert everything to the same measure (classification accuracy). The meta-analysis also showed that grasping accuracies in all these studies were not better than perceptual judgement and overall comparable to manual estimation. Again, we found no evidence for a perception-action dissociation that was initially promised by the original study (Ganel et al., 2012).

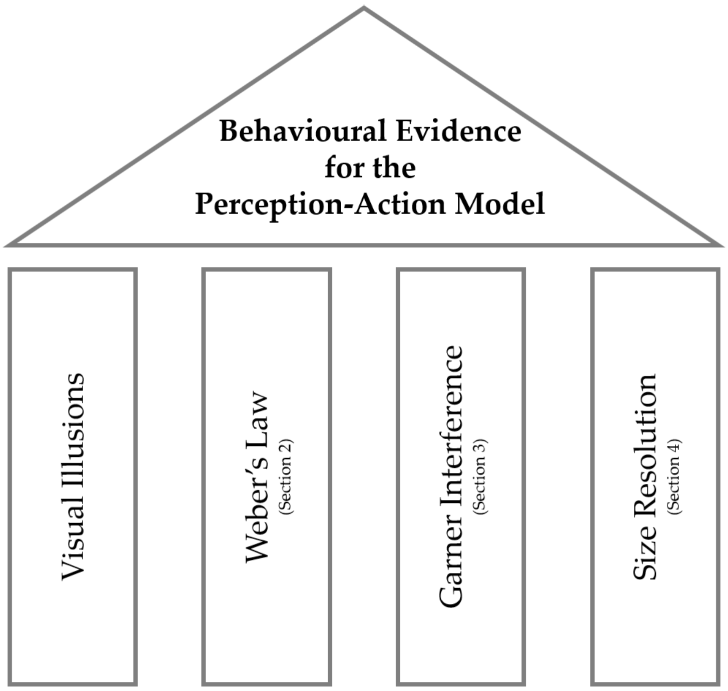
1.7 Overview of This Thesis

The present work contributes to the research on perception-action dissociations with both breadth and depth of investigation: we perform a detailed analysis of *three* different experimental paradigms, and do so with not only rigorous and high-powered replications, but also by aggregating the results of multiple studies using meta-analyses. The three paradigms under scrutiny here are Weber's law, Garner interference and size resolution. Along with visual illusions, these paradigms were reported to provide evidence supporting the PAM, and form the evidential basis for behavioural perception-action dissociations (see Figure 5).

Section 2 examines the apparent violation of an ubiquitous psychophysical principle, Weber's law, in grasping. We find that this seeming violation occurs because the non-linearity in the grasping response function was not considered for the calculation of the just-noticeable-difference. When correcting for this oversight, grasping does follow Weber's law. Section 3

Figure 5

Evidence for the Perception-Action Model From Different Behavioural Paradigms



Note. Perception-action dissociations from visual illusions, Weber's law, Garner interference and size resolution are considered to be the main evidential foundations of the Perception-Action Model in healthy humans. This dissertation investigates the latter three paradigms as described in Sections 2-4.

is an extensive investigation into whether Garner interference, caused by distractions from irrelevant stimulus features, is present in a (perceptual) manual estimation task, and whether it is really absent in grasping. Four replications, a comprehensive literature review and meta-analysis suggest that Garner interference in both these tasks is about the same. Section 4 discusses the resolution of small sizes in grasping versus perceptual judgements. The original report of grasping having better size resolution than perception resulted from comparing different measures in the two tasks. When measures in both tasks are made comparable, we observe that grasping is not better than perception in discriminating sizes. Section 5 brings these results together and considers the consequences for the Perception-Action Model and other theories explaining perception-action dissociations. The dorsal versus ventral distinction is then contextualised within psychology and cognitive neuroscience by drawing parallels to other existing dichotomies in the field. The thesis ends with a discussion of metascience tools and themes of open science that were used here that may improve future research on perception and action.

2. Weber's Law

The content and figures of this section are based on the following publication. The text has been modified to fit to this dissertation. Only minor cosmetic changes were made to the figures.

Bhatia, K., Löwenkamp, C., & Franz, V. H. (2022). Grasping follows Weber's law: How to use response variability as a proxy for JND. ***Journal of Vision*****,** ***22*****(12), 13. https://doi.org/10.1167/jov.22.12.13**

Abstract

Weber's law is a fundamental psychophysical principle. It states that the just noticeable difference (JND) between stimuli increases with stimulus magnitude. Consequently, larger stimuli should be estimated with larger variability. However, visually-guided grasping seems to violate this expectation: When repeatedly grasping large objects, there is similar variability as when grasping small objects. Based on this result, it was often concluded that grasping violated Weber's law. This astonishing finding generated a flurry of research, with contradictory results and potentially far-reaching implications for theorising about the functional architecture of the brain. We show that previous studies ignored non-linearities in the scaling of the grasping response. These non-linearities result from, for example, the finger-span being limited such that the opening of the fingers reaches a ceiling for large objects. We describe how to mathematically take these non-linearities into account and apply this approach to our own data as well as to the data of three influential studies on this topic. In all four data sets, we found that — when appropriately estimated — JNDs increase with object size, as expected by Weber's law. We conclude that grasping obeys Weber's law, as do essentially all sensory dimensions.

2.1 Introduction

"Weber's law is the first and still most widely tested (and confirmed) formal principle in modern psychological science" (Baird & Noma, 1978; Ganel et al., 2008, p. R599) and can be found in almost all sensory dimensions (Teghtsoonian, 1971), including visual size perception. Weber's law states that the just noticeable difference (JND) between two stimuli increases with stimulus magnitude (Baird & Noma, 1978; Fechner, 1860, eq. 4.1).

Given the ubiquity of Weber's law it was very astounding when researchers reported that grasping—a central human ability—does not obey Weber's law (Ganel et al., 2008). The main experimental result leading to this claim has been replicated many times and far-reaching theoretical consequences for the understanding of the functional architecture of the brain were derived (Ayala et al., 2018; Christiansen et al., 2014; Freud et al., 2019; Ganel et al., 2008; Hadad et al., 2012; Heath & Manzone, 2017; Heath et al., 2011, 2012; Heath et al., 2017; Holmes & Heath, 2013; Holmes et al., 2011; Hosang et al., 2016; Jazi & Heath, 2017; Löwenkamp et al., 2015; Namdar et al., 2018; Ozana & Ganel, 2017, 2018; Ozana et al., 2018; Utz et al., 2015).

We will first describe the rationale that leads to the claim of a violation of Weber's law in grasping. Then, we will show that this rationale does not account for the non-linear scaling of grasping as a function of physical object size. When this non-linear scaling is appropriately taken into account, then grasping does obey Weber's law. This is so in our own experiment (specifically designed to test these issues), as well as in re-analyses of three published studies, including the original landmark study by Ganel et al. (2008). Finally, we will discuss consequences for the far-reaching theoretical implications that have been derived from the violation of Weber's law in grasping.

2.1.1 The Initial Finding: A Violation of Weber's Law in Grasping

Ganel et al. (2008) were the first to report that Weber's law is violated in grasping. Participants performed three tasks, one grasping task and two perceptual tasks. The grasping task seemed to violate Weber's law while the perceptual tasks seemed to obey Weber's law.

In the grasping task, participants grasped objects of different sizes and Ganel et al. (2008) measured the maximum grip aperture (MGA). This is the maximum opening between index finger and thumb during grasping and is a function of physical object size: The larger the object, the larger the MGA (Franz, 2003; Hesse & Franz, 2009; Jeannerod, 1984; Smeets & Brenner, 1999). Ganel et al. (2008) then calculated the within-subjects standard deviation of the maximum grip aperture (SD_{MGA}) as a proxy to the corresponding JND and found that (SD_{MGA}) does not increase with object size. From this they concluded that Weber's law is violated in grasping.

In the perceptual tasks, participants either adjusted a comparison line on a monitor to match the size of visually presented objects (perceptual adjustment) or indicated the size of these objects with the span between index finger and thumb (manual estimation)[1]. Again, Ganel et al. (2008) calculated the within-subjects standard deviations of each of these responses ($SD_{Response}$) as a proxy to the corresponding JND and found for both perceptual tasks that $SD_{Response}$ did increase with object size. From this they concluded that Weber's law holds for perceptual tasks — in accordance with the well-known ubiquity of Weber's law in most sensory dimensions (Teghtsoonian, 1971).

In short, Ganel et al. (2008) used for each task the within-subjects standard deviations of the response ($SD_{Response}$) as a proxy to the corresponding JND, as did subsequent studies on Weber's law in grasping. However, we will show that this approach is only valid if there is a perfectly linear relationship between stimulus and response. Any small non-linearity will make this approach problematic and can lead to erroneous conclusions. For ease of exposition, we will focus on grasping, where the typically measured response is MGA, such that the within-subjects standard deviation of the response is SD_{MGA}, but all our arguments apply equally well to other tasks and responses. For the sake of generality, we will use the term $SD_{Response}$ to subsume multiple possible responses but refer to SD_{MGA} in concrete cases of grasping. Before describing why it is problematic to use SD_{MGA} as a proxy for JND, we first need to describe a more general problem.

[1] Ganel et al. (2008) work in the framework of the perception-action model, which considers certain tasks as being driven by 'perception' and other tasks as being driven by 'action' (see General Discussion for details). For ease of exposition, we will follow this labeling, albeit it could be questioned whether, for example, manual estimation is truly only a 'perceptual' task (e.g., Franz, 2003).

2.1.2 A Subtle Pitfall: The Erroneous Equalization of Stimulus and Response

Studies on grasping often use MGA because of its strong dependence on physical object size: The larger the object, the larger the MGA. This allows for relatively straightforward inferences about which object size was used by the motor system to prepare a movement.

Nevertheless, some care needs to be applied when making such inferences. This is so, because MGA is not identical to the object size. For example, it is well known that the MGA is always larger than the to-be-grasped object, such that there is a safety margin (cf. Uccelli et al., 2021) that prevents the fingers from colliding with the object (for a laborious measurement of this response function, see Figure 6a of Hesse & Franz, 2009; for a comprehensive review, see Figure 6a of Smeets & Brenner, 1999).

Here is a simple example that demonstrates the potential pitfalls. Consider that researchers had presented multiple objects of different sizes (e.g., blocks of different lengths) to a participant and measured the response function: MGA as a function of object size. The response function would show the customary safety margin: MGA is always larger than the target object. Now, assume the participant grasped one of the objects, but the researchers did not know which object. All the researchers knew was that the grasp was performed with an MGA of 70 mm. What should the researchers conclude about the object size for which the motor system prepared this grasp?

Given the researchers' knowledge about the response function and the safety margin, it would be an obvious mistake to believe the motor system had prepared for a 70 mm object. Instead, they have to correct for the safety margin. This can easily be done by assessing the response function to see which object size typically corresponds to an MGA of 70 mm. A typical value for the safety margin could be 40 mm, such that the researchers would arrive at the correct conclusion that the motor system had prepared for a 30 mm object.

Had researchers, however, inferred an object size of 70 mm from an MGA of 70 mm, then they would be erroneously equating the response with the stimulus, because they would be confusing the response (here: MGA) with the stimulus (here: physical object size that prompted the motor system to prepare the grasp) by implicitly assuming that those two were identical. Instead, what the researchers should do is to invert the response function: While they first had measured MGA as a function of object size, now they need to calculate object size as a function of MGA in order to find the stimulus that elicited the response. We will see that a similar problem exists when SD_{MGA} is used as proxy for JND.

2.1.3 Why was SD_{MGA} Used as a Proxy for JND?

When Ganel et al. (2008) wanted to assess whether grasping obeys Weber's law, they had a problem: It is not clear how to assess Weber's law in grasping. Weber's law requires an experiment, where a participant compares two objects of different sizes and decides whether they are of equal or different sizes. The JND is then the difference in physical sizes between the two objects at which the participant responds 50% of the time 'different' and 50% 'equal'. Weber's law states that the JND is (roughly) proportional to the absolute size of the object. However, such a comparison is not possible in grasping and even less so in 'natural grasping' (target-oriented grasping, see Goodale, Jakobson, & Keillor, 1994) as is prescribed by the perception-action model if one wants to measure the dorsal stream (see General Discussion). These problems arise because grasping is typically targeted at a single object and does not easily allow for a comparison of two objects.

The solution of Ganel et al. (2008) was to assess the within-participants standard deviation of the response (SD_{MGA} for grasping) as a proxy to JND. Following their lead, subsequent studies also based their investigations of Weber's law in grasping on SD_{MGA} or on similar measures (cf. Section 2.6). However, we will show that this choice constitutes again an erroneous equalization of response and stimulus because SD_{MGA} is related to the variability in the response, while JND is related to the variability of the stimulus (it gives us the amount we would have to change the physical object until this change is detected).

2.1.4 A More Principled Approach to Arrive at a Proxy for JND

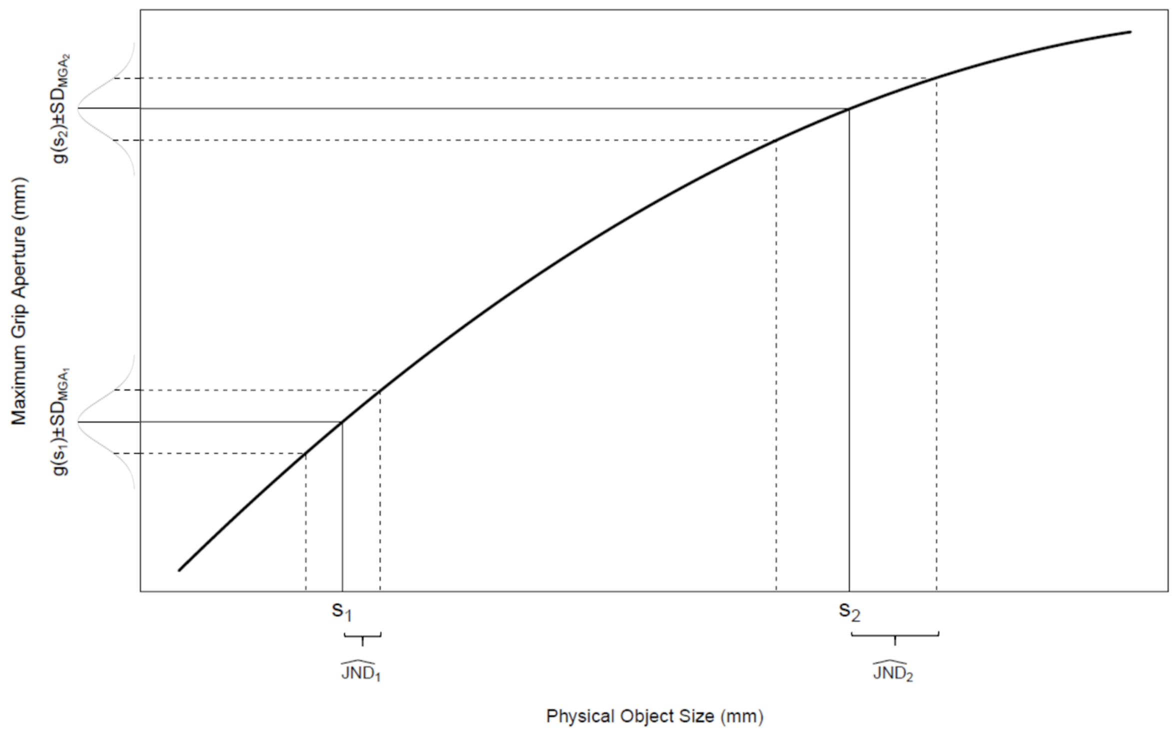
To see what a more appropriate solution looks like, consider the following situation: A participant is presented with a stimulus of size s_1 and responds with a certain MGA_1 and SD_{MGA_1} (Figure 6). Now, we increase the stimulus until this change can be detected in the response. For this detection, we have to set a certain threshold, but this is not critical and standard practice in signal detection models. Therefore, let us set the threshold to ± 1 SD_{MGA_1}, such that we consider the physical size change as being detected when it creates a change in MGA that corresponds to one SD_{MGA_1} (our results would not change had we used a factor other than one here). Now, all we have to do, is determine how much we have to change the stimulus to create this one SD_{MGA_1} change. To determine this, we have to invert the response function and map SD_{MGA_1} back to the stimuli. Let us call the change in stimulus size that is needed to elicit a one SD_{MGA_1} change the $\widehat{JND}_1$ (for 'estimated JND'). This JND_1 tells us how much we would need to change the stimulus s_1 to detect a one SD_{MGA_1} change in the response. Section 2.8.1 (in the Appendix) gives the corresponding math: All one has to do is to calculate at every object size the local slope (the first derivative) of the response function that relates object size to MGA and then to divide the SD_{MGA_1} by this local slope to obtain $\widehat{JND}_1$ (the math is similar to the famous error propagation formula in statistics). We then can use $\widehat{JND}_1$ as a proxy to the JND for this stimulus.

However, Ganel et al. (2008) used SD_{MGA} directly as a proxy to JND. Thereby, they equated the MGA with the physical stimulus size, erroneously equating response and stimulus. In a nutshell: Their intuition to use an SD as a proxy to JND is acceptable, but they used the wrong SD – at the level of the response, rather than the stimulus. Still the use of SD_{MGA} instead of $\widehat{JND}$ would not have dramatic consequences, if the response function that relates object size to MGA were perfectly linear. In that case, all local slopes are equal (i.e., for each object size the response function has the same slope) and the transformation from SD_{MGA} to $\widehat{JND}$ is always by the same constant factor (because, we always divide by the same slope). Therefore, SD_{MGA} could still be used as a proxy to JND when one wanted to assess Weber's law. However, in grasping the response function is not linear. This slight non-linearity has relatively large effects when trying to use SD_{MGA} as a proxy to JND instead of $\widehat{JND}$.

To understand the effects of the slightly bent response function, consider the second stimulus with physical size s_2 in Figure 6. This stimulus has exactly the same SD_{MGA} as the stimulus

Figure 6

Apparent Violation of Weber's Law in Grasping



Note. Illustration of the apparent violation of Weber's law in grasping due to a non-linear response function $g(s)$. First, consider, we already knew that Weber's law holds in grasping, such that uncertainty about object size were smaller for small objects than for large objects (compare $\widehat{JND}_1$ with $\widehat{JND}_2$, respectively). This larger uncertainty is, however, not necessarily reflected in the variability of the response because the response function in grasping becomes shallower for large objects (compare SD_{MGA_1} and SD_{MGA_2}, respectively). This illustrates how the non-linear response function can mask an underlying adherence to Weber's law in grasping. Now, consider what needs to be done if a researcher only knew SD_{MGA} and the response function but not $\widehat{JND}$. The researcher would need to invert the response function and map SD_{MGA} back to the corresponding uncertainty at the level of object size. Only then, the researcher would arrive at the correct estimates for $\widehat{JND}$. For mathematical details see Section 2.8.1 (in the Appendix).

with size s_1, but because the response function is slightly bent, we have to change the physical size of s_2 much more than that of s_1 to achieve the same effect on the MGA: Although SD_{MGA_2} and SD_{MGA_1} are identical (which would be interpreted by Ganel et al., 2008, as a violation of Weber's law), $\widehat{JND}_2$ is much larger than $\widehat{JND}_1$ — just as expected by Weber's law!

Of course, the response function could be bent even more. In this case, it is easily possible that SD_{MGA} is even smaller for large than for small stimuli (Bruno et al., 2016; Löwenkamp et al., 2015; Utz et al., 2015), while nevertheless Weber's law could still hold (i.e., $\widehat{JND}$ could still increase as predicted by Weber's law). All this can only be tested and decided when the appropriate proxy for JND is used.

2.1.5 Overview of This Study

We have shown that non-linear effects in the scaling of the grasping response can erroneously mask Weber's law when SD_{MGA} is used as a proxy to JND. To avoid this pitfall, researchers need to first calculate $\widehat{JND}$ and use this as a proxy to JND. Only then does it make sense to draw inferences about Weber's law.

In the following, we will apply this approach to grasping and manual estimation using four different data sets: Experiment 1 consists of newly collected data using a design that was specifically optimized for this purpose. Then, we present three reanalyses of previously published studies (Heath et al., 2011; Löwenkamp et al., 2015), including the pioneer study on this subject (Ganel et al., 2008).

We chose the studies for re-analysis with the following logic: Löwenkamp et al. (2015) was chosen because we had the full data available and all methodological details were known. Ganel et al. (2008) was reanalyzed because it was the first landmark study on this topic and we tried to replicate their findings. Next, we looked for highly cited studies investigating grasping and Weber's law, which had at least 10 participants and 20 trials per object size (see Section 2.6.1.4), and where the data was either available or given in tables. The most cited study that fulfilled these criteria was Heath et al. (2011), and this research group has contributed a lot to grasping and Weber's law, therefore it would be representative of studies in the field to reanalyze their work.

We will show that when our analysis is applied, grasping is consistent with Weber's law. That is, $\widehat{JND}$ increases with object size in a linear fashion and the corresponding slope is in the range that can be expected from the literature for size estimation (i.e., the Weber constant k is between 0.02 - 0.06, as we would expect from classic studies, cf. McKee & Welch, 1992; Teghtsoonian, 1971).

2.2 Experiment 1: Weber's Law in Grasping and Manual Estimation

First, we conducted our experiment with a grasping and a manual estimation task. The design was optimized to investigate Weber's law: (a) We minimized biomechanical constraints by using functionally "graspable" object sizes between 20 and 50 mm (Ayala et al., 2018; Heath & Manzone, 2017; Heath et al., 2017), (b) Each object was repeated 50 times (instead of the usual $\leq$ 20 repetitions in such experiments, cf. Table 5 in the Appendix) to improve the parameter estimates, and (c) We used a relatively large sample size of N=20 participants. We calculated $\widehat{JND}$ as described above and in Section 2.8.1 (in the Appendix). In a nutshell: At each object size and for each participant, we divided the within-subjects standard deviation of the responses ($SD_{Response}$) by the local slope of the response function (Figure 6). This results in $\widehat{JND}$. Weber's law holds when $\widehat{JND}$ increases linearly with object size.

2.2.1 Method

2.2.1.1 Participants

Twenty participants (14 females, 6 males; age range: 19 to 38 years) took part in the grasping task. Twenty new participants (17 females, 3 males; age range: 18 to 36 years) took part in the manual estimation task. Participants were either undergraduate students who received course credits or paid volunteers, native German speakers, self-declared right-handed dominant and with normal or corrected-to-normal vision.

2.2.1.2 Ethics Statement

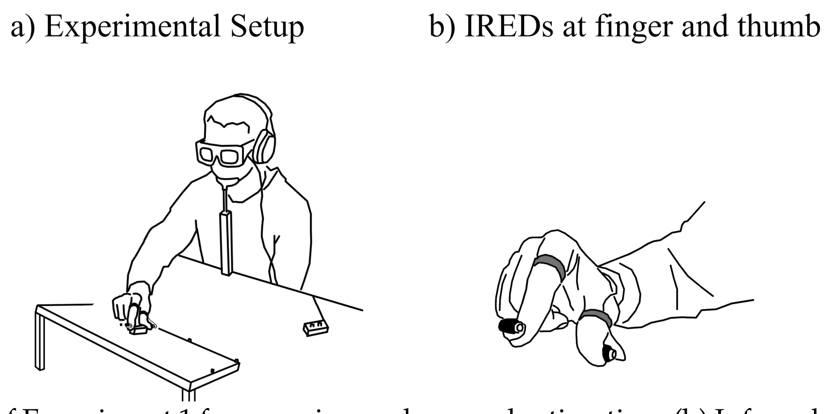
Written informed consent was obtained from all participants. The study was conducted in accordance with the 1964 Declaration of Helsinki and in keeping with the ethical guidelines of the Professional Association of German Psychologists (BDP) (2005, C.III) and the German Psychological Society (DGPs). This study was conducted within the International Graduate Research Group "Cross-modal Interaction in Natural and Artificial Cognitive Systems" (CINACS) that was reviewed and approved by the German Research Foundation (DFG, project number IGK-1247).

2.2.1.3 Apparatus and Procedure

The experimental setup is depicted in Figure 7. Participants sat at a table with their heads positioned in a chin rest. To control the timing of visual presentation, participants wore liquid-crystal shutter goggles (PLATO, Translucent Technologies Inc., Toronto, Ontario, Canada, cf. Milgram, 1987). To present the acoustic start signal and shield from possible sounds of stimulus placement, participants wore headphones with isolation against ambience attenuation of 35 dB (beyerdynamic, DT 770 M 80 Ohm, Heilbronn, Germany). Target objects were plastic blocks that were 20, 30, 40, 50 mm in length and 15 mm in width and depth. They were loosely attached at a 40° sloped platform.

Figure 7

Experimental Set-Up for Experiment 1



Note. (a) Setup of Experiment 1 for grasping and manual estimation. (b) Infrared light emitting diodes (IREDs) were fixed to index finger and thumb to record the trajectories of the movements.

At the beginning of each trial, participants placed their right index finger and thumb pinched together at a start position on the sloped platform 3 cm to the right of the target object. We used a short distance between start position and target object to reduce the amount of motor noise in the transport component of the grasping response. When the experimenter pressed a button, the shutter goggles became transparent and enabled full vision of the target object lying on the sloped platform. Participants were prompted to respond by a 1000 Hz tone after a fixed time interval of 960 ms plus a random time interval drawn from an exponential distribution with a mean of 240 ms (see also Löwenkamp et al., 2015).

In the grasping task, participants grasped the object with index finger and thumb of the right hand. Movement onset caused the shutter goggles to close, preventing sight of the object during grasping (open-loop grasping). After lifting the object and putting it on the desk in front of the sloped platform, participants returned their finger and thumb to the start position. The goggles remained closed until the experimenter set up the next object and started the following trial.

Here is a short justification of a few design choices used in our experiment: Open-loop grasping was chosen because it allows assessment of visuomotor responses solely based on initial visual information, independent of online visual feedback (Haffenden & Goodale, 1998; Post & Welch, 1996). Furthermore, it is typically not problematic or unusual for participants to perform open-loop grasping, and it has been shown that eye-movements "often moved on to the next object in the sequence before completion of the preceding action" (Land & Hayhoe, 2001, p. 3559). A between-subjects design was used, because it is common practice in this field and was also used by the pioneer study, (Ganel et al., 2008) and the other study we reanalyzed (Heath et al., 2011). We also focused on JNDs at the time of MGA, and not 100% of movement time, because MGA is not contaminated by physical contact with the target object, which biases the response heavily to the true physical size. We employed a "natural" grasping task which involves grasping a physically present, 3D object in a real set-up with haptic feedback provided on contact with the object. When grasping an object in a virtual environment, or if the object is 2D, or not physically present (pantomimed or simulated grasping), or when no feedback is provided on grasping the object, it is assumed by the perception-action model to use "stored perceptual information", due to which one would a priori assume Weber's law in such kinds of "unnatural" grasping (Goodale, Jakobson, & Keillor, 1994).

In the manual estimation task, participants moved their right hand approximately 5 cm to the right of the start position and performed manual estimation by indicating the visual size of the object with the span between index finger and thumb, as accurately and spontaneously as possible. Movement onset caused the shutter goggles to close, preventing sight of the object during manual estimation (open-loop manual estimation Haffenden & Goodale, 1998). Participants indicated when they were showing the size of the target object by pressing a button with the left hand. If the button press did not occur within 2.5 s after the start tone, or movement velocity between index finger and thumb at the time of the button press was larger than 30 mm/s (see Franz, 2003), the trial was considered invalid and repeated at a random later time. After estimating the target object (without returning to the start position) participants grasped the object. This was performed to provide a similar amount of haptic feedback in manual estimation as in grasping and is a standard procedure (Ganel et al., 2008; Haffenden & Goodale, 1998; Heath et al., 2011; Holmes et al., 2011; Löwenkamp et al., 2015). After lifting the object and putting it on the desk in front of the sloped platform, participants returned their fingers to the start position. The goggles remained closed until the experimenter set up the next object and started the following trial.

In both tasks, the four target objects were presented randomly and each of the target objects was repeated 5 times during practice trials (i.e., 20 trials) and 50 times during experimental trials (i.e., 200 trials).

An Optotrak Certus (Northern Digital Inc., Canada) with a sampling rate of 200 Hz was used to record the trajectories of the infrared light emitting diodes (IREDs). Three IREDs were placed on the platform for spatial reference. Two IREDs were fixed with adhesive putty (UHU-Patafix, UHU GmbH, Bühl, Germany) on the fingernail of index finger and thumb (Figure 7). Control of stimulus presentation and data recording was obtained with the Psychophysics Toolbox (Brainard, 1997) and the Optotrak Toolbox by V. H. Franz (http://www.ecogsci.cs.uni-tuebingen.de/OptotrakToolbox) within Matlab (Mathworks, Natick, MA, USA).

2.2.1.4 Data Analysis

Movement onset was determined when at least one IRED crossed a sphere with a radius of 30 mm around the start position and movement velocity in at least one IRED exceeded 25 mm/s. Movement offset was determined as the time of the first contact with the object (either thumb or index finger). For this purpose, a mirror foil was mounted at each target object reflecting the infrared signal of an IRED mounted 2 cm to the left of the target object. This mirror image was tracked by the Optotrak and allowed to record subtlest movements of the object (Franz et al., 2005). The first contact with the object (movement offset) was determined as the time when the velocity of the mirror image of the IRED exceeded 6 mm/s. MGA was defined as the peak distance between the IREDs of index finger and thumb between movement onset and offset. The response in manual estimation (ME) was calculated as the distance between the finger and thumb of the participant's right hand at the time of the button press. A trial was considered invalid and repeated randomly later in the experiment if movement onset occurred before the start signal or if an IRED was occluded. In grasping, 23 trials of the 4000 trials were excluded because MGA equaled the aperture at the time of movement offset, indicating that the MGA occurred at the time of or after the contact with the object. This was done to prevent any corrections of the MGA using feedback given by physical contact with the object. Nonetheless, we also analyzed the data including these trials and obtained essentially identical results. One trial was excluded because the MGA had not been recorded. Practice trials were not included in the analyses (we also analyzed the data including practice trials, which produced essentially the same results).

Mean, standard deviation, and skewness (Type 2 Joanes & Gill, 1998) of the response were calculated for each object size and participant. Quadratic regressions ($g(s) = a + bs + cs^2$) were fitted for each participant (cf. Section 2.8.2 in the Appendix). To allow for a meaningful interpretation of the linear term b of the quadratic regression, the predictor (i.e., size) was centered on its mean, such that the linear term b of the quadratic regression describes the slope at the mean object size (i.e., 35 mm) and equals the slope b of a simple, linear regression. $\widehat{JND}$ was calculated by dividing the within-subjects standard deviation of the response by the local slope of the participant's individual quadratic regression function at each size for each participant (Section 2.8.1 in the Appendix). Linear regressions relating $\widehat{JND}$ to object size were then fitted for each participant in order to assess Weber's law. The linear regression allowed for a non-zero intercept. Strictly speaking, Weber's law does not include an intercept. However, it is known that the generalized form of Weber's law (which includes an intercept) is a better descriptor of behavior, and it is standard practice to model Weber's law with a non-zero intercept (Baird & Noma, 1978; Galanter, 1962; Miller, 1947). We discuss this issue further in Section 2.6.1.3.

Analyses were conducted using R (R Core Team, 2021) and Matlab (Mathworks, Natick, MA, USA). For all analyses, a significance level of α = .05 was applied and p values of .001 or less are depicted as $p < .001$. Between-participants means, and corresponding standard errors are depicted as mean ± 1 SEM. We also report 95% confidence intervals (95% CI) for the slopes of the linear regression of SDs and $\widehat{JNDs}$ on object size (for the studies where we have the full data).

Data and analysis scripts are available at OSF (https://osf.io/ent2y/).

2.2.2 Results

2.2.2.1 Grasping

Results are summarized in Figure 8 and regression coefficients are listed in the Appendix (Section 2.8.3). The quadratic regressions revealed a curvilinear relationship between MGA and object size (Figure 8a). Figure 8b shows the difference between response and physical object size. The linear coefficient was b_{MGA} = 1.04 ± 0.013, and the quadratic coefficient was c_{MGA} = -0.0037 ± 0.0005 mm^{-1}. The residuals of the linear and quadratic fits are depicted in Figure 15. The residuals of the linear fit indicate a systematic relationship, which disappears in the residuals of the quadratic fit. The sign of the quadratic coefficient was negative, indicating a concave relationship between MGA and object size: The responsiveness of MGA decreases with increasing object size.

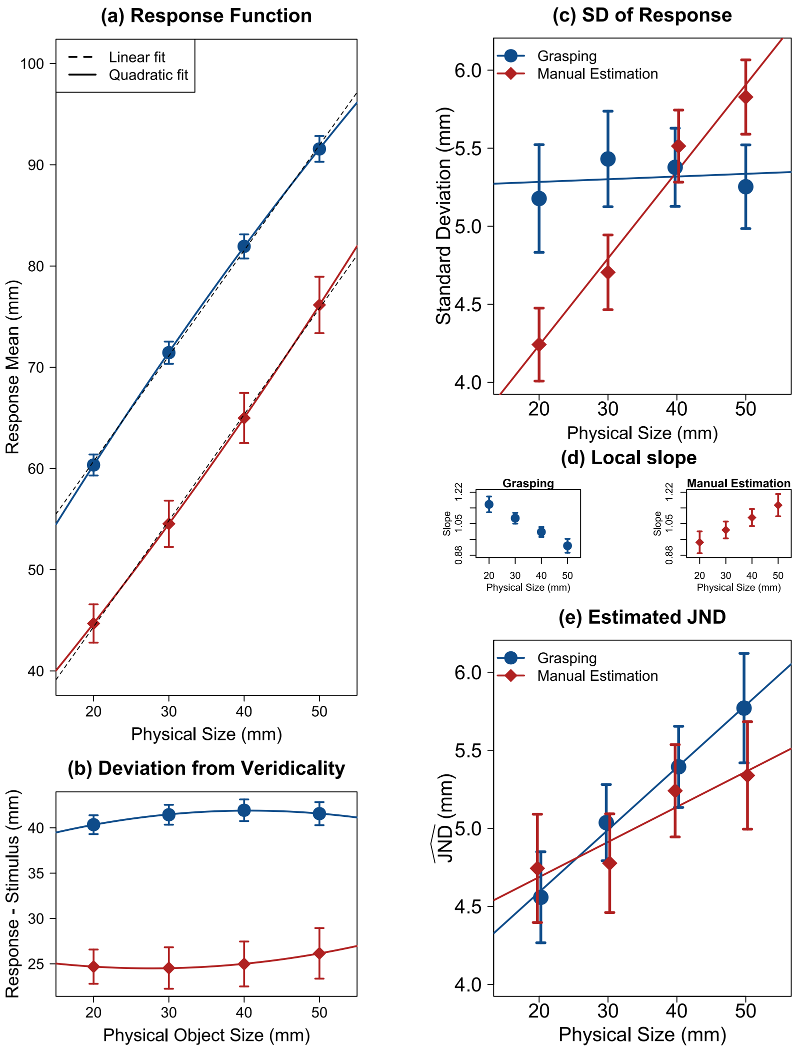
SD_{MGA} did not scale with object size, b = 0.002 ± 0.010, $t(19)$ = 0.18, p = .859, 95% CI [-0.018 0.022] (Figure 8c). Thus, we replicated the finding of previous studies that the uncertainty of the response in grasping does not increase with object size. Based on such a result, it would often be concluded that grasping violated Weber's law (Ganel et al., 2008). However—as we have shown above—this conclusion would be premature. We first have to calculate $\widehat{JND}_{MGA}$ before we can assess Weber's law. To do this, we need to divide the SD_{MGA} by the local slope of the response function (computed from quadratic regression on individual participants) at that object size. These slopes are shown in Figure 8d.

After doing this, we found that $\widehat{JND}_{MGA}$ increased linearly with object size. The slope of this function corresponds to Weber's constant: k_{MGA} = 0.040 ± 0.013, $t(19)$ = 3.18, p = .005, 95% CI [0.014 0.066] (Figure 8e). This value of Weber's constant fits nicely to the expected range from the literature for size perception (McKee & Welch, 1992; Teghtsoonian, 1971, pp. 0.02–0.06). Thus, when using an appropriate proxy for the JNDs, the uncertainty of the grasping response does increase with object size and thus follows Weber's law.

Finally, we checked whether grasping followed the well-known temporal pattern from the literature: Movement onset occurred 288 ± 1 ms after the goggles turned transparent. The

Figure 8

Results of Experiment 1



Note. Results of Experiment 1 for grasping and manual estimation: (a) Mean responses as function of object size. Quadratic regressions are shown as solid color curves; linear regressions as black dashed lines. (b) Difference between response (and quadratic fit) and physical stimulus size. The non-linearity in the responses can be seen in the curvature of these differences. (c) $SD_{response}$ as function of object size. (d) The local slope at every object size in the grasping and manual estimation. This is the value that the SD is divided by to calculate $\widehat{JND}$. (e) $\widehat{JND}$ as function of object size. Error bars depict ±1 SEM (between subjects).

movement duration (from onset until offset of the movement) was 293 ± 6 ms and MGA was achieved on average 217 ± 8 ms after movement onset, such that MGA occurred at 71.2 - 76.6% of the movement duration; as expected from the literature (Jeannerod, 1984; Smeets & Brenner, 1999).

2.2.2.2 *Manual Estimation*

The quadratic regressions revealed a curvilinear relationship between ME and object size (Figure 8a/b; for regression coefficients see Table 1). The linear coefficient was b_{ME} = 1.05 ± 0.021, and the quadratic coefficient, c_{ME} = 0.0033 ± 0.001 mm^{-1}, were different from zero. The residuals (Figure 15) show a systematic relationship which disappears for the quadratic fit.

SD_{ME} increased with object size, b = 0.056 ± 0.008, $t(19)$ = 6.74, $p < .001$, 95% CI [0.038 0.073] (Figure 8c). This finding is consistent with previous studies that also found such a scaling for ME. Based on such a result, it would often be concluded that manual estimation follows Weber's law (Ganel et al., 2008). But again, this conclusion would be premature. We first have to calculate $\widehat{JND}$ before we can assess Weber's law. Again, we divided the SD_{ME} by the local slope (see Figure 8d) to calculate the $\widehat{JND}$.

We found that $\widehat{JND}_{ME}$ increased with object size, resulting in a Weber constant of k_{ME} = 0.023 ± 0.014, $t(19)$ = 1.65, p = .116, 95% CI [-0.006 0.051] (Figure 8e). We cannot claim that this result differs from zero, but crucially, k approached the typical magnitude expected for size perception (0.02-0.06, McKee & Welch, 1992; Teghtsoonian, 1971). Given that we found clearly significant Weber's constant in manual estimation in the other studies we analyzed, and since researchers do not question that manual estimation adheres to Weber's law, we think this single non-significant result is no reason to question Weber's law in manual estimation.

2.2.3 Discussion

We replicated the traditional results which are based on $SD_{Response}$ as a proxy to JND: Following this approach, manual estimation seems to follow Weber's law and grasping seems to violate it (Ganel et al., 2008). However, this conclusion would be premature because $SD_{Response}$ is not a good proxy to JND when the response function is non-linear. Therefore, we first have to calculate $\widehat{JND}$ before we can assess Weber's law. When we do this, then grasping and manual estimation both seem to follow Weber's law and the corresponding Weber constants k are in the range we would expect from the literature for size perception. This raises the question of how general our results are. To assess this, we reanalyzed three studies from the literature and calculated the Weber constants k based on $\widehat{JND}$. For better comparison, we depicted all those Weber constants in Figure 9.

2.3 Reanalysis of Löwenkamp et al. (2015)

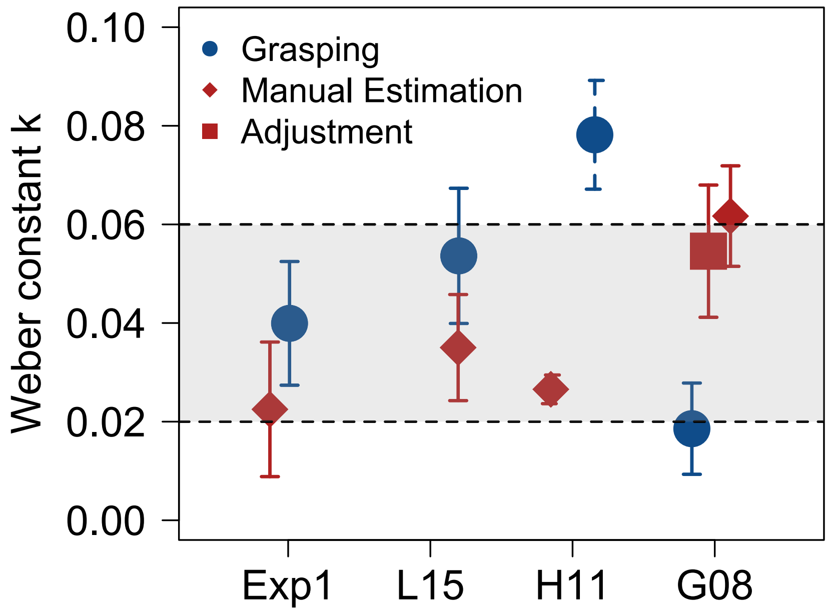
The first study we reanalyzed was published by our own group (Löwenkamp et al., 2015) and served as a test case, because here all data were fully available (including trial-by-trial data) and all methodological details were known.

2.3.1 Method

Six objects (20, 30, 40, 50, 60 and 70 mm) were presented 20 times to fifteen participants for grasping, and to fifteen different participants for manual estimation. Both grasping and manual estimation were performed open-loop. For further details, we refer to the original publication.

Figure 9

Comparison of Weber Constants k



Note. Weber constant k based on $\widehat{JND}$ for all our analyses. From the literature, we expect k to be between 0.02 – 0.06 for visual size perception, as indicated by the shaded area. The k values we obtained are very close to this expected range. Values are shown as mean ± SEM. The values for H11 are dashed because we only had aggregate data for this study. Exp 1 = Experiment 1, L15 = Löwenkamp et al. (2015), H11 = Heath et al. (2011) , G08 = Ganel et al. (2008).

2.3.2 Results and Discussion

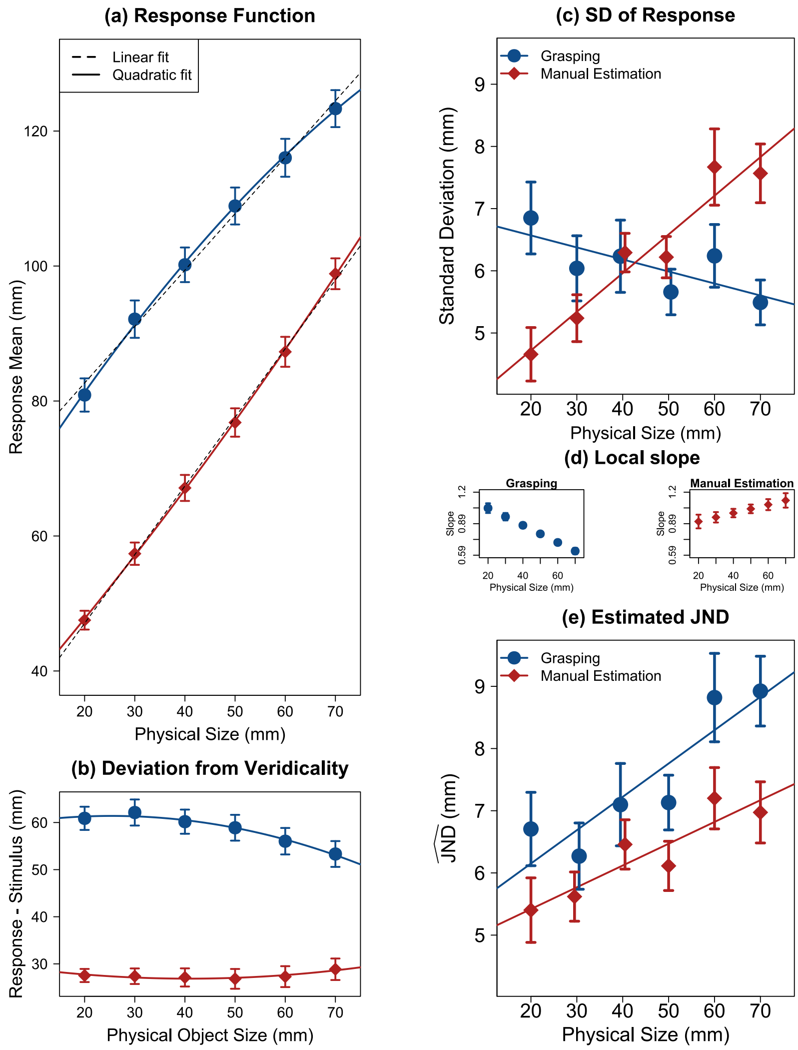
Results are summarized in Figure 10 and regression coefficients are given in Table 2. Figure 10a shows the response functions and Figure 10b deviations of the response from physical object size. The linear term b of the regression function for MGA was b_{MGA} = 0.84 ± 0.009 and for ME was b_{ME} = 1.02 ± 0.02. The quadratic term c was negative for MGA (c_{MGA} = -0.0042 ± 0.0003 mm^{-1}), and positive for ME (c_{ME} = 0.0021 ± 0.0004 mm^{-1}). As in Experiment 1, there was a concave relationship between MGA and object size (sign of c was negative). That is, the responsiveness of MGA decreases with increasing object size, whereas the responsiveness of ME changes much less.

SD_{MGA} did not scale significantly with object size (b = -0.019 ± 0.01, $t(14)$ = -1.88, p = .08, 95% CI [-0.041 0.003]; see Figure 10c, see also Section 2.6.2.5) but SD_{ME} increased significantly with object size (b = 0.062 ± 0.007, $t(14)$ = 8.56, $p < .001$, 95% CI [0.046 0.078]). Based on such a pattern of results, it would often be concluded that grasping violated Weber's law, while manual estimation followed Weber's law (Ganel et al., 2008). However, we again have to calculate $\widehat{JND}$ first, before we can assess Weber's law.

In grasping, $\widehat{JND}_{MGA}$ increased significantly with object size, resulting in a Weber constant of k_{MGA} = 0.054 ± 0.014, $t(14)$ = 3.91, p = .002, 95% CI [0.024 0.083] (Figure 10e). Similarly,

Figure 10

Results of Löwenkamp et al. (2015)



Note. Reanalysis of Löwenkamp et al. (2015). The sub-panels are identical to Figure 8.

in manual estimation, $\widehat{JND}_{ME}$ also increased significantly, with a Weber constant of k_{ME} = 0.035 ± 0.011, $t(14) = 3.26$, $p = .006$, 95% CI [0.012 0.058]. In short: Grasping and manual estimation show Weber constants which are perfectly in the range we expect for size perception (0.02-0.06, McKee & Welch, 1992; Teghtsoonian, 1971), see also Figure 9.

2.4 Reanalysis of Heath et al. (2011)

Next, we investigated whether the data obtained in our own laboratory can be corroborated by data from other laboratories. For that, we first reanalyzed the data published by Heath et al. (2011). This was the only study we reanalyzed where only aggregated data (means across participants) were available (we tried without success to obtain the full data, see also Wicherts et al., 2006). For the other studies (Experiment 1 Ganel et al., 2008; Löwenkamp et al., 2015) where we had full data, we made a comparison of our results with full vs. aggregate data and found only minor differences. Therefore, we expect also only small differences to a full-data analysis of Heath et al. (2011). Given that we do not have access to the full data, the results might be slightly different when the participant-by-participant data are analyzed, compared to those reported below with aggregated data. Because we are only able to roughly estimate the Weber's constant without having the full data, we do not show significance tests but only mean estimates with SEM and 95% confidence intervals.

2.4.1 Method

Five objects (20, 30, 40, 50, 60 mm) were presented to sixteen participants 20 times for grasping and to eleven participants 20 times for manual estimation. Manual estimation was performed under full-vision conditions. For grasping, we used the closed-loop mean values given in Table 1 of Heath et al. (2011). Since the data had already been averaged over participants, our reanalysis was carried out at the level of the aggregated data. For further details on the experimental procedure, see the original publication.

2.4.2 Results and Discussion

Results are summarized in Figure 11 and regression coefficients are given in Table 3. Figure 11a shows the response functions and Figure 11b shows difference of the response from physical object size. The linear term *b* for MGA was b_{MGA} = 0.76 and ME was b_{ME} = 0.88. The sign of the quadratic term *c* was negative for MGA (c_{MGA} = -0.0038 mm^{-1}) and positive for ME c_{ME} = 0.0044 mm^{-1}).

SD_{MGA} (*b* = 0.001 ± 0.004, 95% CI [-0.012 0.014]) did not change with object size (Figure 11c), while SD_{ME} increased with object size (*b* = 0.062 ± 0.003, 95% CI [0.052 0.072]), confirming the typically obtained result in such studies. Based on this pattern of results, it would often be concluded that manual estimation follows Weber's law, while grasping does not (Ganel et al., 2008; Heath et al., 2011). But again, this conclusion would be premature. We first have to calculate $\widehat{JND}$ before we can assess Weber's law.

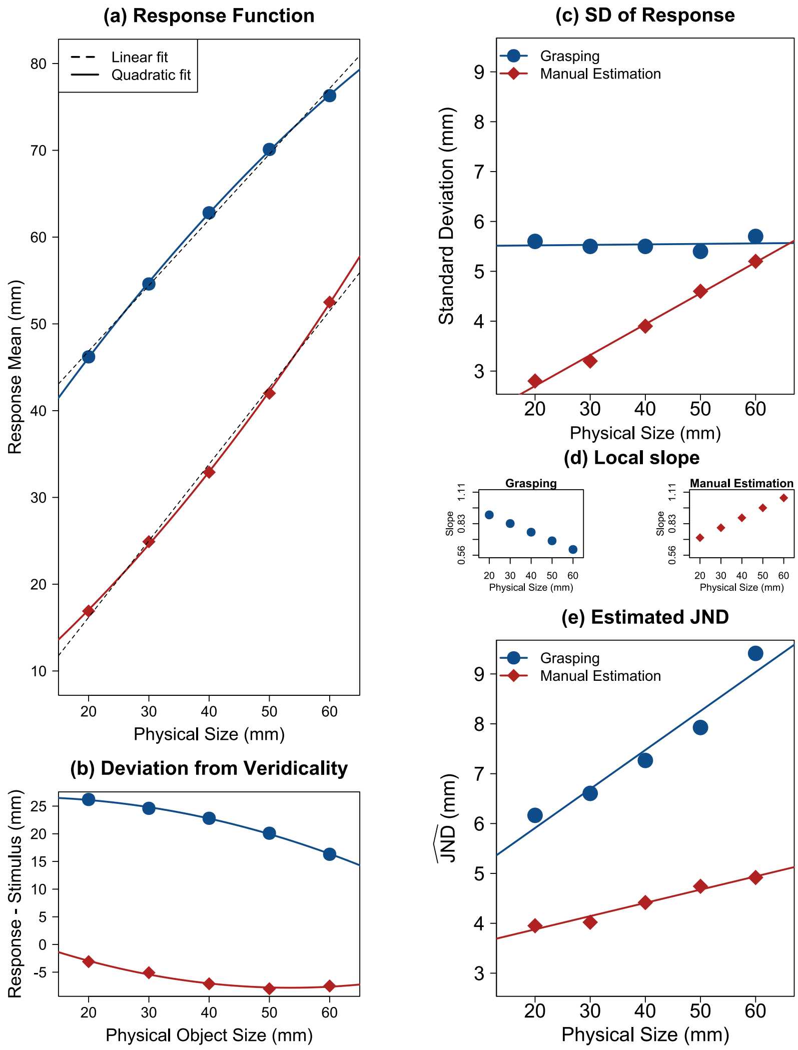
In grasping, $\widehat{JND}_{MGA}$ increased with object size, resulting in a Weber constant of k_{MGA} = 0.078 ± 0.011, 95% CI [0.043 0.113]. In manual estimation, $\widehat{JND}_{ME}$ also increased with object size, resulting in a Weber constant of k_{ME} = 0.027 ± 0.003, 95% CI [0.017 0.036] (Figure 11e). These values again fit nicely to the expected range from the literature for size perception (0.02-0.06, McKee & Welch, 1992; Teghtsoonian, 1971), see also Figure 9. In short, even for data from another laboratory (Heath et al., 2011), we find indications that grasping follows Weber's law if an appropriate proxy for JND is used. This raises the question whether that is also true for the first, most influential landmark study on this topic (Ganel et al., 2008).

2.5 Reanalysis of Ganel et al. (2008)

Finally, we applied our method to the data from the pioneering study on this subject (Ganel et al., 2008), that was the first to claim that grasping does not follow Weber's law.

Figure 11

Results of Heath et al. (2011)



Note. Reanalysis of Heath et al. (2011). The sub-panels are identical to Figure 8. Error bars absent because individual participant data was not available.

2.5.1 Method

Six objects (20, 30, 40, 50, 60 and 70 mm) were presented 20 times to participants in grasping (n = 13), manual estimation (n = 11), and perceptual adjustment (i.e., adjustment of a comparison line on a monitor, n = 6, we will refer to the response as ADJ). All tasks were performed in full-vision conditions. We obtained the data at the participant level from the authors. For further details on the experimental procedure, see the original publication.

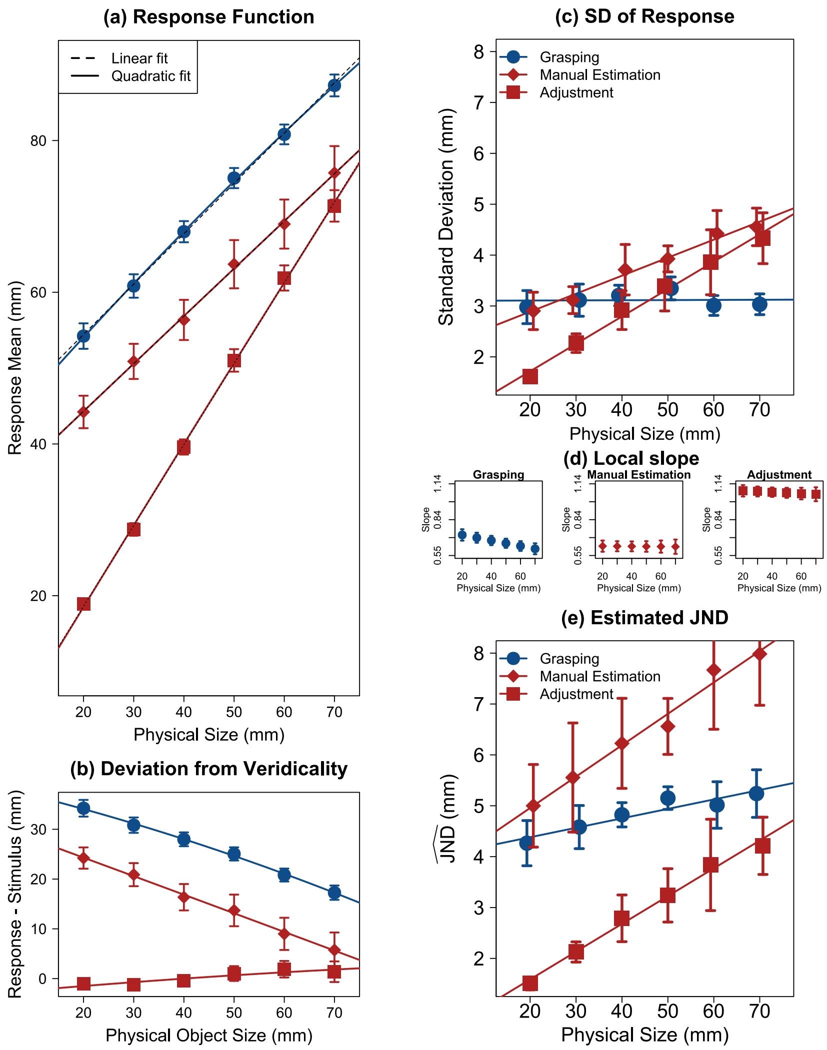
2.5.2 Results and Discussion

Results are summarized in Figure 12 and regression coefficients are given in Table 4. Figure 12a shows the response functions and Figure 12b shows the difference between response and physical object size. The linear term *b* of the regression function for MGA was b_{MGA} = 0.66 ±

0.015, for ME was b_{ME} = 0.63 ± 0.16, and for ADJ was b_{ADJ} = 1.07 ± 0.02. The quadratic term c for MGA was c_{MGA} = -0.0011 ± 0.0002 mm^{-1}), for ME was c_{ME} = -0.00001 ± 0.0003 mm^{-1} and ADJ was c_{ADJ} = -0.0003 ± 0.0003 mm^{-1} (see also Table 4). It is interesting to note that the value of c for ME and ADJ is very close to zero, because the response function is almost perfectly linear (we will further discuss this in Section 2.6.1.2 below).

Figure 12

Results of Ganel et al. (2008)



Note. Reanalysis of Ganel et al. (2008). The sub-panels are identical to Figure 8, with the exception that Ganel et al. (2008) also had a perceptual adjustment task (red squares).

The SD_{MGA} (linear term b = 0.0003 ± 0.004, $t(12)$ = 0.078, p = .939, 95% CI [-0.008 0.009]) did not scale with object size, while SD_{ME} (b= 0.035 ± 0.005, $t(10)$ = 7.23, $p < .001$, 95% CI [0.025 0.046]) and SD_{ADJ} (b = 0.054 ± 0.01, $t(5)$ = 5.46, p = .003, 95% CI [0.029 0.079]) scaled with object size (Figure 12c). This was interpreted as an absence of Weber's law in grasping by Ganel et al. (2008). However, as we have shown, conclusions about Weber's law should only be made after calculating the $\widehat{JND}$.

The $\widehat{JND}_{MGA}$, $\widehat{JND}_{ME}$ and the $\widehat{JND}_{ADJ}$ all increased linearly with object size (Figure

12e). The values of the Weber constant *k* for MGA (k_{MGA} = 0.019 ± 0.009, *t*(12) = 2.01, p = .068, 95% CI [-0.002 0.039]), ME (k_{ME} = 0.062 ± 0.010, *t*(10) = 6.05, $p < .001$, 95% CI [0.039 0.084]), and ADJ (k_{ADJ} = 0.055 ± 0.013, *t*(5) = 4.07, p = .010, 95% CI [0.020 0.089]) were again consistent with the expected values from the literature on size perception (0.02-0.06;see also Figure 9, McKee & Welch, 1992; Teghtsoonian, 1971). The Weber's constant in grasping did not reach significance, however the value was in the expected range. Also, the 95% confidence interval overlaps with the expected range of *k*. Further, in the three other studies we analyzed, the Weber's constant in grasping was highly significant. Ganel et al. (2008) had only thirteen participants which may have been too few leading to low power. Overall and based on the results from all studies, we conclude that there is evidence for grasping following Weber's law.

2.6 General Discussion

Research on Weber's law in grasping has typically used the response variability (SD_{MGA}) as a proxy to JND—starting with Ganel et al. (2008). We showed that this were only acceptable if the response function were linear. If, however, the response function is non-linear—as is the case in grasping—then we first have to transform the response variability back to the corresponding stimulus variability (Figure 6). That is, we have to transform the hitherto used SD_{MGA} to corresponding $\widehat{JND}s$ (Section 2.8.1 in the Appendix). Only then does it make sense to assess Weber's law.

Using this toolkit, we first analyzed our own data of Experiment 1 and showed that we were able to replicate the results for grasping: SD_{MGA} does not increase with object size. Traditionally, this result would have been interpreted as a violation of Weber's law (Ganel et al., 2008). However, the response function of MGA in grasping is non-linear: It is concave, such that responsiveness decreases for larger object sizes (one reason could be because the finger span is limited and grasping needs to trade-off a safety margin with the ability to still enclose the target object, see Section 2.6.2.4). Therefore, it is not appropriate to use SD_{MGA} as a proxy to JND. Instead, we need to transform SD_{MGA} back to the corresponding variability at the stimulus level. When we do this and calculate $\widehat{JND}_{MGA}$, then we find that $\widehat{JND}_{MGA}$ does increase with object size. The corresponding Weber constant *k* (i.e., the slope of the linear function relating $\widehat{JND}_{MGA}$ to object size) is perfectly in the range we would expect from the literature for size perception (Figure 9).

Next, we used the same toolkit to reanalyze the data of three already published studies which tested Weber's law for grasping; including the landmark study by Ganel et al. (2008). In all cases, we find similar results for grasping: (a) SD_{MGA} does not increase with object size, (b) The response function of MGA in grasping is non-linear, (c) $\widehat{JND}_{MGA}$ seems to increase with object size and the corresponding Weber constant is well in the expected range (Figure 9). We conclude that there is evidence for Weber's law in grasping.

Tasks other than grasping have been employed, most notably manual estimation. We calculated $\widehat{JND}_{ME}$, as described above for grasping, and the corresponding Weber constants, and found them again to be in the expected range and similar to the Weber constants for grasping (Figure 9). We conclude that there seems to be no dissociation between grasping, manual estimation, and other measures regarding Weber's law.

What are the consequences for theorizing? First of all, there is a coherent picture of this psychophysical law again: Researchers can trust that Weber's law, the first and most widely tested psychophysical principle (Baird & Noma, 1978; Ganel et al., 2008), is almost universally correct (Teghtsoonian, 1971). Second, there is a chance that the wide and contradictory literature that was inspired by the claim of a violation of Weber's law in grasping (Ayala et al., 2018; Christiansen et al., 2014; Freud et al., 2019; Ganel et al., 2008; Hadad et al., 2012; Heath & Manzone, 2017; Heath et al., 2011, 2012; Heath et al., 2017; Holmes & Heath, 2013; Holmes et al., 2011; Hosang et al., 2016; Jazi & Heath, 2017; Löwenkamp et al., 2015; Namdar et al., 2018; Ozana & Ganel, 2017, 2018; Ozana et al., 2018; Utz et al., 2015) might be rectified to a coherent view again. In the following, we will first discuss details of our approach and then specific consequences for theorizing about information processing in the brain.

2.6.1 Further Details Related to Weber's Law in Grasping and Manual Estimation

There are some more technical issues related to our arguments and approach that we want to address.

2.6.1.1 What Happens When IQR is Used as Proxy to JND?

Some studies on Weber's law in grasping (Bruno et al., 2016; Utz et al., 2015) used the interquartile range ($IQR_{Response}$) or similar measures of dispersion to assess Weber's law, instead of the most often used within-subject standard deviation ($SD_{Response}$). The main motivation was the well-established fact that these measures are more robust against extreme values and outliers than the $SD_{Response}$. However, our arguments apply equally to these alternative measures because they still quantify the variability at the level of the response, not the stimulus. Due to the non-linear response function in grasping, it is therefore still possible for the $SD_{Response}$ to not scale with object size, while the corresponding $\widehat{JND}$ does (the arguments are analogous to those we present for $SD_{Response}$ in Figure 6). Therefore, even when $IQR_{Response}$ is used, it should be divided by the local slope at every object size to obtain the corresponding $\widehat{JND}$. In the present study, we focused on $SD_{Response}$ because this is the measure that was used by studies inferring a strong violation of Weber's law in grasping. Studies based on $IQR_{Response}$ or other alternative measures typically favored the biomechanical constraints approach which is consistent with our main conclusions and which we will discuss below in Section 2.6.2.4.

2.6.1.2 Studies on Other Topics Also Used SD as a Proxy to JND. Are They All Wrong?

Weber's law has been demonstrated in almost every sensory domain (Teghtsoonian, 1971). Some studies that reported Weber's law in domains other than grasping also used $SD_{Response}$ for this assessment (for a list, see Ganel et al., 2014). The question now arises whether all those studies need to be re-analyzed by calculating the $\widehat{JND}s$ instead. This would require to divide at each stimulus magnitude the $SD_{Response}$ by the local slope of the response function (i.e., the function relating stimulus magnitude to response).

Fortunately, such a major undertaking does not seem necessary: In most cases, the response function will be linear, such that the local slope is constant for each stimulus magnitude. That is, the $SD_{Response}$ would at each stimulus magnitude be divided by the same constant value, such that $\widehat{JND} = \frac{SD_{Response}}{constant}$. This constant scaling of $SD_{Response}$ will not change the assessment of whether the $\widehat{JND}s$ scale with object size, such that the answer to the question of whether the sensory domain adheres to Weber's law will not change. In many cases, the slopes will even be close to one, such that $SD_{Response} \approx \widehat{JND}$ so that both measures will even give the same numerical answer (e.g., the perceptual adjustment task of Ganel et al., 2008, see Figure 12d). However, in situations where the response function clearly deviates from linearity, as is the case for grasping, the $SD_{Response}$ is not appropriate for assessing Weber's law, and $\widehat{JND}_{Response}$ must be calculated.

2.6.1.3 Should the Function Relating JND to Object Size Have a Zero Intercept?

Researchers investigating Weber's law typically test for a linear relationship between stimulus magnitude and JND. That is, they allow for a non-zero intercept of the linear function relating stimulus magnitude to JND (e.g., Equation 4.1. of Baird & Noma, 1978; Galanter, 1962; Miller, 1947; von Helmholtz, 1924). This is often called the generalized Weber's law (Miller, 1947; Ono, 1967). This is also the approach we used and our results are nicely consistent with the literature (Figure 9). However, the strict version of Weber's law predicts a proportional relationship between stimulus magnitude and JND. That is, a linear function with a zero-intercept (e.g., Equation 3.1. of Baird & Noma, 1978). Therefore, the question arises whether it would be better to use this strict version of Weber's law on the current data.

We will discuss this issue in two strands: First, we will argue that the large psychophysical literature on Weber's law in different sensory domains is often based on the generalized version of Weber's law, such that for comparison with this literature, we need to use the generalized version. Second, we will show that Weber's law holds for the current data even if we assumed a strict version of Weber's law with zero-intercept. In fact, the estimated Weber constants would even increase when using such a strict version of Weber's law. That is, we are being conservative with respect to our main result that grasping follows Weber's law, when we use the generalized Weber's law.

So, let us first describe that the psychophysical literature often uses the generalized version of Weber's law. For example, Teghtsoonian (1971) summarized studies on size perception in a seminal review and used the generalized Weber's law, thereby allowing for a non-zero intercept. Also, we know that other tasks and modalities show similar non-zero intercepts and that the strict version of Weber's law does not provide good fits (Baird & Noma, 1978; Galanter, 1962; Miller, 1947; von Helmholtz, 1924). Therefore, using the generalized version of Weber's law is not problematic for the claim that grasping or manual estimation are consistent with Weber's law. Specifically, if allowing for a non-zero intercept was considered to be an argument against Weber's law in grasping, then the same argument could also be used against Weber's law in manual estimation, because manual estimation also shows a non-zero intercept. Similarly, if the non-zero intercept were considered to be an argument against our method of calculating $\widehat{JND}$, then the same argument could be used against the traditional method that uses $SD_{Response}$ as a proxy for JND, because this method also finds non-zero intercepts for grasping and manual estimation (Ganel et al., 2008; Heath et al., 2011, see also Tables 1 - 4).

Second, let us describe the empirical results when using the strict version of Weber's law. This strict version comes in two variants: (a) In Section 2.8.5.1 in the Appendix, we show the results when fitting linear models with zero intercept. The obtained Weber constants (Table 6) are much larger than those obtained with the generalized version of Weber's law (Figure 9). (b) In Section 2.8.5.2 in the Appendix, we use an alternative analysis that was suggested by a reviewer and is based on Smeets and Brenner (2008). The Weber constants attained by this method are also larger (Table 7) than those attained with the generalized version of Weber's law (Figure 9). This shows that we are being conservative with respect to Weber's law in grasping when we use the generalized version of Weber's law. Any of the proposed strict versions of Weber's law would yield larger Weber constants. The fact that we used the most conservative analysis makes our finding of Weber's law in grasping even stronger.

2.6.1.4 *Technical Details Regarding Non-Linear Calculation of* $\widehat{JND}s$

To estimate the JND, the within-participants SD at each object size for each participant should be divided by the local slope (see panel d of Figures 8, 10-12) of the response function (for that participant) at that object size. Essentially, the $\widehat{JND}$ is a ratio with the measured slope in the denominator. If the measured slope for any participant is a small value close to zero, this can lead to inflated values (and variability) in the final $\widehat{JND}$. This problem of ratios is well-known from statistical calibration (Buonaccorsi, 2001) and there also exist methods to ameliorate this problem (Franz, 2007; von Luxburg & Franz, 2009). One reason why measured slopes may be close to zero is not having enough trials (ca. $<$ 20 trials per object size). Therefore, researchers applying this method to their own data and other data need to be careful that there were sufficient trials per object size. In Experiment 1, we used 50 trials per object size and we reanalyzed only those studies which had 20 or more trials per object size.

2.6.1.5 *Influences of Sensory or Motor Noise*

One might ask how motor noise influences the responses in grasping and manual estimation. Could it be that the variability generated during the movement overwrites the variability of some internal estimate that was used to generate those movements? We will argue that this question is interesting, but not so relevant for our investigation. This is so, because Weber's law describes a relationship between the physical stimulus magnitude and the JND, the physical change in the stimulus that is detectable by the participant. Therefore, everything is at the level of the physical stimulus, and discussion of internal estimates is not required or crucial for Weber's law. We merely found that grasping does indeed follow Weber's law. The question of internal estimates would be more urgent if we did not find Weber's law, but suspected that, for example, the variability of some internal estimate scaled nevertheless with object size (even when the JNDs did not). Here we simply establish that, contrary to previous research, grasping does follow Weber's law. Determining the contribution of sensory or motor noise to this Weberian scaling of JNDs in grasping is an undertaking for future research.

2.6.2 Consequences for Theories About Information Processing in the Brain

As mentioned above, the reports of an apparent violation of Weber's law generated a number of different explanations. Given that we found Weber's law to not be violated in grasping when the $\widehat{JNDs}$ are assessed, we will discuss the consequences of our findings for these explanations.

2.6.2.1 Perception-Action Model: Are There Two Parallel Visual Processing Streams?

Ganel et al. (2008) interpret the presumed violation of Weber's law in grasping as strong evidence for the perception-action model. This model assumes that there are fundamental and qualitative differences in the neural processing of size information for the purposes of action and perception (Goodale, 2008, 2011; Goodale & Milner, 1992; Milner & Goodale, 1995, 2008). According to the perception-action model, visual information used for perception (such as in perceptual estimations, but also certain "perceptual" actions as manual estimation), is processed in the ventral cortical pathway and is based on relative metrics. In contrast, visual information used in natural actions (such as in natural grasping), is assumed to be processed in the dorsal cortical pathway and based on absolute metrics. The apparent violation of Weber's law in grasping was seen as one line of evidence for such a strict division of labor in the brain (Ganel & Goodale, 2014; Ganel et al., 2008). However, the results of the present study suggest that grasping does follow Weber's law. Accordingly, there is no need to postulate differences in the visual encoding of size information between grasping and manual estimation, as suggested by Ganel et al. (2008). This calls into question another line of evidence that has been put forward in support of the perception-action model, as have been other lines of evidence (e.g., Brenner & Smeets, 1996; de la Malla et al., 2019; Franz & Gegenfurtner, 2008; Franz et al., 2000; Hesse & Schenk, 2014; Kopiske et al., 2016; Medendorp et al., 2018; Schenk, 2006; Smeets & Brenner, 1995; Smeets et al., 2020)

2.6.2.2 Double-Pointing Hypothesis: Is Grasping Guided by Position and Not Size?

An alternative explanation for the presumed absence of Weber's law in grasping has been proposed by Smeets and Brenner (2008). They argued that grasping does not follow Weber's law because grasping uses position information about the contact points of the fingers on the object instead of size information (Smeets & Brenner, 1999; Smeets et al., 2020; Smeets & Brenner, 2019). That is, the fingers are moved individually to the contact points on the object, such that object size is not used. Consequently, researchers cannot expect Weber's law in grasping when object size is manipulated. However, given that we do find Weber's law in grasping, this alternative explanation for an apparent absence of Weber's law is no longer relevant.

We should stress, however, that this state of affairs does not need to be an argument against the double-pointing hypothesis itself. This is so, because the presence or absence of Weber's law is not necessarily considered to be a strong test case for the double-pointing hypothesis. Notwithstanding that, there is one question that arises from the current results and that might be interesting for future research on grasping and the double-pointing hypothesis: Smeets and Brenner (1999) showed that the double-pointing hypothesis predicts a small, positive quadratic term for the relationship between MGA and object size. That is, the responsiveness in grasping should increase with object size. However, we found that the quadratic terms in grasping were slightly negative. This apparent contradiction should be investigated in future research - as well as the more general question of whether grasping is guided by position information, size information, or a mixture of both. For examples of such research, see Schot et al. (2017) on prism adaptation, or Smeets et al. (2020) on certain visual illusions.

2.6.2.3 Boundary Conditions: When is Weber's Law Violated in Grasping?

A number of studies assessed the boundary conditions for a presumed violation of Weber's law in grasping. Typically, the idea was to learn something about the mechanisms that cause the presumed violation of Weber's law. These studies investigated, for example, whether grasping adhered to Weber's law when the object is shown only in 2D (Hosang et al., 2016), when the object is distorted by certain visual illusions which selectively distort the size of the object but not the positions of the grasp points on the object (Smeets et al., 2020), in pantomimed grasping (Jazi & Heath, 2016, 2017; Jazi et al., 2015), when grasping 3D objects underneath a glass surface (Ozana & Ganel, 2017), or when grasping with both hands in a virtual environment (Ozana et al., 2020). Some studies (Holmes et al., 2011) also looked at the time course and development of Weber's law over the entire grasping trajectory (but see Foster & Franz, 2013). However, all these studies relied on SD_{MGA} as a proxy to JND. Therefore, it is difficult to judge the results. For a full assessment, we would need to transfer SD_{MGA} to $\widehat{JND}$ first. This is all the more important as it is plausible that those manipulations not only change the variability of the response, but also the response function – in one or the other way (larger or smaller safety margin, depending on the specific manipulation). For example, it is well known that the safety margin of MGA is smaller in 2D and pantomimed grasping, conditions where no object is physically grasped. Weber's law should then be assessed by calculating the $\widehat{JND}s$.

2.6.2.4 Biomechanical Constraints and Ceiling Effects in the Motor Response

Biomechanical constraints (e.g., the limited finger span) have been proposed as another alternative explanation for the presumed violation of Weber's law in grasping (Löwenkamp et al., 2015; Utz et al., 2015). These studies also investigated the response function in detail and found that for larger object sizes the response function is bent (consistent with what we found in the present study). They argued that for large objects the fingers simply cannot open wider and that this will automatically restrict the variability of grasping. Therefore, so they argue, it is plausible that Weber's law is masked by these biomechanical constraints in grasping and that there is no need to postulate a violation of Weber's law based on the fact that SD_{MGA} does not increase with object size.

Those studies and their interpretation corroborate our current findings: They also find the response function to be bent and they provide a plausible mechanism for why SD_{MGA} does not increase with object size. The difference to the present study is that we now have a toolkit that allows to quantitatively assess whether Weber's law does or does not hold, independent of the exact mechanisms that cause the response function to be bent. It is important to note here, that our results do not rest upon biomechanical constraints being the reason for non-linearity in the grasping response function – it is just one plausible mechanism that has been discussed by others in the literature.

Interestingly, we found some evidence of such effects in Experiment 1 - the skewness of the response distributions scaled negatively with object size (i.e., the frequency of relatively large responses decreased with object size) in grasping (b_{skew} = -0.0085 ± 0.003, 95% CI [-0.015 -0.002]), but not in manual estimation (b_{skew} = -0.0037 ± 0.004, 95% CI [-0.012 0.005]). Note, that we found this result even within a range of medium objects (i.e., 20-50 mm in Experiment 1, see also Löwenkamp et al., 2015), which have been termed "functionally graspable" and for which it was sometimes assumed that the influence of biomechanical constraints can be excluded (Ayala et al., 2018; Heath et al., 2017). Nevertheless, it seems plausible that optimization processes in the generation of the MGA, such as the generation of comfortable or efficient grip apertures, may cause these effects even at small, graspable object sizes. A recent study (Uccelli et al., 2021) assessed Weber's law in small-to-medium object sizes (5 – 40 mm), and reported that the skewness of the MGA increases with object size up to 40 mm. In a previous study by the same group (Bruno et al., 2016), where stimuli larger than 40 mm were used as well, small effects for a negative scaling of skewness at objects larger than 40 mm were found. We agree with those authors' conclusion that a study investigating the skewness of the MGA in the full range of object sizes up to the limit of the handspan, would be useful to make definite claims (Uccelli et al., 2021). It is possible that the skewness follows an inverse-U shaped function of object size.

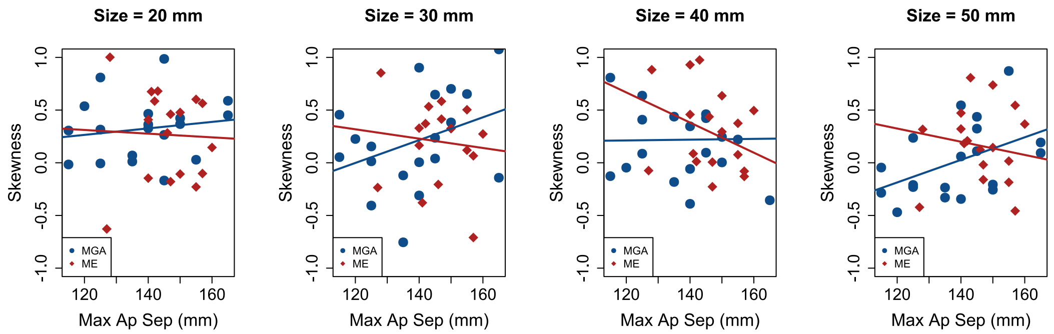
Additionally, biomechanical constraints will not affect all participants equally, but rather depend on the hand size and maximum opening in relation to the target object size. To investigate this, we analyzed the skewness at every object size as a function of the participants' hand size (maximum aperture separation, MAS; see Figure 13). For our largest object size (50 mm), we found that participants' skewness increased with hand size in grasping (b_{skew} = 0.011 ± 0.005, 95% CI [0.000 0.021] – we had MAS values for 19 out of 20 participants in grasping). This scaling of skewness with hand size is negligible at our smallest object size (20 mm).

2.6.2.5 Apparent Inversion of Weber's Law: A Puzzle for Certain Theories

Several studies (Bruno et al., 2016; Löwenkamp et al., 2015; Utz et al., 2015) reported a puzzling result of decreasing variability in the MGA with object size, or an apparent inversion of Weber's law in grasping. This result was especially confusing, because none of the theories proposed to explain the absence of Weber's law in grasping (Perception-Action Model or Double-pointing hypothesis, see Sections 2.6.2.1 and 2.6.2.2), could accommodate this finding. Utz et al. (2015) reasoned that biomechanical constraints (see Section 2.6.2.4) on the finger aperture could cause ceiling effects in grasping large objects. These constraints combined with a non-linear grasping response function, can readily explain this strange result of apparently inverted Weber's law. When grasping a large object, the finger aperture will be larger than the to-be-grasped object (including the safety margin) and this is capped by the maximum possible opening of the hand. As object sizes increase after the point where object size + safety

Figure 13

Skewness as a Function of Hand Size



Note. The skewness in the response of every participant at every object size is plotted as a function of the hand size or the maximum aperture separation (MAS) of that participant. Also depicted are the regression lines for skewness as a function of MAS.

margin is close to the maximum possible hand opening, the safety margin will decrease in compensation, therefore leading to decreasing variability in the response. When we reanalyzed Löwenkamp et al. (2015), the apparent inversion of Weber's law disappeared and the $\widehat{JND}$ scaled positively with object size, as expected by Weber's law, and notably, with values of Weber's constant k (slope) consistent with the literature (Figure 9). Therefore, our approach can readily explain these inconsistencies in the large literature on Weber's law in grasping.

2.7 Conclusions

Weber's law is one of the most fundamental psychophysical principles. It relates JND to stimulus magnitude and therefore makes a statement at the level of the physical stimuli. Studies reporting a violation of Weber's law for grasping used SD_{MGA} as proxy to JND and therefore forsook the stimulus level. We showed that this is problematic when the response function is non-linear (as in grasping) and that instead $\widehat{JND}$ needs to be calculated, which brings us back to the stimulus level. If we do this, then grasping follows Weber's law: In our own data as well as in previous studies that claimed a violation of Weber's law for grasping. Our method is general and can also be used in other tasks and sensory domains, whenever a direct assessment of JND is not possible.

2.8 Appendix to Section 2

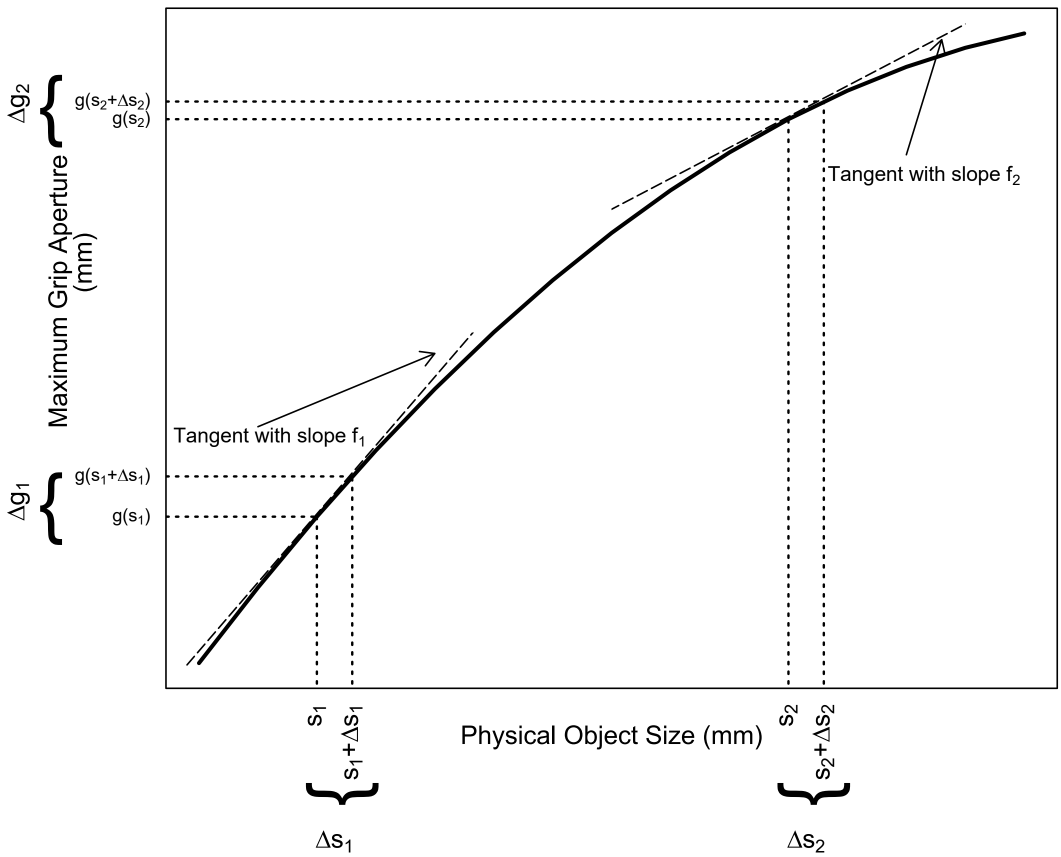
2.8.1 How to Determine $\widehat{JND}$ from SD_{MGA}

In the main text, we have argued that SD_{MGA} is not an appropriate proxy for the corresponding JND and that we have to use $\widehat{JND}$ instead. Here, we describe how to calculate $\widehat{JND}$. For ease of exposition, we will derive our formulae for the special case of grasping, albeit all formulae can directly be generalized to other responses (as, for example, manual estimation, size adjustment, etc.).

Our scenario is shown in Figure 14 (which is similar to Figure 6 of the main text, but contains more technical details). A participant is presented with objects of different sizes s. When the participant grasps those objects, their sizes are transferred to MGAs by the response function $g(s)$. For simplicity of exposition, we focus on the stimulus with physical size s_1.

Figure 14

Concave ("bent") Grasping Response Function $g(s)$



Forward direction: Here, we are interested in the effect an increase of object size by a small amount has on grasping (this small amount could, for example, be one JND). For this, assume the participant grasped first an object of size s_1, resulting in an MGA of $g(s_1)$. We now increased the size of the object by a small amount (which we denote as Δs_1), such that the second object had the size $s_1 + \Delta s_1$, resulting in an MGA of $g(s_1 + \Delta s_1)$. The effect of increasing the size of the object by Δs_1 on MGA in grasping is then

$$\Delta g_1 \quad = \quad g(s_1 + \Delta s_1) - g(s_1). \tag{1}$$

Now, we want to find a simple expression for this effect. We perform a first-order Taylor-series approximation

$$g(s_1 + \Delta s_1) \quad = \quad g(s_1) + \left.\frac{dg}{ds}\right|_{s_1} \Delta s_1 + \text{higher order terms} \tag{2}$$

$$\approx \quad g(s_1) + \left.\frac{dg}{ds}\right|_{s_1} \Delta s_1, \tag{3}$$

and combine this approximation with equation 1

$$\Delta g_1 \quad \approx \quad g(s_1) + \left.\frac{dg}{ds}\right|_{s_1} \Delta s_1 - g(s_1) = \left.\frac{dg}{ds}\right|_{s_1} \Delta s_1. \tag{4}$$

For simplicity, we rename $\left.\frac{dg}{ds}\right|_{s_1}$ (which is the slope of the tangent to $g(s)$ at the position s_1) as $f_1 := \left.\frac{dg}{ds}\right|_{s_1}$; such that we obtain

$$\Delta g_1 \quad \approx \quad f_1 \, \Delta s_1. \tag{5}$$

This is the main result for the forward direction: When we increase object size by a small amount Δs_1, then MGA is increased by this amount times the slope f_1 (the first derivative) of the response function $g(s)$ that relates object size to MGA.

Some comments might be helpful here: (a) By a small amount we, of course, mean an increase of object size for which the local linear approximation of the Taylor series is satisfactory. Given that we are interested in $JNDs$ and that the response functions show only relatively small non-linearities, this is a reasonable approximation. (b) Because equation 5 holds for any small size change, we can directly infer that this will also hold for the $JNDs$ as well as for related SDs, such that

$$SD_{MGA_1} \quad \approx \quad f_1 \, \widehat{JND}_1. \tag{6}$$

Backward direction: Now we are interested in the inverse problem: We observe some small change in the MGA of grasping Δg_1 and want to know to which change in object size Δs_1 this corresponds. Given our local linear approximation, this is now easy to do. We only need to invert equation 5, such that we obtain

$$\Delta s_1 \quad \approx \quad \frac{\Delta g_1}{f_1}. \tag{7}$$

Because the factor f_1 in this equation is constant for any small size change, we can directly infer which $\widehat{JND}$ corresponds to a SD_{MGA}

$$\widehat{JND}_1 \quad \approx \quad \frac{SD_{MGA_1}}{f_1}. \tag{8}$$

This is the main result for the backward direction: When we measured the standard deviation of grasping SD_{MGA} and want to know to which standard deviation this corresponds at the level of physical object size, we just need to divide SD_{MGA} by the slope f_1 (the first derivative) of the response function $g(s)$ that relates object size to MGA.

Application to our data-sets: The above derivations are valid for quite arbitrary non-linear relationships and are therefore very general (only limited by the applicability of the Taylor series approximation). In the practical application to the data we were concerned with, the non-linear relationship was even simpler, because it was dominated by the linear and quadratic terms. This allowed us to simplify the relationships even further by fitting quadratic functions to the data

$$g(s) = a + b\,s + c\,s^2. \tag{9}$$

(where we used a standard least-squares approach for fitting). Of course, all the above derived relationships are also valid in this simpler case. One advantage of the quadratic fit is that we can derive an analytic expression for the scale factor, such that

$$f_1 = \left.\frac{dg}{ds}\right|_{s_1} = b + 2\,c\,s_1. \tag{10}$$

This gives us for the calculation of the proxy to JND for a stimulus of size s_1

$$\widehat{JND}_1 \approx \frac{SD_{MGA_1}}{f_1} = \frac{SD_{MGA_1}}{b + 2\,c\,s_1}. \tag{11}$$

The residuals of the linear and quadratic fits are shown in Figure 15; numerical values of all fitted coefficients are given in Tables 1 - 4.

Assessment of Weber's law: After determining $\widehat{JND}$ for each stimulus size, we were able to assess Weber's law. That is, we tested whether $\widehat{JND}$ depends on stimulus size. For this, we fitted linear functions

$$\widehat{JND}(s) = a + k\,s \tag{12}$$

(where we again used a standard least-squares approach for fitting). The crucial parameter here is k which indicates to which degree $\widehat{JND}$ increases with object size, as predicted by Weber's law. This parameter is traditionally called the Weber constant or Weber fraction. Numerical values for all these fitted coefficients are also given in Tables 1 - 4.

2.8.2 Residuals of Linear and Quadratic Fit

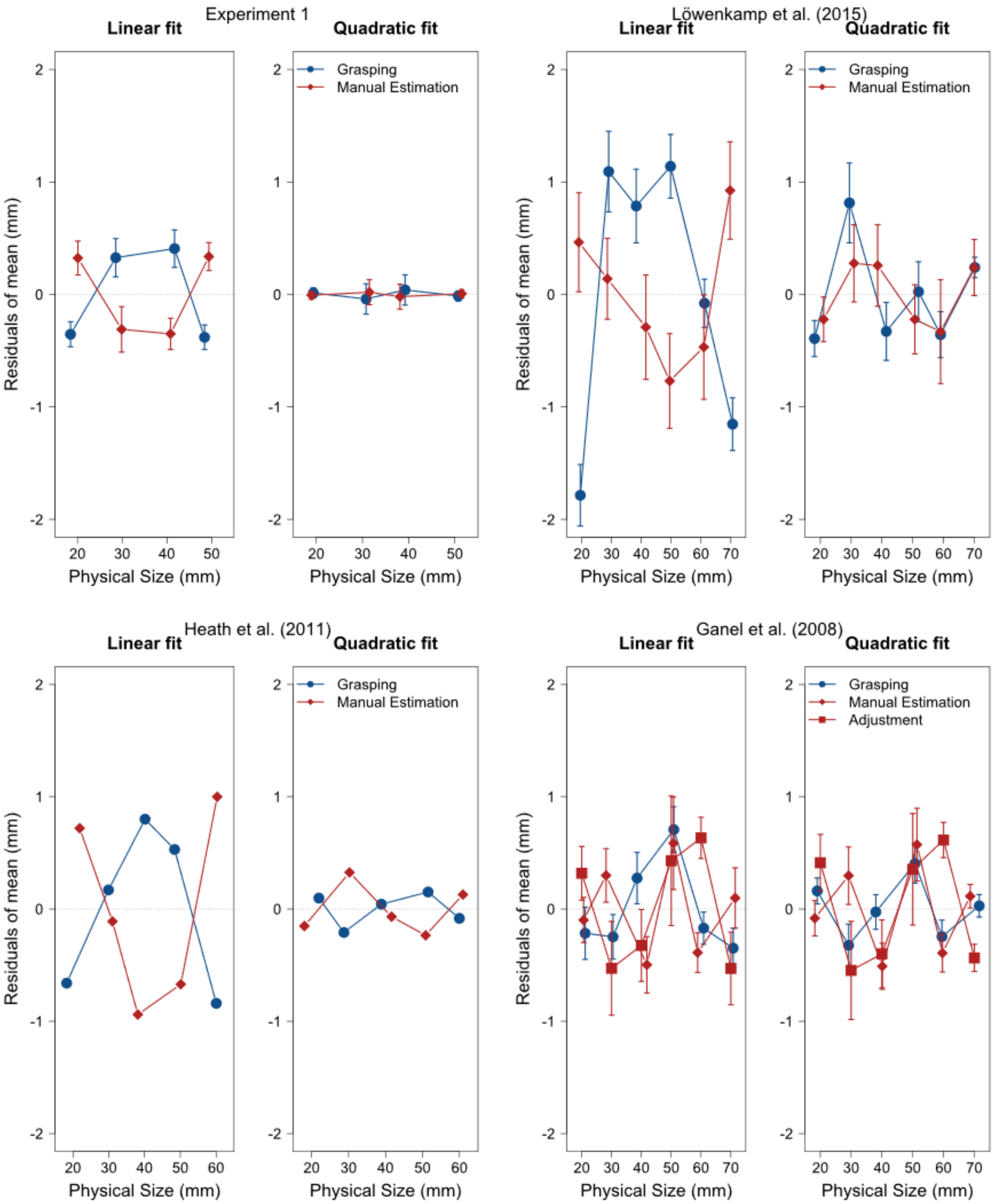
The concavity of the grasping response function can also be seen in the characteristic inverse-U-shape in the residuals of the linear fit of the grasping response (MGA) to the object size depicted in Figure 15. This is present not only in Experiment 1, but in all of the other three studies we reanalysed. On the other hand, manual estimation shows a slight convexity (U-shape of the residuals).

2.8.3 Coefficients for Linear and Quadratic Regressions

We list the numerical values for the coefficients of linear and quadratic regressions of the response to object size, and the linear regressions of $SD_{Response}$ to object size and $\widehat{JND}_{Response}$ to object size in the Tables 1 – 4.

Figure 15

Residuals of Linear and Quadratic Regression



Note. Residuals of the mean in the linear and quadratic regression functions for each dataset. The error bars depict ±1 RSE, where full participant data were available. RSE = residual standard errors.

Table 1

Coefficients for Experiment 1

Coefficient	intercept *a* [mm]	linear *b*	quadratic *c* [mm^{-1}]
MGA	76.8 ± 0.56	1.04 ± 0.013	-0.004 ± 0.001
SD_{MGA}	5.25 ± 0.50	0.002 ± 0.010	
$\widehat{JND}_{MGA}$	3.79 ± 0.47	0.040 ± 0.013	
ME	59.7 ± 1.17	1.05 ± 0.021	0.003 ± 0.001
SD_{ME}	3.12 ± 0.35	0.056 ± 0.008	
$\widehat{JND}_{ME}$	4.24 ± 0.54	0.023 ± 0.014	

Note. Coefficients (mean ± SEM) of linear and quadratic regressions for maximum grip aperture (MGA) and manual estimation (ME) for Experiment 1: Coefficients of quadratic regression relating object size to response (*a* and *b* of linear and quadratic regression are identical because object size was centered). SD: Coefficient of linear regression relating object size to $SD_{Response}$. $\widehat{JND}$: Coefficient of linear regression relating object size to $\widehat{JND}$. For details see Section 2.8.1 in the Appendix.

Table 2

Coefficients for Löwenkamp et al. (2015)

Coefficient	intercept [mm]	linear	quadratic [mm^{-1}]
MGA	104.8 ± 1.08	0.84 ± 0.009	-0.004 ± 0.0003
SD_{MGA}	6.96 ± 0.71	-0.019 ± 0.010	
$\widehat{JND}_{MGA}$	5.08 ± 0.75	0.054 ± 0.014	
ME	71.9 ± 0.78	1.02 ± 0.020	0.002 ± 0.0004
SD_{ME}	3.48 ± 0.40	0.062 ± 0.007	
$\widehat{JND}_{ME}$	4.72 ± 0.58	0.035 ± 0.011	

Note. Coefficients of linear and quadratic regressions for Löwenkamp et al. (2015). See Table 1 for description of abbreviations.

2.8.4 Number of Participants and Trials for Each Task in Each Dataset

Table 5 lists the sample size and number of trials per object size in the four data sets we analysed in the main text. The sample size of our Experiment 1 was greater than the sample size used in typical studies on Weber's law. Furthermore, as mentioned in Section 2.6.1.4, our method of calculating $\widehat{JND}$ might give overestimates of the JNDs if the data is based on fewer than 20 trials per objects size. To increase precision, we used 50 trials per object size in our Experiment 1.

Table 3

Coefficients for Heath et al. (2011)

Coefficient	intercept [mm]	linear	quadratic [mm^{-1}]
MGA	62.8	0.76	-0.004
SD_{MGA}	5.5 ± 0.18	0.001 ± 0.004	
$\widehat{JND}_{MGA}$	4.35 ± 0.47	0.078 ± 0.011	
ME	33.0	0.88	0.0044
SD_{ME}	1.46 ± 0.13	0.062 ± 0.003	
$\widehat{JND}_{ME}$	3.35 ± 0.12	0.027 ± 0.003	

Note. Coefficients of linear and quadratic regressions for Heath et al. (2011). See Table 1 for description of abbreviations.

Table 4

Coefficients for Ganel et al. (2008)

Coefficient	intercept [mm]	linear	quadratic [mm^{-1}]
MGA	71.4 ± 0.53	0.66 ± 0.015	-0.0011 ± 0.0002
SD_{MGA}	3.1 ± 0.34	0.0003 ± 0.004	
$\widehat{JND}_{MGA}$	4.01 ± 0.48	0.019 ± 0.009	
ME	60.0 ± 1.12	0.63 ± 0.16	-0.00005 ± 0.0003
SD_{ME}	2.18 ± 0.35	0.035 ± 0.005	
$\widehat{JND}_{ME}$	3.72 ± 0.83	0.062 ± 0.010	
ADJ	45.3 ± 0.42	1.07 ± 0.02	-0.0003 ± 0.0003
SD_{ADJ}	0.64 ± 0.23	0.054 ± 0.01	
$\widehat{JND}_{ADJ}$	0.50 ± 0.29	0.055 ± 0.013	

Note. Coefficients of linear and quadratic regressions for maximum grip aperture (MGA), manual estimation (ME) and adjusted size (ADJ) for Ganel et al. (2008). See Table 1 for description of abbreviations.

2.8.5 Fitting Strict Versions of Weber's Law

2.8.5.1 Linear Fit With Zero Intercept

As described in Section 2.6.1.3, the question might arise whether it would be better to fit Weber's law with a strictly zero-intercept, such that

$$\widehat{JND}(s) = k\,s \tag{13}$$

(Compare to Equation 12 to see the difference to the standard method based on the generalized version of Weber's law). Although this zero-intercept method would be unusual (Galanter, 1962; Miller, 1947), we implemented it for the current data (Table 6).

Inspection shows that the corresponding Weber constants are much larger than those ob-

Table 5

Participants and Trials in Each Task in Each Dataset

Task		Exp 1	L15	H11	G08
Grasping	Participants	20	15	16	13
	Trials	50	20	20	20
Manual Estimation	Participants	20	15	11	11
	Trials	50	20	20	20
Adjustment	Participants				6
	Trials				20

Note. The number of participants and trials in the tasks for each study that was analyzed. Exp 1 = Experiment 1, L15 = Löwenkamp et al. (2015), H11 = Heath et al. (2011), G08 = Ganel et al. (2008).

Table 6

Weber Constants With Zero-Intercept Regression

Task	Exp 1	L15	H11	G08
Grasping	0.138 ± 0.007	0.152 ± 0.009	0.175 ± 0.174	0.097 ± 0.006
ManEst	0.132 ± 0.007	0.127 ± 0.007	0.101 ± 0.013	0.133 ± 0.017
Adjustment				0.064 ± 0.01

Note. Results of Weber constants *k* (mean ± SEM) with zero-intercept regression between $\widehat{JND}$ and object size. Study abbreviations are identical to Table 5.

tained by the standard method (compare Table 6 to Figure 9 in the main text and Tables 1 - 4). The standard method used by us therefore provides rather conservative estimates of the Weber constants.

2.8.5.2 *Alternative Method of Smeets and Brenner (2008)*

One reviewer (Jeroen Smeets, signed review) suggested an interesting alternative analysis that was initially proposed by Smeets and Brenner (2008). In a nutshell, they suggested to model the $\widehat{JND}$ as a combination of two independent variances, one constant (intercept term) and one depending on stimulus intensity. This gives a non-linear relationship between $\widehat{JND}$ and stimulus size

$$\widehat{JND}(s) = \sqrt{a^2 + k^2\, s^2} \tag{14}$$

with a being the constant source of variability and k being interpreted as Weber's constant. The equation can be reformulated to

$$\widehat{JND}(s)^2 = a^2 + k^2\, s^2 \tag{15}$$

such that a simple linear regression can be performed on these quadratic terms (with a^2 corresponding to the intercept and k^2 corresponding to the slope; for further details see Smeets & Brenner, 2008).

Table 7

Weber Constants With Smeets and Brenner (2008) Method

Task	Exp 1	L15	G08
Grasping	0.069 ± 0.011	0.085 ± 0.014	0.039 ± 0.010
ManEst	0.055 ± 0.011	0.062 ± 0.011	0.090 ± 0.012
Adjustment			0.058 ± 0.010

Note. Weber constants *k* (mean ± SEM) obtained from the alternative method based on Smeets and Brenner (2008). Study abbreviations are identical to Table 5.

A small glitch can occur, when the regression results in negative values for a^2 and k^2, such that *a* and *k* are undefined. In these cases, reduced models with the corresponding parameter set to zero were fitted (e.g., if a^2 would be negative in the full model, then a model with zero intercept is fitted). The reviewer suggested to use the Smeets and Brenner (2008) method instead of the standard method as has been employed in our study (cf. Equation 12) as well as in most psychophysical studies (Galanter, 1962; Miller, 1947). We therefore implemented this method for those studies where full per-participant data were available (Table 7).

Results are comparable to the results obtained by the standard method (compare Table 7 to Figure 9 and Tables 1 - 4), but consistently larger. The standard method used by us therefore provides rather conservative estimates of the Weber constants.

3. Garner Interference

The content and figures of this section are based on the following publication. New data from an experiment conducted after the publication of the paper were added to this section. Minor cosmetic changes were made to the figures.

Bhatia, K., Osenberg, A., Janczyk, M., & Franz, V. H. (2025). Reviewing evidence for the Perception–Action Model from Garner interference. *Journal of Experimental Psychology: Human Perception and Performance*, *51*(2), 217–242. https://doi.org/10.1037/xhp0001260

Abstract

It is a widely accepted notion that visual information in the brain is processed via two parallel but separate cortical pathways, the ventral stream for visual perception and the dorsal stream for visuomotor actions. Perception-action dissociations from behavioural experiments are often cited as supportive evidence and one such example is Garner interference: It is assumed that perceptual/ventrally-processed tasks suffer Garner interference while visuomotor/dorsally-processed tasks are immune to it (Ganel & Goodale, 2003). Ideally, this dissociation is demonstrated by comparing manual size estimation (assumed ventrally-processed) with grasping (assumed dorsally-processed). However, few studies actually made this comparison. We addressed this empirical shortage with two improved replications, yielding smaller effects of Garner interference in manual estimation than previous studies reported. In two subsequent experiments, we attempted to modulate Garner interference by manipulating the temporal profile of participants' responses, building on previous work (Hesse & Schenk, 2013) and extending it to manual estimation. We conclude with a literature review covering all relevant studies on Garner interference. Contrary to previous claims, the currently available evidence for a perception-action dissociation from Garner interference is insufficient to support a ventral-dorsal dissociation.

3.1 Introduction

Do the dorsal and ventral cortical streams process information in different ways? According to the Perception-Action Model (PAM; Goodale & Milner, 1992), there is a sharp and fundamental division of labour between these streams: Visually-guided actions are assumed to be processed in the dorsal stream, while visual perception is assumed to be processed in the ventral stream. The ventral stream is assumed to be involved in computation of "object descriptions that permit identification and recognition"; functions that are "generally understood as 'visual perception'" (Goodale & Milner, 1992, p. 20). As is customary in this literature, we will henceforth use the term 'perception' to refer to these functions.

While even opponents of the PAM concede that it is a useful scientific model (Schenk & Hesse, 2018), it turns out that evidence that has been counted as strong support for the PAM has been called into question. This contradictory evidence comes from effects of visual illusions (Kopiske et al., 2016) and adherence to Weber's law (Bhatia et al., 2022) in perception as well as in action. We here focus on one further central experimental approach thought to provide evidence for the PAM: Garner interference (Garner, 1974). In the following, we provide an overview of those studies that used Garner interference in the context of the PAM starting with Ganel and Goodale (2003). In this course, we will highlight that only very few studies (Ganel & Goodale, 2003, 2014) provide the critical comparison between perception and action that would be necessary to support the PAM. This surprising lack of empirical data will be the starting point of our own investigation involving four experiments. The total available evidence is assessed in the final section (Section 3.6).

3.1.1 Behavioural Perception-Action Dissociations

The PAM was first proposed based on perception-action double dissociations in brain lesion patients with visual form agnosia (most notably patient DF) and optic ataxia (Goodale et al., 1991). However, these findings have been subject to debate and controversy (Schenk, 2006; for reviews see Schenk, 2010; Schenk et al., 2011; Westwood & Goodale, 2011). For this reason, behavioural experiments and neuroimaging studies have been put forward as additional evidence in favour of the PAM, and we here focus on such behavioural evidence from healthy adults. Broadly speaking, three lines of behavioural results (perception-action dissociations) are thought to support the idea of the PAM: (1) actions may be immune to visual illusions (Aglioti et al., 1995), (2) actions may not adhere to Weber's law (Ganel et al., 2008), and (3) actions may not suffer Garner interference (Ganel & Goodale, 2003). Whether there is a perception-action dissociation regarding visual illusions was a hotly debated topic (Franz & Gegenfurtner, 2008) which was tackled by a large, multi-lab registered report (Kopiske et al., 2016), with the conclusion that both perception and action are sensitive to effects of visual illusions (see also Kopiske et al., 2017; Whitwell & Goodale, 2017). Recently, it was also suggested that actions like grasping do indeed follow Weber's law, as do perceptual tasks (Bhatia et al., 2022). Thus, the first two lines of evidence cannot be considered as unambiguously supporting the PAM. Therefore, the third line of evidence, that is, Garner interference, becomes particularly important to investigate. Several studies investigated the prediction of the PAM that Garner interference is absent in actions, but present in perceptual tasks (Eloka et al., 2015; Ganel & Goodale, 2003, 2014; Hesse & Schenk, 2013; Janczyk & Kunde, 2010, 2016; Janczyk et al., 2010; Kunde et al., 2007; Löhr-Limpens et al., 2020; Schum et al., 2012). However, as will be detailed below, most of these studies compared tasks with dissimilar task demands and, hence, cannot be taken as strong tests for the PAM.

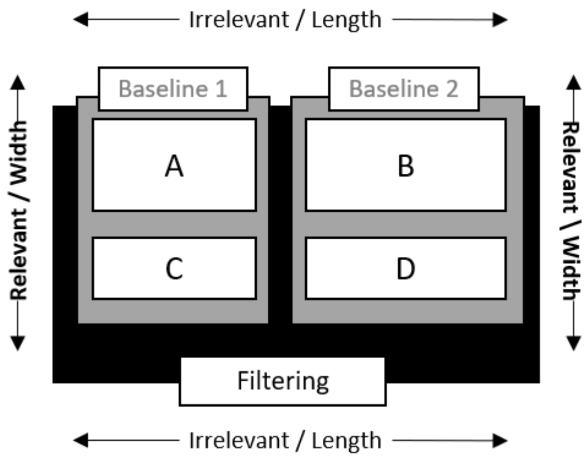
3.1.2 Garner Interference

Garner interference is assessed with a classic experimental design developed to test whether certain stimulus properties, or dimensions, can be processed independently of each other (Garner, 1974). Consider the prototypical example of a rectangle with dimensions length and width. A stimulus set of four rectangles is created by a factorial combination of two lengths and two widths (Figure 16; cf. Felfoldy, 1974). Width is the task-relevant dimension, meaning that the objects should be classified along their width as either "narrow" or "wide". It is then tested whether participants can ignore changes in the task-irrelevant dimension length by comparing the reaction times (RT) between two conditions in a speeded-classification task (Figure 16): In the baseline condition, the stimulus set consists of only objects of the same length but with differing widths, and therefore there is only variation along the task-relevant dimension. By contrast, in the filtering condition, the stimulus set consists of all four objects, which have differing width and length, thereby creating variation of task-relevant and task-irrelevant dimensions. For some dimensions, like length and width of a rectangle, the typical result is that participants are faster in the baseline condition as compared to the filtering condition (Garner, 1974). This RT difference is called Garner interference and the dimensions are termed integral dimensions. An example of non-integral or separable dimensions that do not result in Garner interference is the angle and size of the diameter of a circle (Garner & Felfoldy, 1970).

Studies in the context of the PAM used object dimensions that were known to be integral (length and width of rectangles, see Felfoldy, 1974) and interpreted the presence of Garner interference as indicating that variation in the task-irrelevant dimension could not be ignored and interfered with processing of the task-relevant dimension. In the following, we describe how the presence or absence of Garner interference is then typically used to demonstrate a perception-action dissociation.

Figure 16

Illustration of Baseline and Filtering Conditions in a Garner Experiment



Note. Stimuli in baseline and filtering conditions of a typical Garner experiment with four rectangular objects. The relevant dimension is width; therefore, participants must classify the objects as “wide” or “narrow”. The baseline condition consists of objects differing only along the relevant dimension width. There are two baseline blocks: baseline 1 which consists of only short objects (A, C), and baseline 2 with only long objects (B, D). The filtering condition consists of two identical blocks with all four objects (A, B, C, D) in each block.

3.1.3 Garner Interference and the Two Visual Streams

To demonstrate perception-action dissociations, two tasks are typically compared: an action task (assumed to be dorsally-processed), and a perceptual task (assumed to be ventrally-processed). Ideally, the action task is precision grasping (using index finger and thumb), and the perceptual task is manual (size) estimation. In manual estimation, participants estimate and indicate the size of a target object with their index finger and thumb. Manual estimation is assumed to tap into ventral, perceptual processes and provide a "manual read-out of what participants perceive" (Haffenden & Goodale, 1998, p. 125), while keeping many aspects of precision grasping. Thus, it is an ideal comparison to grasping. This is important because the PAM assumes different underlying processing in grasping and manual estimation, while both are considered to involve similar task demands (Ganel & Goodale, 2003). In our arguments, we will accept this assumption to be true, although one may question whether manual estimation is really a perceptual task (Franz, 2003) or if the task demands are comparable to grasping (e.g., see Section 3.7 and Figure 27).

Ganel and Goodale (2003) were the first to use Garner interference in the context of the PAM. They reasoned that perception requires a representation that encodes both relevant and irrelevant features in a holistic way, thereby preventing access to a single dimension and yielding Garner interference. Actions, on the other hand, would need an absolute and analytical representation of only the relevant features, thereby allowing access to the relevant dimension and being able to ignore the task irrelevant dimension. Consequently, actions should not show Garner interference.

Ganel and Goodale (2003) used four cuboidal objects made of a factorial combination of two different lengths and widths (same as those used by Felfoldy, 1974). These stimuli were used in two tasks in their Experiment 1: In perceptual speeded-classification (used originally by Garner, 1974), participants pressed buttons to judge a stimulus as "narrow" or "wide". In grasping, participants grasped a stimulus along its width. In speeded-classification, RTs were shorter in baseline than in filtering conditions, thus showing Garner interference. In grasping, however, RTs (and other dependent variables) were similar in both conditions, such that Garner interference was small and not significantly different from zero. Ganel and Goodale (2003) inferred that object shape is holistically processed in speeded-classification, while it is analytically processed in grasping. They concluded that this result "helps to explain why separate cortical pathways have evolved for these two different kinds of visual processing: a ventral stream for perception and a dorsal stream for action" (Ganel & Goodale, 2003, p. 667).

Importantly, however, Ganel and Goodale (2003) conceded that the two tasks used in their Experiment 1 had very different task demands, and the results might simply be explained by this dissimilarity, and not by a dissociation at the neural level. To address this, participants in their Experiment 2 estimated the width of the rectangular objects with their finger and thumb, thus performing a manual estimation task. The PAM assumes that task demands in grasping and manual estimation are sufficiently similar such that performance differences can be interpreted as differences in dorsal versus ventral processing (Goodale, Jakobson, & Keillor, 1994; Haffenden & Goodale, 1998). Strikingly, manual estimation showed large Garner interference in RTs (and other dependent variables). These effects were even larger than in speeded-classification (see Figure 21). This strong dissociation was therefore interpreted as indicating holistic processing in manual estimation and speeded-classification (both ventral stream), but analytical processing in grasping (dorsal stream).

To summarise, the crucial comparison is between grasping and manual estimation. In the framework of the PAM, only these tasks are sufficiently similar to draw strong inferences from the comparison. Given this, it is surprising that only two studies actually investigated manual estimation and reported Garner interference (Ganel & Goodale, 2003, 2014). In one other study, participants performed manual estimation, but Garner interference was not significant and the results were only reported in a footnote (Schum et al., 2012, footnote 2). Thus, there seems to be a shortage of empirical support for Garner interference in the crucial manual estimation task. The experiments reported in the present study aim to fill this gap.

3.1.4 Overview of This Study

Our primary goal was to add empirical data on Garner interference in manual estimation. Experiment 1 is a pre-registered replication of Ganel and Goodale (2003) with a repeated-measures design and two grasping tasks (open-loop and closed-loop), manual estimation, and perceptual speeded-classification. No previous study employed such a comprehensive repeated-measures design with all these tasks.

The Garner interference effect in manual estimation in our Experiment 1 was very small in contrast to previous studies (Ganel & Goodale, 2003, 2014). We therefore focused on manual estimation in Experiments 2-4. However, in none of these experiments did we replicate the expected and previously reported 20-30 ms Garner interference in manual estimation.

To better understand the nature of these tasks, we quantitatively compared the size of the Garner interference effect across the tasks, that is, how much Garner interference is observed in grasping or speeded-classification or manual estimation (rather than only focusing on whether it is significantly different from zero or not, as was the focus in Ganel & Goodale, 2003, and many other studies). Thus, we adopted an "estimation mind-set" (Stanley & Spence, 2014), and performed a comprehensive and quantitative literature review of studies on Garner interference to summarise and compare the currently available data on this topic.

3.2 Experiment 1: All Tasks in a Repeated-Measures Design

This experiment attempted to replicate the results of Ganel and Goodale (2003). While that study employed a between-participants design, we used a repeated-measures design and included four tasks: perceptual speeded-classification, closed-loop grasping (i.e., visual input available during the grasping movement), open-loop grasping (i.e., without visual input), and manual estimation (closed-loop). We also increased the sample size to n = 24 (compared to $n \leq 12$ in Ganel & Goodale, 2003) to achieve more power. Both the full repeated-measures design and the increased sample size are improvements and extensions of the original study. We expected to replicate the results of Ganel and Goodale (2003): large Garner interference in speeded-classification and manual estimation (perceptual tasks) and small, non-significant Garner interference in closed- and open-loop grasping.

3.2.1 Method

The study design, stimuli, and analyses of Ganel and Goodale (2003) were closely followed. Some details which were not provided in the original publication were taken from Ganel and Goodale (2014).

3.2.1.1 *Transparency and Openness*

This experiment was pre-registered on AsPredicted (https://aspredicted.org/YLL_WOC). Data and analysis scripts of all experiments are available at OSF (https://osf.io/tvqp7/). Data collection took place in 2021. Data of all experiments were analysed and figures were created using R, Version 4.1.1. (R Core Team, 2021) and the packages "pwr" (Champely, 2020), "plotrix" (Lemon, 2006), and "ez" (Lawrence, 2016). The upper panels of Figures 17 and 18 contain data digitised from Ganel and Goodale (2003, Figures 2 and 3) and were recreated in R.

3.2.1.2 *Participants and Power Analysis*

Twenty-four right-handed participants (17 women, 7 men, age range = 18-44 years, mean age = 26.6 years) took part in the experiment. Most participants were students or employees at the University of Tübingen, from diverse nationalities and spoke either German or English. Participation was voluntary and participants gave written, informed consent prior to data collection. They were compensated with 10€/hour or course credit for participation. The study was approved by the ethics committee of the University of Tübingen and was conducted in accordance with the principles of the Declaration of Helsinki.

We planned to collect 24 valid participants (after exclusions, but note that our exclusion criteria did not lead to the exclusion of any participants, see below). Our effect of interest is Garner interference in all tasks. Detailed power analyses are described in the Section 3.8.1 in the Appendix. Based on effect sizes from Ganel and Goodale (2003), we had a power of $1-\beta = .96$ for detecting Garner interference in speeded-classification and $1-\beta = .99$ in manual estimation (see Table 19) with one-tailed paired t-tests. The most important comparison for the PAM is the prediction of Garner interference in manual estimation being greater than in grasping. We therefore tested for a difference between those effects (i.e., larger Garner interference in manual estimation than in grasping). The power for this comparison was at least $1-\beta = .92$ for a one-tailed paired t-test (see Table 20).

3.2.1.3 *Stimuli*

The stimuli were identical to those used by Ganel and Goodale (2003), that is, rectangular blocks made of black, rigid plastic in a factorial combination of two different widths (30 and 35.7 mm) and lengths (63 and 75 mm). Each block was 15 mm thick.

3.2.1.4 *Apparatus*

Participants sat in a height-adjustable chair in front of a table on which an LCD monitor was placed with the screen facing up. The LCD monitor (screen diagonal: 54.6 cm; Samsung Syncmaster2233, Samsung group, Seoul, South Korea) was connected to a computer and used to display instructions, start location, and stimulus positions. Participants performed the experiment on the surface of this monitor. Participants wore liquid-crystal shutter goggles (PLATO goggles, Translucent Technologies Inc., Toronto, Ontario, Canada; see Milgram, 1987) to control stimulus presentation time. RTs and grip apertures were calculated from data recorded by an Optotrak Certus (Northern Digital, Waterloo, Ontario, Canada) using small infra-red LEDs (IREDs/markers) attached to the nails of the index finger and thumb of the participant's right hand using adhesive putty (UHU-Patafix, UHU GmbH, Bühl, Germany). Coordinates in 3D space were recorded at a sampling frequency of 200 Hz. Participants' responses in the speeded-classification and manual estimation tasks were registered through custom-built buttons, digitised with a DT9812 box (EconSeries Data-Translation/Acquisition circuit, Measurement Computing Corporation, Georgetown, MA, USA). Matlab (Mathworks, Natick, MA, USA) was used for stimulus presentation with the Psychophysics Toolbox (Brainard, 1997; Kleiner et al., 2007) and the Optotrak Toolbox by V. H. Franz (http://www.ecogsci.cs.uni-tuebingen.de/OptotrakToolbox.

3.2.1.5 Procedure

All participants performed four tasks: perceptual speeded-classification, manual estimation, open-loop grasping, and closed-loop grasping. The stimuli were presented in two conditions, baseline and filtering (Figure 16). At the beginning of each task, participants performed 8-10 practice trials, until they felt comfortable with the task. Participants performed two blocks of each condition and every block consisted of 32 trials, for a total of 128 trials (per task) in four blocks. The condition order was counterbalanced such that participants performed four blocks of BBFF or FFBB (B = baseline, F = filtering) for each task. The order of tasks was partially counter-balanced. Participants were instructed to be as accurate and fast as possible in all the tasks. In all tasks, the experimenter placed the stimulus at a specified location, and then the trial began with the goggles turning transparent.

In the *perceptual speeded-classification* task, participants judged the stimulus as narrow or wide. For all participants, the left button mapped to a "narrow" response, which they pressed using their right-hand index finger, and the right button, pressed using their right-hand middle finger, mapped to a "wide" response (following the procedure of Ganel & Goodale, 2003).

In the *manual estimation* task, participants estimated the width of the stimulus with the distance between their index finger and thumb. At the start of a trial, participants kept their index finger and thumb pinched together at the start position. When the goggles turned transparent, participants moved their fingers to a specified location on the monitor surface, made a width estimate with index finger and thumb, and pressed a button with their left-hand indicating completion of the estimation. Then, they grasped the object with their right-hand index finger and thumb, placed it at a specified location to their right, and returned their hand to the start position. The post-estimation grasp was performed so that participants receive equivalent haptic feedback in manual estimation as in grasping from touching the target object. This is standard practice in manual estimation tasks and followed previous studies on Garner interference (Ganel & Goodale, 2003, 2014; Schum et al., 2012), although it is unclear if the delayed haptic information in manual estimation is comparable to the immediate feedback available in grasping. The goggles turned opaque after 2,000 ms (closed-loop manual estimation). The distance between the start position and manual estimate position was 15 cm, and the distance between the start position and the stimulus was 32 cm. Trials where participants had problems with the post-estimation grasp (collided with the object or dropped it after grasping) or could not complete the task before goggles turned opaque, were deleted and repeated at a random time later in the block. The experimenter also deleted trials (repeated randomly later) where the participant's aperture velocity at the time of button press was too high, meaning that the participant did not synchronise indication of the estimate with the button press. Trials with missing position information (Optotrak markers obstructed from view of Optotrak) at the time of indicating the width estimate were also deleted and repeated.

In *closed-loop grasping*, participants grasped the stimulus along its width with their index finger and thumb (i.e., with a precision grip), and placed it at a nearby location. A trial began with participants' index finger and thumb pinched together at the start position, and when the goggles turned transparent, they reached toward the object to grasp it. The goggles turned opaque after 2,000 ms. The participants had full vision of their hand and the stimulus throughout. Distance between the object and start position was approximately 32 cm. Trials where participants had problems with the grasp (collided with the object or dropped it after grasping), or could not complete the task before goggles turned opaque, or trials with missing position information were deleted and repeated at a random time later.

Open-loop grasping was identical to closed-loop grasping in all respects, with the exception that the goggles turned opaque as soon as the participants' hand began to move, that is, at movement onset. Therefore, no online visual feedback about the relation between hand and object was available to the participants.

3.2.1.6 Dependent Variables

RTs in the perceptual speeded-classification task were calculated as the time between the goggles turning transparent and the button press. We also calculated the accuracy of the responses.

RTs in the grasping tasks were measured by the Optotrak as the time point when the participants' fingers left the start position (movement onset). This was determined by a velocity criterion: The first time point when either the finger or thumb marker's velocity exceeded 0.025 m/s. The touched time or total time in grasping was calculated as the first time point when either finger or thumb marker was closer than 60 mm to the midpoint of the object and less than 5 mm above the object (in the Z-direction; see Franz et al., 2005) relative to movement onset. The maximum grip aperture (MGA) was calculated as the maximum distance between the finger and thumb occurring during the movement. The MGATime was the time point at which the MGA occurred.

RTs in the manual estimation task were determined in the same way as for grasping. The time to complete manual estimation, ManEstTime, was the time from the goggles becoming transparent to the button press indicating completion of the estimate. Movement time (MT) was calculated as the time between movement start (RT) and completion (ManEstTime), therefore, MT = ManEstTime - RT. Since the ManEstTime includes the RT, the ManEstTime will be correlated with the RT. The MT should thus be a more independent measure (from RT) than ManEstTime. Finally, the manual estimate (ManEst) of the width of the stimuli was determined as the finger aperture at the time point of the button press.

We also performed all analyses when applying slightly different methods to determine movement onset and offset as used by Ganel and Goodale (2014) to calculate the dependent variables in grasping and manual estimation. These analyses led to essentially similar results (see Table 22 in the Appendix, Section 3.8.2).

3.2.1.7 Pre-registered Analyses

Trials with RTs shorter than 100 ms or longer than 1,500 ms were first excluded. Trials with RT beyond the mean ± 2 SD for each participant and condition were also excluded. For *speeded-classification*, any participant with more than 10% errors would have been excluded, but all participants achieved accuracies above 90%. All these exclusion criteria were pre-registered and led to the exclusion of 7% trials in speeded-classification, 6% trials in closed-loop grasping, 5% trials in open-loop grasping, and 5% trials in manual estimation (we also analysed the data including these trials with essentially the same results, aside from small numerical differences).

For *grasping*, there was a further exclusion criterion that was not pre-registered: trials where the MGA was achieved at the time of touching the object were excluded. This is necessary, because touching the object biases the MGA to the true object size. This led to the exclusion of further 1% trials each in closed- and open-loop grasping. A repeated-measures Analysis of Variance (ANOVA) on RTs with factors task (speeded-classification, manual estimation, grasping open-loop, grasping closed-loop) and condition (baseline, filtering) was performed to investigate differences in the Garner interference effect across tasks. For better comparison with the literature, we also used one-tailed paired-samples *t*-tests to test for a difference between baseline and filtering (i.e., the presence of Garner interference) in single tasks.

3.2.1.8 Analyses That Were Not Pre-Registered

In addition to the pre-registered analyses, we also performed some analyses in response to reviewers' suggestions, and as sanity checks to compare our results with those of previous studies, and we describe them below.

Ganel and Goodale (2003) reported Garner interference in ManEstTime in addition to RT. Hence, we also checked for Garner Interference in MT and ManEstTime with one-tailed paired *t*-tests. We also analysed 'variability-based Garner interference', as suggested by Ganel and Goodale (2014). They argued that even when RTs and movement times do not show Garner interference, it might still be reflected in reduced accuracy in filtering than in baseline conditions (the idea being that participants might be able to have the same speed in filtering as in baseline, but at the cost of reduced accuracy). Therefore, they proposed to investigate the within-participant standard deviation of the dependent variables (MGA / ManEst). Because this had not been considered in their 2003 study, Ganel and Goodale (2014) reanalysed those older data together with their new data and showed for both studies variability-based Garner interference for manual estimation but not for grasping — consistent with the PAM. We performed the same analysis: For each participant, we calculated the within-participants standard deviation of MGA/ManEst (SD_{MGA} / SD_{ManEst}) in each condition and object size, averaged[2] across object sizes, and performed an ANOVA with factors task (manual estimation, grasping

[2]Ganel and Goodale described this procedure in their 2014 study. For better comparison, we follow this procedure, although one might argue that it is statistically more sensible to pool the SDs, rather than averaging them.

open-loop, grasping closed-loop) and condition (baseline, filtering). One-tailed paired *t*-tests were also performed for results comparable to the literature.

Ganel and Goodale (2003) performed another analysis to check for holistic versus analytical processing: they reasoned that, if the irrelevant dimension (length) has an influence on the response (MGA in grasping and ManEst in manual estimation), the response should be larger for shorter objects than for longer objects, because shorter objects will appear wider than longer objects do. This has been named the height-width illusion (Beck et al., 2013; Mazuz et al., 2023; Zitron-Emanuel & Ganel, 2020), which was first reported by Müller-Lyer (Müller-Lyer, 1889). This illusion was observed by Ganel and Goodale (2003) in manual estimation, but not in grasping, and was interpreted as further evidence for analytical processing in grasping, but holistic processing in manual estimation. We thus calculated the illusion effect by subtracting the responses to the long object (appears narrow due to illusion) from the short object (appears wide), and submitted them to an ANOVA with factors task (grasping open-loop, grasping closed-loop, manual estimation) and condition (baseline, filtering). We added the factor condition because Ganel and Goodale (2003) reported the illusion effect for the filtering condition only and we wanted to check if this effect is influenced by condition (see Figure 24). Our effect of interest is a main effect of task, which would indicate that illusion effects are different across tasks.

Reviewers suggested that we also compute Bayes factors to quantify evidence for the competing hypotheses. We reported one-tailed Bayes factors with default priors (prior for the null is a point mass on zero, and prior for the alternative is a truncated Cauchy distribution with width = 0.707, cf. Rouder et al., 2009) for t-tests in all experiments along with the frequentist results (with results being by-and-large consistent). For this, we used the standard settings of the function 'ttestBF' from the R package 'BayesFactor' (Morey & Rouder, 2024). In addition, we report Bayes factors using theory-driven priors (Dienes, 2008, 2023), which enabled us to compare the size of Garner interference in manual estimation with grasping and speeded-classification. We will henceforth refer to this analysis as the 'Bayesian comparison'. To perform this comparison, we focused on RTs, because this is the only variable that can be determined in all tasks and is typically reported in studies (Figures 21-24). The comparison can be achieved by using the results of Experiment 1 from speeded-classification and grasping as priors: The prior for the null hypothesis was a normal distribution with mean and SEM of Garner interference in speeded-classification, and the prior for the alternative hypothesis was a normal distribution with mean and SEM of Garner interference in grasping (see Table 8). Therefore, the Bayes factor will tell us whether Garner interference in manual estimation is more likely under the null hypothesis (H_0: Garner interference in manual estimation is the same as in speeded-classification) than under the alternative hypothesis (H_1: Garner interference in manual estimation is the same as in grasping). This is a critical comparison, because it directly tests the results of manual estimation against the assumptions of the PAM, which posits that larger Garner interference occurs in tasks assumed to be processed in the ventral stream like speeded-classification, while smaller Garner interference occurs in tasks assumed to be processed in the dorsal stream like grasping (see Dienes, 2008, for a general introduction to this approach of directly testing the theoretical approaches in question). If the Bayesian comparison results in a Bayes factor $BF_{10} > 1$, then there is evidence for the alternative hypothesis, that is, that Garner interference in manual estimation is more similar to grasping, which is assumed to be dorsally processed. If the $BF_{10} < 1$, then there is evidence for the null hypothesis that Garner interference in manual estimation is more similar to speeded-classification, which is assumed to be ventrally processed. We interpreted the strength of evidence given by the Bayes factors following Jeffreys (1961): We speak of strong evidence for H_0 for Bayes factors smaller than $\frac{1}{10}$, substantial evidence for H_0 for Bayes factors between $\frac{1}{10}$ and $\frac{1}{3}$, inconclusive results for Bayes factors between $\frac{1}{3}$ and 3, substantial evidence for H_1 for Bayes factors between 3 and 10, and strong evidence for H_1 for Bayes factors above 10. Experiments 2, 3, and 4 only involved manual estimation, therefore we used the grasping and speeded-classification results of Experiment 1 for the Bayesian comparison to the manual estimation results. The analysis code used for the Bayesian comparison is based on Dienes (2008) and provided at OSF (https://osf.io/tvqp7/).

All values are reported as mean ± SEM, unless otherwise specified. Standardised effect sizes are reported as Cohen's d_z (for repeated-measures) or generalised eta squared (η^2_G). The Greenhouse-Geisser method (Greenhouse & Geisser, 1959) was used to correct *p* values for ANOVAs with more than two factor levels and the corresponding ε values are reported. For all tests, a significance level of α = .05 was used.

3.2.2 Results

3.2.2.1 Reaction Times

Accuracies in the speeded-classification task were 98.2 ± 0.3% (baseline condition), and 97.1 ± 0.5% (filtering condition). The slightly higher accuracy in the baseline condition is not simply a speed-accuracy trade-off, because participants are also faster in this condition (see below).

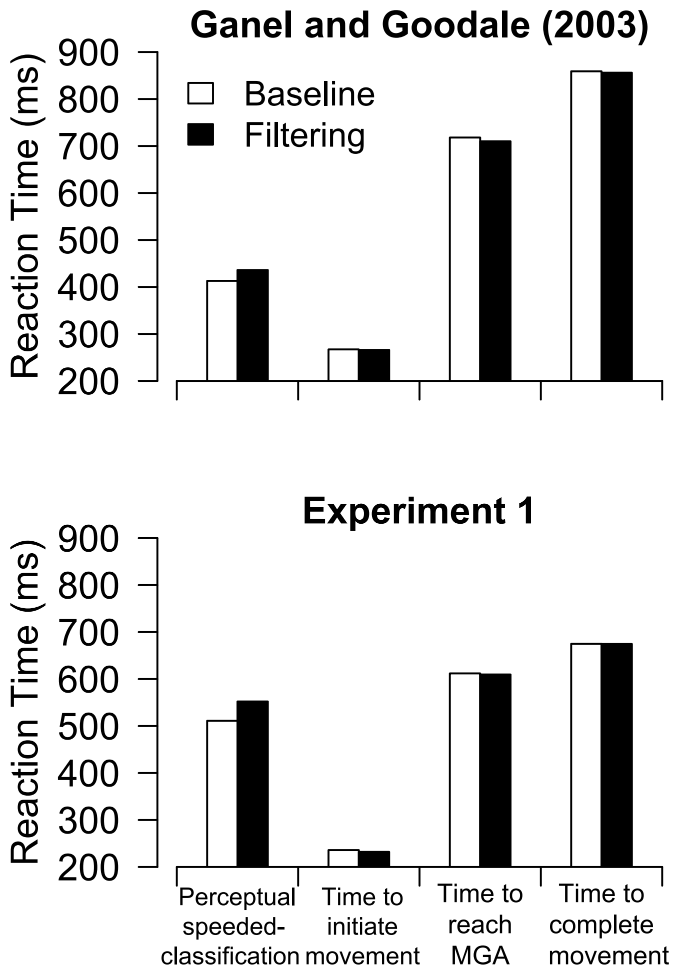
RTs as well as the differences in RTs between filtering and baseline conditions (i.e., the Garner interference effects) are listed in Table 8. Later, when we perform our literature review, those values will also be depicted in Figure 21 (for comparison to other studies). We also plotted our results side-by-side to the results of Ganel and Goodale (2003): Figure 17 shows this comparison for speeded-classification and closed-loop grasping; Figure 18, shows manual estimation. On inspection, most results seem comparable, with one notable exception: Manual estimation seems to show smaller Garner interference in our study than in Ganel and Goodale (2003).

The ANOVA on RTs revealed a significant main effect of task, meaning that the tasks had significantly different RTs (see General Discussion and Figure 27), $F(3,69) = 162.31$, $\varepsilon = .65$, $p < .001$, $\eta^2_G = .77$. There was a non-significant overall Garner interference effect (main effect of condition), $F(1,23) = 3.59$, $p = .071$, $\eta^2_G < .01$. Instead, the Garner interference effect was modulated by task, with a significant task × condition interaction, $F(3,69) = 5.59$, $\varepsilon = .72$, $p = .005$, $\eta^2_G = .02$.

Next, we tested which task showed a Garner interference effect in RTs. Results are summarised in Table 8: Garner interference was significant in speeded-classification but neither in grasping nor in manual estimation. These results partly resemble those of Ganel and Goodale

Figure 17

Comparison of Experiment 1 of Ganel and Goodale (2003) and Our Experiment 1



Note. Results of speeded-classification and closed-loop grasping. Axis labels are identical to Ganel and Goodale (2003) and represent different time-related dependent variables: Perceptual speeded-classification = RT in speeded-classification; time to initiate movement = RT in grasping; time to reach MGA = MGA time in grasping; time to complete movement = touched time in grasping. Upper panel: Adapted from "Visual control of action but not perception requires analytical processing of object shape." by T. Ganel and M. A. Goodale, 2003, *Nature, 426(6967)*, p. 666 (https://doi.org/10.1038/nature02156). Copyright 2003 by Springer Nature. Adapted with permission.

(2003), but while these authors reported a significant Garner interference in manual estimation, we did not observe it.

Further, we tested whether Garner interference was larger in manual estimation than in grasping. Again, we found non-significant effects: both in manual estimation vs. closed-loop grasping (difference = 9 ± 12 ms), $t(23) = 0.73$, p = .235, $d_z = 0.15$, $BF_{10} = 0.42$, and in manual estimation vs. open-loop grasping (difference = 5 ± 12 ms), $t(23) = 0.45$, $p = .328$, $d_z = 0.09$, $BF_{10} = 0.30$.

The Bayesian comparison of whether Garner interference in manual estimation is more

Table 8

Reaction Times in Milliseconds for Experiment 1

Task	Baseline	Filtering	Difference	t(23)	p	d_z	BF_{10}
SpeededClass	511 ± 19	552 ± 19	41 ± 11	3.62	<.001	0.74	64.2
CL-Grasp	236 ± 7	232 ± 6	-4 ± 4	-0.94	.822	-0.19	0.12
OL-Grasp	246 ± 10	246 ± 12	0 ± 7	-0.06	.525	-0.01	0.21
ManEst	350 ± 16	355 ± 14	5 ± 13	0.39	.352	0.08	0.29

Note. The reaction times in milliseconds for baseline and filtering conditions, as well as the Garner interference effect (Difference = filtering – baseline) for each task of Experiment 1. Values are reported as mean ± standard error of the mean.

similar to Garner interference in speeded-classification (H_0) than in closed-loop grasping (H_1), resulted in a Bayes factor of BF_{10} = 10.0, which is substantial evidence that Garner interference in manual estimation is more similar to grasping (H_1) than to speeded-classification (H_0). For MT, the observed Garner interference in manual estimation was numerically large, but not significant (37±22 ms), t(23) = 1.68, p = .053, d_z = 0.34, BF_{10} = 1.37. A similar result was obtained for ManEstTime (42±25 ms, see Figure 18), t(23) = 1.70, p = .051, d_z = 0.35, BF_{10} = 1.37.

3.2.2.2 *Variability*

We also analysed Garner interference in the response variability in grasping (MGA) and manual estimation (ManEst) from our data. The ANOVA revealed main effects of task, F(2,46) = 10.47, ε = .97, $p < .001$, η^2_G = .08, and condition, F(1,23) = 5.50, p = .028, η^2_G = .01, but the interaction was not significant, F(2,46) = 0.03, ε = .89, p = .960, $\eta^2_G < .001$. This suggests that the Garner interference in the variability of the response was not significantly different between tasks (see Table 9 and Figure 23).

Table 9

Variability of Grip Aperture in Millimeters for Experiment 1

Task	Baseline	Filtering	Difference	t(23)	p	d_z	BF_{10}
CL-Grasp	3.34 ± 0.31	3.62 ± 0.26	0.29 ± 0.17	1.72	.050	0.35	1.42
OL-Grasp	3.67 ± 0.25	3.93 ± 0.36	0.27 ± 0.30	0.90	.188	0.18	0.49
Man.Est.	2.78 ± 0.15	2.99 ± 0.21	0.21 ± 0.15	1.42	.084	0.29	0.92

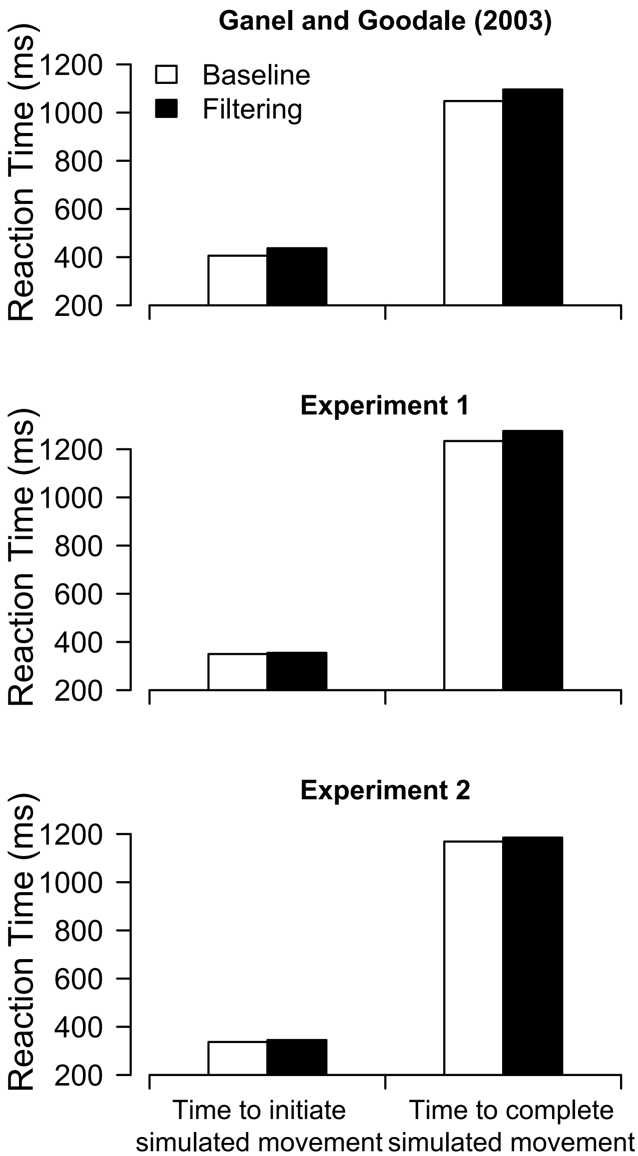
Note. Values are reported as mean ± standard error of the mean.

3.2.2.3 *Height-Width Illusion*

Regarding the height-width illusion effect, the ANOVA resulted in only non-significant main effects of task, F(2,46) = 2.53, ε = .85, p= .100, η^2_G = .04, and condition, F(1,23) = 0.09, p = .769,

Figure 18

Comparison of Manual Estimation: Ganel and Goodale (2003) and Our Experiments 1-2



Note. Results of manual estimation ("simulated grasping" Ganel & Goodale, 2003). Axis labels are identical to Ganel and Goodale (2003) and represent different time-related dependent variables: Time to initiate simulated movement = RT in manual estimation; time to complete simulated movement = ManEstTime. Upper panel: Adapted from "Visual control of action but not perception requires analytical processing of object shape." by T. Ganel and M. A. Goodale, 2003, *Nature, 426(6967)*, p. 666 (https://doi.org/10.1038/nature02156). Copyright 2003 by Springer Nature. Adapted with permission.

$\eta^2_G < .001$, and a non-significant interaction, $F(2,46) = 2.92$, $\varepsilon = .93$, $p = .069$, $\eta^2_G = .03$. Therefore, the illusion effect was not significantly different for grasping and manual estimation (see also Figure 24 for a meta-analysis).

3.2.3 Discussion

Experiment 1 was an attempt to replicate the results of Ganel and Goodale (2003) in a repeated-measures design with perceptual speeded-classification, open-loop grasping, closed-loop grasping, and manual estimation tasks. For RTs, we were able to corroborate the results in speeded-classification and in grasping. However, we were not able to replicate the important Garner interference in manual estimation. Further, it seems that the difference between grasping and manual estimation is at least smaller than previously assumed, largely due to the very small effect in manual estimation (note that Ganel & Goodale, 2003, did not report a direct comparison between Garner interference in grasping and manual estimation).

The picture is similar for the other movement parameters (time to complete movement, etc.): We can corroborate the results for grasping, but there is no clear Garner interference in manual estimation.

We also found relatively small values for variability-based Garner interference, and those values were similar in manual estimation and in grasping. By contrast, Ganel and Goodale (2014) found larger values for variability-based Garner interference in manual estimation than in closed-loop grasping. In the following experiments, we therefore tried to further scrutinise whether Garner interference is present in manual estimation.

3.3 Experiment 2: Manual Estimation With More Trials and Alternating Blocks

The results for manual estimation obtained in Experiment 1 differed from those of Ganel and Goodale (2003, 2014). We therefore made a second replication attempt, where we focused exclusively on manual estimation. This allowed us to increase the number of trials per participant considerably (from 128 to 256 trials), thereby increasing statistical power. We also speculated that a different sequence of baseline/filtering blocks might increase Garner interference.

3.3.1 Method

Twenty-four new right-handed participants (17 women, 6 men, 1 non-binary person, mean age = 24.3 years, age range = 19-48 years) were recruited for this experiment. The experiment consisted of only the manual estimation task and was almost identical to Experiment 1 (we describe only differences to Experiment 1 here). We doubled the number of trials to 256 trials to increase precision, such that the total number of blocks increased to eight, presented in counterbalanced, alternating sequences of BFBFBFBF or FBFBFBFB (with B: Baseline and F: Filtering condition). This alternating block-sequence differed from Experiment 1, where we used counterbalanced sequences of repeated blocks (BBFF or FFBB). We made this change because we assumed Ganel and Goodale (2003) might have also used a sequence of alternating blocks (their article did not specify this). However, during the review process we learned that Ganel and Goodale (2003) had used the same repeated-block sequence as we had used in Experiment

1. Nevertheless, both sequences have been used frequently (e.g., repeated-block sequences were used by: Eloka et al., 2015; Janczyk & Kunde, 2010, 2016; Janczyk et al., 2010; Kunde et al., 2007; Schum et al., 2012; and alternating sequences were used by: Hesse & Schenk, 2013; Löhr-Limpens et al., 2020). Comparing results of our Experiments 1 and 2 will show that the type of the sequence does not seem to make a big difference.

Data collection took place in 2022. This experiment was not separately pre-registered, because we followed the same specifications as in Experiment 1. Outliers and exclusion criteria were also identical to Experiment 1 and led to the exclusion of 5% trials overall (including them made no difference to the results). The power to find Garner Interference in manual estimation was about 1-β =.89 (see Table 20).

3.3.2 Results

The RT and ManEstTime for baseline and filtering conditions are depicted in Figure 18, bottom panel. The RT, MT, ManEstTime, and SD_{ManEst} results are also listed in Table 10, along with the Garner interference effects.

The Garner interference effect in manual estimation in RT was 8 ± 4 ms (depicted also in Figure 21). A comparison to Experiment 1 (Tables 8, 9 and 10) shows that the effects were numerically similar and that the larger number of trials successfully yielded more precise measurement. In consequence, the Garner interference effect in manual estimation was less variable and statistically significant. Nevertheless, it was much smaller than previously reported in the literature (see Section 3.7 and Figure 21).

Table 10

Results for Manual Estimation in Experiment 2

Variable	**Baseline**	**Filtering**	**Difference**	***t*(23)**	***p***	**d_z**	**BF_{10}**
RT (ms)	337 ± 16	345 ± 16	8 ± 4	1.99	.029	0.41	2.25
MT (ms)	832 ± 34	840 ± 34	8 ± 7	1.17	.126	0.24	0.66
ManEstTime (ms)	1169 ± 39	1185 ± 39	17 ± 9	1.89	.036	0.39	1.88
SD_{ManEst} (mm)	3.53 ± 0.21	3.84 ± 0.19	0.31 ± 0.09	3.38	.001	0.69	35.1

Note. Values are reported as mean ± standard error of the mean.

For the Bayesian comparison to test whether Garner interference in manual estimation is more similar to grasping (H_1) than to speeded-classification (H_0), we used the grasping and speeded-classification results from Experiment 1 as priors, because Experiment 2 (and Experiments 3-4) involved only manual estimation (see Section 3.2.1.8 for details). This yielded a BF_{10} = 10.5, which presents strong evidence that Garner interference in manual estimation is more similar to grasping than to speeded-classification.

Garner interference was 8 ± 7 ms in MT and 17 ± 9 ms in ManEstTime, much smaller than in Experiment 1. There was now also a significant variability-based Garner interference effect in the ManEst. The height-width illusion effect for the baseline condition was -0.65 ± 0.44 mm, *t*(23) = -1.5, *p* = .925, d_z = -0.30, BF_{10} = 0.10, and for the filtering condition 0.76 ± 0.18 mm, *t*(23)

= 4.33, $p < .001$, d_z = 0.88, BF_{10} = 243.

3.3.3 Discussion

While previous studies by Ganel and Goodale (2003, 2014) found Garner interference for RTs in a manual estimation task, our first replication attempt (Experiment 1) could not corroborate this and yielded only very small Garner interference (5 ± 13 ms). Experiment 2 was therefore a second replication attempt with more statistical power. But again, we observed only very small Garner interference (8 ± 4 ms) which was numerically much smaller than the 31 ± 13 ms and 22 ± 10 ms effects reported by Ganel and Goodale (2003, 2014), respectively. Furthermore, the Bayesian comparison revealed strong evidence that Garner interference in manual estimation is more similar to grasping than to speeded-classification.

Regarding ManEstTime, the results are mixed. In Experiment 1, we found a numerically large (42 ± 25 ms) Garner interference in ManEstTime. In Experiment 2, this was much smaller (17 ± 9 ms). Interestingly, Ganel and Goodale (2003) reported a Garner interference effect in ManEstTime of 48 ± 20 ms, but in their subsequent study (Ganel & Goodale, 2014), no ManEstTime results were reported. However, a re-analysis of the data showed only a small (and not significant) Garner interference effect for this variable (9 ± 13 ms; data were provided via personal communication by Tzvi Ganel). Therefore, it is unclear if Garner interference is to be expected in ManEstTime. Note that one other study with manual estimation (Schum et al., 2012) also did not report a significant Garner interference effect in manual estimation for either variable (RT = -7 ± 8 ms, ManEstTime = 6 ± 38 ms; their footnote 2).

Even after increasing precision with more trials, the discrepancy between our results in manual estimation and Ganel and Goodale (2003) remained. We therefore searched for differences that could potentially influence the results. We list these differences in Table 11. The block sequence was already mentioned and does not seem to make a difference in the results between Experiment 1 and 2 (compare Table 8 and 10). Three further issues were identified: task instructions, stimulus placement, and distance to ManEst location.

Regarding task instructions, Ganel and Goodale (2003) emphasised speed in their grasping and speeded-classification tasks but did not explicitly mention the instruction for manual estimation, and presumably it was also speeded for consistency. Furthermore, since the focus was on RTs, we expect the task to be speeded. Ganel and Goodale (2014) emphasised accuracy. In our own experiments, we asked participants to be as fast and as accurate as possible, thereby striving for a middle ground.

Our stimulus placement was consistent with Ganel and Goodale (2003), with the larger surface area of the cuboids horizontal to the surface of the table (see Figure 1 of Ganel & Goodale, 2003). Ganel and Goodale (2014) instead placed the stimuli vertically (see Figure 2 of Ganel & Goodale, 2014). This was done “to allow subjects to grasp the objects without potentially hitting the surface of the tabletop” (Ganel & Goodale, 2014, p. 4). We do not expect this issue to be a big problem for manual estimation, therefore it is unlikely to be the reason for our small Garner effects.

Finally, one methodological detail that was missing from Ganel and Goodale (2003) was the distance between the start position and the location where the manual estimate was performed.

Table 11

Set-Up and Design Differences in Manual Estimation Across Studies

Parameter	GG03	GG14	Exp 1	Exp 2
Block Sequence	BBFF/FFBB	BBFF/FFBB	BBFF/FFBB	BFBF/FBFB
Task Instructions	Speed (?)	Accuracy	Both	Both
Stimulus Placement	Horizontal	Vertical	Horizontal	Horizontal
Distance to ManEst	?	25 cm	15 cm	15 cm

Note. B = Baseline, F = Filtering.

Ganel and Goodale (2014) used 25 cm while in our Experiments 1-2, this distance was 15 cm. There is some evidence that suggests that the movement distance (or amplitude) can influence RTs and Garner interference in RTs (Hesse & Schenk, 2013). This might cause a Garner effect in manual estimation to be masked depending on the set-up. In the following experiments, we varied the movement amplitude in manual estimation to investigate if it can modulate the Garner interference effect and explain our results.

3.4 Experiment 3: Manual Estimation With Varying Decision Amplitude

Experiments 1 and 2 attempted to replicate Garner interference in manual estimation. Contrary to previous reports, and to our expectations, we observed only very small values of Garner interference in RTs in Experiments 1-2. In an effort to resolve this empirical inconsistency, we explored possible reasons for a modulation of Garner interference in Experiment 3. For example, Ganel and Goodale (2003) did not report the distance between their start button and the location where participants indicated their manual estimate. This means that there might have been a difference between our set-up and that of Ganel and Goodale (2003) regarding this distance. Below we describe how and why this difference might explain smaller Garner interference in our manual estimation task.

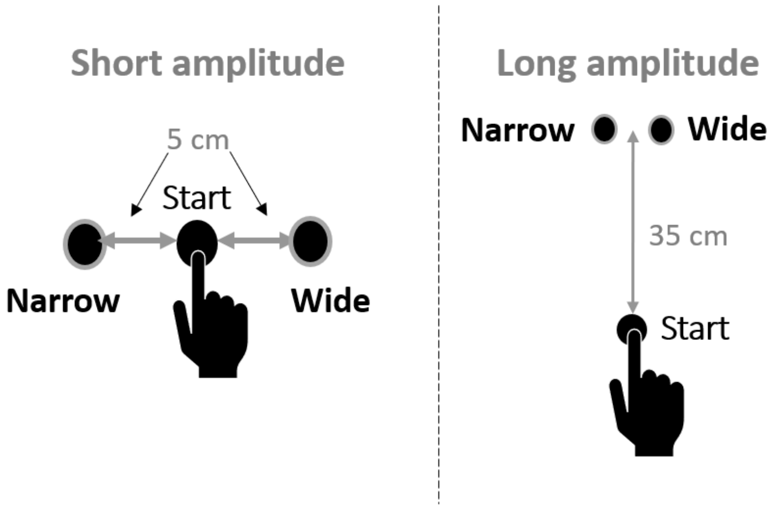
3.4.1 Garner Interference in Reaction Time May Depend on Decision Amplitude

Hesse and Schenk (2013) had argued that Garner interference, especially in RTs and regardless of the task, may depend on and be modulated by the temporal profile of the response. Put simply, presence or absence of Garner interference is determined by whether RT includes the decision time or not. In the perceptual speeded-classification task, participants can only press the appropriate button once a decision has been reached, therefore RT includes the decision time. However, in grasping (and likely in manual estimation as well), RT is measured at movement onset, but the decision about narrow/wide may occur later during the movement, because it is not required for movement onset. Therefore, RT does not necessarily include the decision time. In sum, if the participant's decision occurs before movement onset, RTs will show Garner interference. However, if the task allows participants to delay their decision until after movement onset, RTs will not show Garner interference.

To test this, Hesse and Schenk (2013) manipulated the temporal profile by placing a start button either at a short (5 cm) or long distance (35 cm) from the response (wide/narrow) buttons (see Figure 19) in speeded-classification. It was hypothesised that participants will have sufficient time after movement onset in the long amplitude condition, such that they will delay the decision to after releasing the start button. If this were true, the measured RT will not include decision time and Garner interference will not occur. On the other hand, there would not be sufficient time after movement onset in the short amplitude condition, such that participants are likely to make the decision before moving and RTs will include decision time and show Garner interference. The results supported this hypothesis and showed a clear dissociation: Garner interference was observed in the short amplitude condition, but Garner interference was not significant in the long amplitude condition of the same speeded-classification task that is assumed to be ventrally processed.

Figure 19

Illustration of the Set-Up Used by Hesse and Schenk (2013)



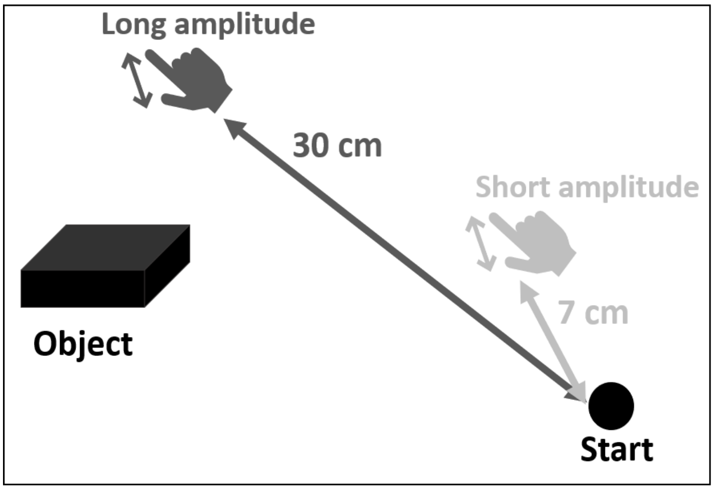
Note. The short and long amplitude conditions of Hesse and Schenk (2013). The decision amplitude determines the amount of time available to make the decision about the object's width.

For grasping, they reasoned that open-loop conditions (i.e., without visual feedback after movement onset) would force participants to make their decision before movement onset, as no feedback would be further available. Interestingly, they observed (small) Garner interference for open-loop grasping (contrary to Ganel & Goodale, 2003, supplementary material and our Experiment 1). Overall, Hesse and Schenk (2013) showed that Garner interference in RTs could be induced or reduced within the same task, further questioning the mapping of holistic versus analytic processing to ventral versus dorsal processing.

Critically, Hesse and Schenk (2013) did not include manual estimation in their study. We here applied and extended their approach to manual estimation, to investigate whether Garner interference in this task might also be influenced by the decision amplitude. In our design, we created long and short amplitude conditions by changing the distance between the start button and the position where the width estimate was to be indicated (see Figure 20). The idea was to allow insufficient time between leaving the start button and indicating the manual estimate in the short amplitude condition, thereby forcing participants to make their decision before movement onset. This should induce Garner Interference in RTs. On the other hand, in the long amplitude condition, there should be sufficient time during the movement to the location of manual estimation and, accordingly, participants can delay their decision to after movement onset.

Figure 20

Illustration of the Set-Up Used in Experiment 3



Note. The long and short amplitude conditions for manual estimation in Experiment 3 following Hesse and Schenk (2013). The time provided for making a decision was manipulated by varying the amplitude, that is, by changing the distance between the start button and the location where participants indicated their estimate of the object's width.

3.4.2 Method

3.4.2.1 Transparency and Openness

This experiment was pre-registered at AsPredicted (https://aspredicted.org/RFF_ZRR). Data collection for this experiment took place in 2022-23.

3.4.2.2 Participants and Power Analysis

Thirty-four new participants performed the experiment but two were excluded: one participant was left-handed but took part in the experiment for a research seminar and was excluded *a priori*, and one further participant failed to understand the task (during and after the experiment they posed questions to the experimenter about how to perform the task; results were almost identical even with the data of these two participants). Therefore, the data of thirty-two right-handed participants (25 women, 7 men, mean age = 22.7 years, age range = 18-27 years) were analysed. The critical effect we wanted to investigate is a modulation of Garner interference in RTs by amplitude (i.e., larger Garner interference in the short amplitude condition than in the long amplitude condition). For this comparison, we estimated the power to be at least 1-β =.79 (cf. Table 21). All other details regarding ethics, consent, and compensation were identical to Experiment 1.

3.4.2.3 Stimuli, Apparatus, and Procedure

Only the manual estimation task was used and stimuli and apparatus were identical to Experiments 1 and 2. Participants performed four combinations of conditions: Long-Baseline, Long-Filtering, Short-Baseline, Short-Filtering. The order of the conditions was counterbalanced and alternated. Participants performed four blocks (BFBF or FBFB) of one amplitude, and then four blocks of the other amplitude. Thus, the Garner condition as well as amplitude was counterbalanced. Participants performed eight blocks in total and each block consisted of 48 trials, resulting in 384 trials overall. Participants were instructed to be as accurate and fast as possible. In the long condition, participants estimated the width of the objects at a distance of 30 cm from the start position. In the short condition, this distance was 7 cm (see Figure 20). Hesse and Schenk (2013) used 5 cm for their short condition in a speeded-classification task. We slightly increased this distance to 7 cm because it seemed more comfortable for manual estimation during the piloting phase, with the expectation that a distance of 5 cm versus 7 cm would not lead to differences when compared to 30 cm. Regardless, in Experiment 4, we conducted also a short condition with 3 cm amplitude with essentially the same results (see Table 14).

3.4.2.4 Dependent Variables and Analyses

Trial exclusions were based on the criterion used by Hesse and Schenk (2013): Outliers corresponding to RTs shorter than 100 ms and longer than 2.5 SDs above the mean of the participant (in a certain condition) were excluded from the analysis. This led to the exclusion of 2.5% of trials as outliers. Pilot experiments revealed that there was large within-participant variability in the time-based measures, therefore, a further exclusion criterion was used (and pre-registered): Trials with MT and/or ManEstTime beyond the mean ± 2 SDs for each participant (in a certain condition) were also excluded from the analysis. We used the same dependent variables as described in Experiment 1 for manual estimation: RT, MT, ManEstTime, and variability. We performed separate ANOVAs with the factors condition (baseline, filtering) and amplitude (long, short) as repeated-measures on these variables. We also performed the Bayesian comparison on RTs in a similar way as Experiments 1-2.

3.4.3 Results

3.4.3.1 Reaction Times

The Garner interference effects are provided in Tables 12 – 13 and depicted also in Figure 21 below. The ANOVA for RT resulted in a non-significant condition × amplitude interaction, $F(1,31) < 0.01$, p = .974, $\eta^2_G < .01$, and a non-significant main effect of Garner condition $F(1,31)$ = 1.94, p = .174, $\eta^2_G < .01$. Only the main effect of amplitude was significant, $F(1,31)$ = 10.46, p = .003, η^2_G = .04, therefore the overall RTs were significantly different for each amplitude condition. For consistency with the power analysis (cf. Table 21), we also performed a one-tailed t-test for the difference between Garner interference in RTs of short and long amplitude conditions. As evidenced by a non-significant ANOVA interaction, there was no significant difference between the conditions: 0.28 ± 8 ms, $t(31) = 0.03$, $p = .487$, $d_z = 0.01$, $BF_{10} = 0.19$.

Table 12

Garner Interference Effects for Experiment 3 in the Short Amplitude Condition

Variable (unit)	Baseline	Filtering	Difference
RT (ms)	313 ± 10	320 ± 11	6 ± 6
MT (ms)	652 ± 30	660 ± 29	8 ± 8
ManEstTime (ms)	966 ± 37	980 ± 36	14 ± 13
SD_{ManEst} (mm)	3.53 ± 0.17	3.88 ± 0.22	0.35 ± 0.16

Note. Values are reported as mean ± standard error of the mean.

Table 13

Garner Interference Effects for Experiment 3 in the Long Amplitude Condition

Variable (unit)	Baseline	Filtering	Difference
RT (ms)	290 ± 12	296 ± 12	6 ± 6
MT (ms)	805 ± 31	807 ± 33	2 ± 10
ManEstTime (ms)	1095 ± 39	1103 ± 39	9 ± 13
SD_{ManEst} (mm)	3.43 ± 0.14	3.65 ± 0.13	0.22 ± 0.12

Note. Values are reported as mean ± standard error of the mean.

A similar result was obtained in MT and ManEstTime: The ANOVAs revealed only a main effect of amplitude on MT, $F(1,31) = 93.39$, $p < .001$, $\eta^2_G = .15$, and on ManEstTime, $F(1,31) = 42.04$, $p < .001$, $\eta^2_G = .08$, but there was again no significant main effect of Garner condition, MT: $F(1,31) = 0.86$, $p = .360$, $\eta^2_G < .01$; ManEstTime: $F(1,31) = 1.64$, $p = .210$, $\eta^2_G < .01$, nor a significant interaction, MT: $F(1,31) = 0.11$, $p = .739$, $\eta^2_G < .01$; ManEstTime: $F(1,31) = 0.07$, $p = .796$, $\eta^2_G < .01$. Thus, we did not find a modulation of Garner interference by amplitude.

The Garner interference effect on RT was 6 ± 6 ms in the short amplitude condition and in the long amplitude condition, also 6 ± 6 ms (see Tables 12 and 13, and Figure 21 below). Comparing these values to Experiment 1 and 2 shows that the numerical values were very similar between experiments.

For the Bayesian comparison, we pooled the results of manual estimation from the short and long conditions (testing these conditions individually led to similar results because the mean and SEM were almost identical). Then, we used the grasping and speeded-classification results from Experiment 1 as priors to calculate Bayes factors to test whether Garner interference in manual estimation is more similar to grasping (H_1) or to speeded-classification (H_0). This resulted in a $BF_{10} = 29.5$, which is strong evidence that Garner interference in manual estimation is more similar to grasping than to speeded-classification.

3.4.3.2 *Variability*

The ANOVA on variability resulted in a main effect of condition, $F(1,31) = 6.02$, $p = .020$, $\eta^2_G = .02$, but no significant main effect of amplitude, $F(1,31) = 1.02$, $p = .321$, $\eta^2_G < .01$, or an interaction, $F(1,31) = 0.60$, $p = .445$, $\eta^2_G < .01$. Variability-based Garner interference in both the long and the short amplitude conditions in Experiment 3 (see Tables 12 and 13) were in a similar range as the values from Experiments 1-2.

3.4.4 Discussion

Experiment 3 followed the logic advanced by Hesse and Schenk (2013) and attempted to demonstrate that Garner interference can be modulated by the decision amplitude. Specifically, we expected that only with a short amplitude Garner interference would be observed in the manual estimation task, while with a long decision amplitude, Garner interference would not be visible, because RTs in this case do not include the decision time. Thus, we reasoned that the probability of observing Garner interference should be increased in the condition with the short amplitude. However, neither did we observe overall Garner interference nor was there a significant interaction pointing to the expected modulation by amplitude. However, decision amplitude had an effect on RT, MT, and ManEstTime. This is certainly expected and obvious for MT and ManEstTime, because MT/ManEstTime would strongly depend on the distance to the manual estimate location. The notable result is the effect on RT: Participants were faster to respond in the long condition than in the short condition (24 ± 7 ms). These faster responses in the long condition might indicate that participants delay their decision to after movement onset. This result is in line with Hesse and Schenk (2013) and their decision amplitude hypothesis. However, based on these results, we cannot conclude whether the distance / decision amplitude played a role in modulating Garner interference in manual estimation in our Experiments 1 and 2.

Our results on variability-based Garner interference were consistent with Experiments 1-2 and additionally, we did not observe an effect of amplitude. Future research should address whether variability-based Garner interference is more robust and immune to effects of decision amplitude than RTs.

Despite our efforts to modulate the Garner interference effect between the short and long conditions, we obtained almost identical results in both conditions, which are also numerically similar to results from Experiments 1-2. The Bayesian comparison was also consistent and revealed strong support for the hypothesis that Garner interference in manual estimation is more similar to grasping than to speeded-classification.

We conducted the following Experiment 4 as a control to check if our results were due to our short condition (7 cm) being longer than the 5 cm in the study by Hesse and Schenk (2013).

3.5 Experiment 4: Open-Loop Manual Estimation and Shorter Amplitude

Our results from Experiment 3 suggest an influence of short versus long response amplitude on the overall RT, but not on Garner interference in RTs. One objection to Experiment 3 might be that our short condition had a distance of 7 cm, while the short condition in Hesse and

Schenk (2013) was 5 cm. To rule out the possibility of our short condition not being "short enough", we conducted another manual estimation experiment, with only one response amplitude condition of 3 cm, that is, even shorter than 5 cm used by Hesse and Schenk (2013).

In addition, we modified the task to further favour the decision-amplitude hypothesis by testing for Garner interference in an open-loop manual estimation task. This meant that after movement onset, participants no longer had visual feedback about the stimulus. Hesse and Schenk (2013) reported Garner interference in their open-loop grasping task and they reasoned that it was due to the open-loop nature of the task. Because participants knew that they will not have visual feedback after movement onset, they took longer to initiate the movement, thereby causing the Garner interference effect in RT (time until movement onset). There is only one other study (Schum et al., 2012) that actually investigated Garner interference in open-loop manual estimation but their result was not significant (-4 ± 14 ms), so there is an urgent need for more data on this task.

Finally, we also included an additional Garner condition in the experiment, called the correlated condition. This condition was part of Garner's original experiments and required two additional blocks: one with stimuli A and D, the other with stimuli B and C (see Figure 16). The idea is that the length and width of the stimuli within a block are either positively (B and C) or negatively correlated (A and D), such that one dimension can predict the other. Therefore, if length and width cannot be independently processed, and correlate with each other, knowing one will facilitate the classification of the other. Accordingly, a comparison of the RTs in the baseline and correlated conditions shows that participants are faster in the correlated condition for integral dimensions (Garner, 1974). We will call this RT difference the Garner facilitation effect (= Baseline – Correlated). Our reasoning for using this additional condition is the following: if it is somewhat inconclusive whether or not there is a Garner interference effect in manual estimation that is larger than in grasping, then alternative evidence may be provided by demonstrating a clear Garner facilitation effect. Furthermore, it addresses the issue of presenting differing numbers of stimuli between the baseline and filtering conditions, two stimuli per block in baseline and four stimuli per block in filtering conditions (see also Dyson & Quinlan, 2010; Janczyk & Kunde, 2012). In the correlated condition, there are also two stimuli presented per block, thus making it more comparable to the baseline condition. To our knowledge, no other study tested for Garner facilitation in manual estimation, while two studies investigated Garner facilitation in grasping: (Eloka et al., 2015) tested it in closed-loop grasping and found a non-significant effect in RT (-5 ± 4 ms), and recently, Warnecke (2024) tested it in both closed and open-loop grasping, with non-significant effects in both RT (closed-loop: -1.5 ± 1.7 ms, open-loop: -2.3 ± 2.3 ms) and variability (closed-loop: 0 ± 0.1 mm, open-loop: 0.2 ± 0.1 mm).

Therefore, in this experiment we performed two modifications that should favour the occurrence of Garner interference and included an additional condition that should allow us to test for alternative evidence for a dissociation between grasping and manual estimation.

3.5.1 Method

3.5.1.1 Transparency and Openness

This experiment was pre-registered at AsPredicted (https://aspredicted.org/VC3_2T4). Data collection took place in 2023-24, and began before the pre-registration (for details see pre-registration). We have pre-registered this experiment for consistency with the other experiments, and to control for optional stopping by setting the final sample size comparable to Experiment 3.

3.5.1.2 Participants

Thirty-two new participants performed the experiment. Two were excluded *a priori* (one was left-handed, the other ambidextrous), but were allowed to participate nevertheless as part of a research seminar (results were similar even when including these data). Therefore, the data of 30 right-handed participants (17 women, 13 men, mean age = 22 years, age range = 19 - 30 years) were analysed. We pre-registered a sample size of 30 participants so that it would be comparable to Experiment 3 and to have balanced groups (six groups resulting from counterbalancing, see below).

3.5.1.3 Stimuli, Apparatus and Procedure

The experiment consisted of only manual estimation. Stimuli and apparatus were identical to Experiments 1-3. Participants performed three conditions: Baseline, Filtering and Correlated. The order of the conditions was fully counterbalanced and alternated (resulting in six possible orders). Participants performed 12 blocks in total and each block consisted of 32 trials, resulting in 384 trials overall. Participants performed manual estimation at a distance of 3 cm from the start position. In contrast to Experiments 1-3, the shutter goggles turned opaque at movement onset and no visual feedback was further available (open-loop manual estimation). One small change in the stimuli compared to the previous experiments was that a 5 mm thick felt padding was glued to the bottom of the rectangular cuboids. This dampened the sound made when they were placed on a surface, which may serve as a warning for participants that the trial is about to begin.

3.5.1.4 Dependent Variables and Analyses

Most analyses were identical to Experiment 2. We additionally calculated the Garner facilitation effect by taking the difference between the Baseline and Correlated conditions. Outliers were determined in the same way as Experiments 1-2 and 4% of trials were thus excluded.

3.5.2 Results

The RT, MT, ManEstTime, and variability of ManEst are provided in Table 14. The Garner effects are listed in Table 15 – 16 and depicted in Figure 21 below. Participants' RTs increased slightly from Experiment 1-3, likely because of the open-loop nature of the task. The MTs decreased in comparison with Experiment 3 because the response amplitude for the manual estimate was now even shorter (3 cm instead of 7 cm) so participants needed less time to move this shorter distance.

We did not find a significant Garner interference or Garner facilitation effect in RT, the most important variable. The situation is similar for ManEstTime and variability of ManEst. But for MT, we found a small and significant Garner interference effect of 7 ms. The Garner facilitation effect in MT was similar in magnitude but did not reach significance.

Table 14

Results of Experiment 4 in Baseline, Filtering, and Correlated Conditions

Variable (unit)	**Correlated**	**Baseline**	**Filtering**
RT (ms)	395 ± 16	401 ± 17	400 ± 15
MT (ms)	577 ± 24	584 ± 25	591 ± 26
ManEstTime (ms)	972 ± 34	985 ± 37	991 ± 36
SD_{ManEst} (mm)	4.40 ± 0.26	4.37 ± 0.21	4.47 ± 0.21

Note. Values are reported as mean ± standard error of the mean.

For the Bayesian comparison to test whether Garner interference in open-loop manual estimation is more similar to open-loop grasping (H_1) than to speeded-classification (H_0), we used the open-loop grasping and speeded-classification results from Experiment 1 as priors, because Experiment 4 involved only manual estimation (see Section 3.2.1.8 of Experiment 1 for details). This yielded a BF_{10} = 638.5, which presents strong evidence that Garner interference in open-loop manual estimation is more similar to open-loop grasping than to speeded-classification.

Table 15

Garner Facilitation Effects and Results of Paired One-tailed t-tests in Experiment 4

Variable (unit)	M ± SEM	$t(29)$	p	d_z	BF_{10}
RT (ms)	6 ± 6	0.98	.168	0.18	0.50
MT (ms)	7 ± 6	1.18	.123	0.22	0.64
ManEstTime (ms)	13 ± 11	1.17	.125	0.21	0.63
SD_{ManEst} (mm)	-0.02 ± 0.16	-0.14	.554	-0.02	0.18

Note. M = mean, SEM = standard error of the mean. Facilitation = Baseline – Correlated.

3.5.3 Discussion

Experiment 4 was conducted to rule out that Garner effects may have been missed because the short amplitude condition in Experiment 3 was not short enough. Therefore, we decreased the amplitude of the short condition to 3 cm in Experiment 4. We also made manual estimation task open-loop and included a correlated condition to check for Garner facilitation effects. All these changes were expected to favour and increase the likelihood of occurrence of Garner effects. The results indicate that the shorter response amplitude and open-loop conditions

Table 16

Garner Inteference Effects and Results of Paired One-tailed t-tests in Experiment 4

Variable (unit)	M ± SEM	$t(29)$	p	d_z	BF_{10}
RT (ms)	-1 ± 5	-0.27	.607	-0.05	0.16
MT (ms)	7 ± 4	1.90	.034	0.35	1.81
ManEstTime (ms)	6 ± 7	0.94	.179	0.17	0.47
SD_{ManEst} (mm)	0.09 ± 0.14	0.68	.252	0.12	0.36

Note. M = mean, SEM = standard error of the mean. Interference = Filtering – Baseline.

slightly increased the RT (compared to the previous experiments), but there was still no significant Garner effect – neither interference nor facilitation. The Bayesian comparison instead revealed strong support for the hypothesis that Garner interference in open-loop manual estimation is more similar to open-loop grasping than to speeded-classification.

In Experiments 1-3, variability-based Garner interference seemed promising and robust enough to detect in manual estimation, but it was not significant in the present experiment. Since there were as many trials and even more participants in Experiment 4 than Experiment 2, we expect there to be sufficient precision to detect an effect as large as in Experiment 2.

Finally, there was a small but significant Garner interference effect in MTs. None of the other results or studies found such an effect on MTs. As explained in Experiment 1, MT is a better measure of Garner interference than ManEstTime, because it is independent from RT. Further research and more data are required to confirm this effect.

3.6 Comprehensive Literature Review

Two studies reported large effects of Garner interference in manual estimation RTs (31 ± 13 ms, Ganel & Goodale, 2003; 22 ± 10 ms, Ganel & Goodale, 2014), but we found much smaller effects across the four experiments reported here. In the present section, we aim to resolve this empirical inconsistency with a comprehensive and quantitative literature review. Many studies measured Garner interference for speeded-classification and grasping, and although they did not include manual estimation, compiling the results across these different tasks and studies may allow us to better estimate these effects (Spence & Stanley, 2024; Stanley & Spence, 2014). In addition to looking at effects from each individual study, we also compute weighted averages across all studies to get an estimate of the effect based on all the currently available data.

3.6.1 Method

3.6.1.1 Study Selection and Data Availability

Based on a literature review, we identified those studies that investigated Garner interference and were comparable to the very first study on this topic by Ganel and Goodale (2003): Eloka et al. (2015), Ganel and Goodale (2014), Hesse and Schenk (2013), Janczyk and Kunde (2010, 2016), Janczyk et al. (2010), Kunde et al. (2007), Löhr-Limpens et al. (2020), and Schum et al. (2012). The following studies were excluded: Janczyk and Kunde (2012) because they did not have a baseline and filtering condition separately, and Freud and Ganel (2015) and the grasping task of Löhr-Limpens et al. (2020) because they presented 2D objects (this is controversial for Löhr-Limpens et al., 2020; see Ganel et al., 2020). Summary statistics reported in the original publications and values from plots (digitised wherever possible) were used to calculate Garner interference from Ganel and Goodale (2003, 2014) and Kunde et al. (2007). Tzvi Ganel and Constanze Hesse kindly provided partial data from Ganel and Goodale (2003, 2014) and Hesse and Schenk (2013) via personal communication, respectively. The full data from the following studies were available through the authors MJ and VHF who were co-authors on these studies: Eloka et al. (2015), Janczyk and Kunde (2010, 2016), Janczyk et al. (2010), and Schum et al. (2012). The data of Löhr-Limpens et al. (2020) were openly available. Details for each study are listed in Table 17.

Table 17

Sample Size and Number of Trials in Studies on Garner Interference

Study	Code	SC		Closed-Loop				Open-Loop			
				Grasp		ME		Grasp		ME	
		N	K	N	K	N	K	N	K	N	K
Ganel and Goodale (2003)	GG03	12	128	12	128	8	128	12	128		
Kunde et al. (2007)	K07	24	288	24	288						
Janczyk and Kunde (2010)	JK10	16	288	16	288						
Janczyk et al. (2010)	J10	32	288								
Schum et al. (2012)	S12	20	128			20	128	20	128	20	128
Hesse and Schenk (2013)	HS13	24	128					20	128		
Ganel and Goodale (2014)	GG14			40	256	40	256				
Eloka et al. (2015)	E15	24	168	24	168						
Janczyk and Kunde (2016)	JK16	32	288					32	288		
Löhr-Limpens et al. (2020)	LL20	24	96								
Experiment 1	Exp1	24	128	24	128	24	128	24	128		
Experiment 2	Exp2					24	256				
Experiment 3 Short	Exp3S					32	192				
Experiment 3 Long	Exp3L					32	192				
Experiment 4	Exp4									30	256
Warnecke (2024)	W24			36	256			36	256		

Note. Code represents the abbreviation used in x-axes of Figures 21–24. N = number of participants, K = number of trials in total (Baseline + Filtering), SC= speeded-classification, ME = manual estimation.

3.6.1.2 *Dependent Variables and Analyses*

We focused on the dependent variables most commonly reported and deemed important and of interest by previous studies. Our analyses therefore included RT (or time to initiate movement), the most often reported dependent variable. For manual estimation, the time to complete manual estimation (ManEstTime; see Experiment 1) was reported by Ganel and Goodale (2003) and Schum et al. (2012). We therefore also analysed this measure and used the MGA-Time as the analogous variable in grasping. Further, we analysed the variability-based Garner interference in MGA/ManEst, and calculated the height-width illusion effect. We calculated SEMs where possible. In addition, we calculated the weighted mean for each dependent variable across the different studies. The weights were determined by the sample size of those studies. Because the SEM for each individual study was not always available, the SEM of the weighted mean was calculated by taking the standard error of the (non-weighted) means of all the studies.

3.6.2 Results

The data presented here comprise two parts: (a) results from studies on Garner interference, and (b) completely new analyses of published data (e.g., variability-based Garner interference and the height-width illusion were not originally reported by many studies). Figures 21-24 depict an overview of the results. Numerical values of the overall Garner interference effects from the figures are also listed in Table 18.

Table 18

Weighted Means ± SEM for Garner Interference in Different Dependent Variables

Variable (unit)	SC	Closed-Loop		Open-Loop	
		Grasp	ME	Grasp	ME
RT (ms)	42 ± 6	2 ± 3	9 ± 5	10 ± 5	-2 ± 2
MGA/ManEstTime (ms)		-3 ± 2	17 ± 6	4 ± 9	-6 ± 16
Variability (mm)		0.10 ± 0.06	0.35 ± 0.06	0.46 ± 0.13	0.16 ± 0.09

Note. SC = speeded-classification, ME = manual estimation.

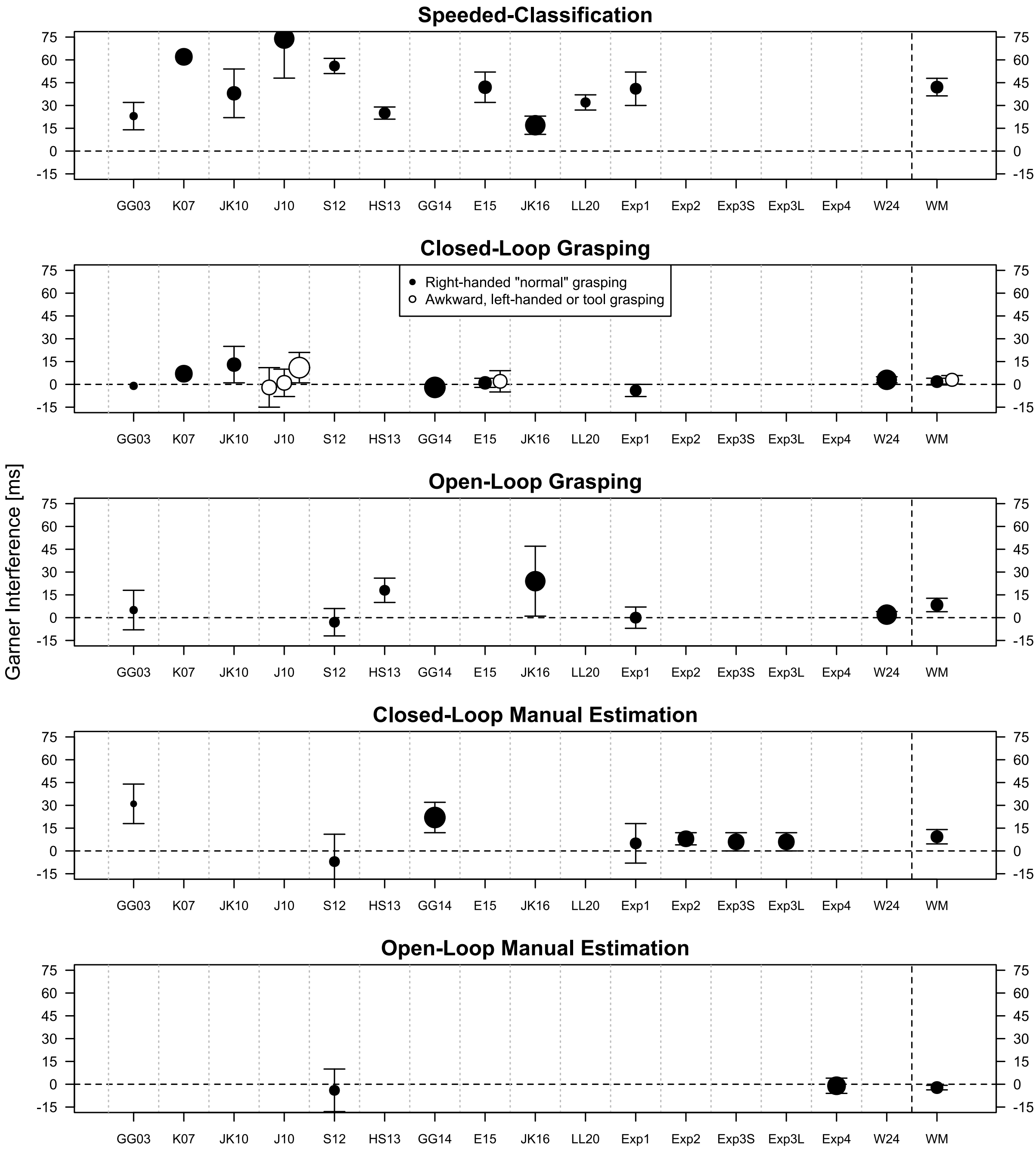
Most studies analysed RTs and therefore we have many data points for this variable available. Comparing the weighted means (Table 18 and Figure 21), it seems clear that speeded-classification has a large effect which is far larger than in grasping and manual estimation, which have a much smaller effect. Furthermore, the open symbols in Figure 21 represent unusual cases of grasping where the PAM predicts a Garner interference effect due to ventral intrusions (see General Discussion). The weighted means however suggest that the effect is similar to cases of "normal" grasping, and is close to zero.

For MGATime/ManEstTime, the picture is unclear. Considering manual estimation, some studies that found a large value (GG03 and our Experiment 1, see Figure 22), could not replicate their own finding when methods were improved (GG14 and our Experiment 2, see Figure

22) and the subsequent result was much smaller, even though the subsequent study was conducted by the same authors. However, it must first be resolved whether Garner interference should be expected in ManEstTime at all.

Figure 21

Garner Interference Effects in Reaction Time

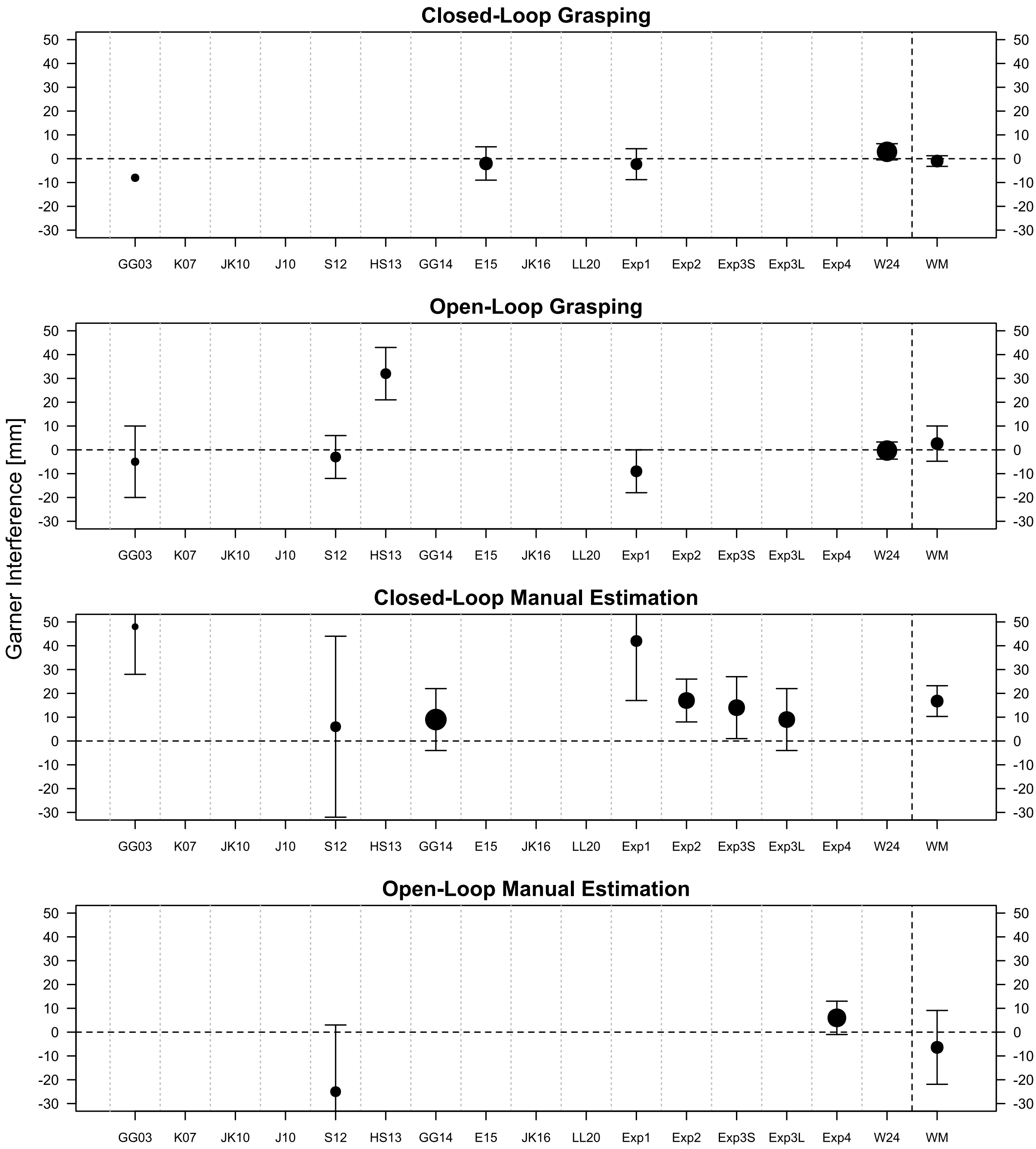


Note. The size of the symbol for each study is scaled according to the square root of the product of the sample size and number of trials in that study. Error bars represent ± 1 SEM. See Table 17 for study abbreviations. WM = Weighted Mean.

Variability-based Garner interference was introduced only later by Ganel and Goodale

Figure 22

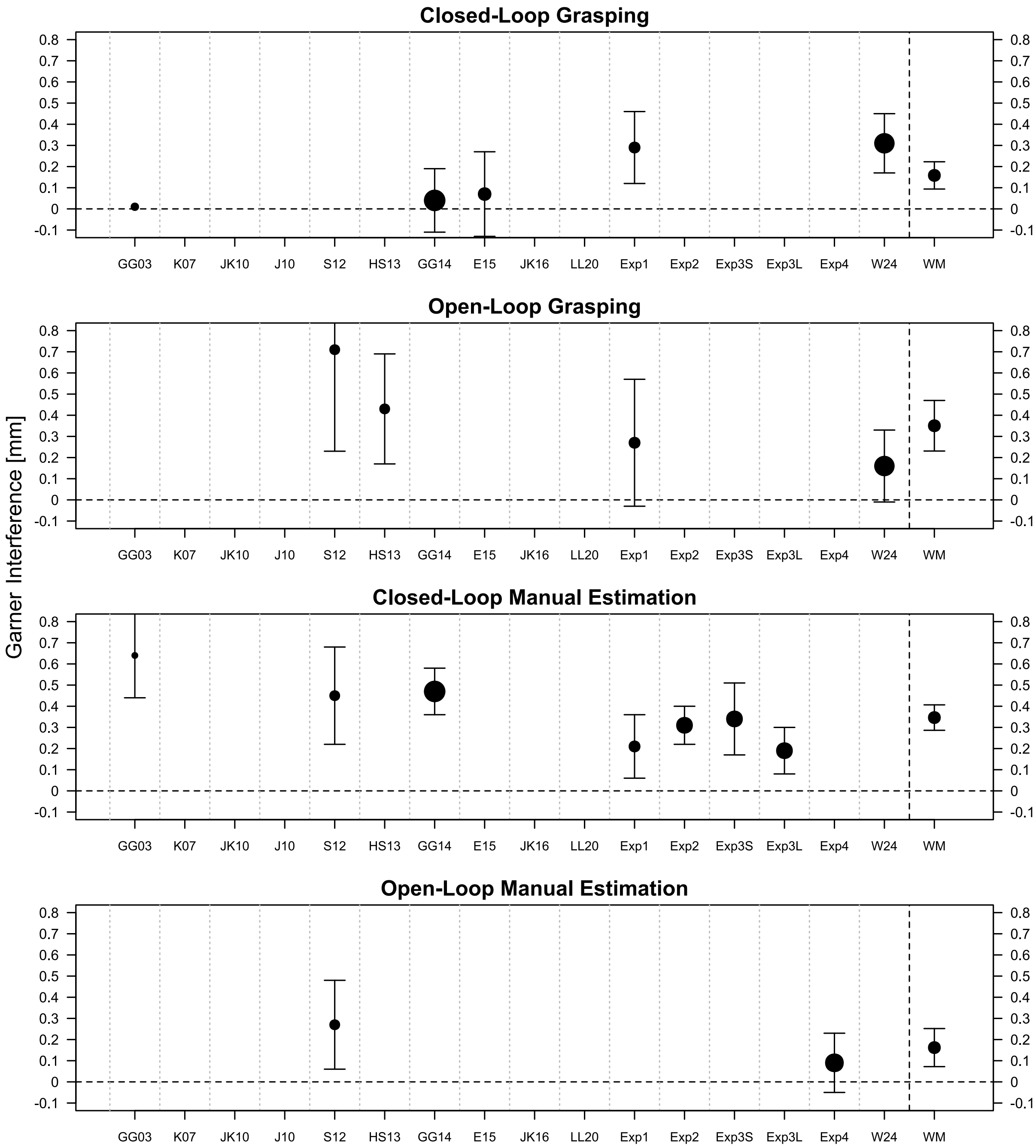
Garner Interference Effects in MGATime / ManEstTime



Note. Garner Interference in MGATime for grasping and ManEstTime for manual estimation. The size of the symbol for each study is scaled according to the square root of the product of the sample size and number of trials in that study. Error bars represent ± 1 SEM. See Table 17 for study abbreviations. WM = Weighted Mean.

Figure 23

Variability-Based Garner Interference Effects



Note. Garner interference in the variability (within-participant standard deviation) of grasping (MGA) and manual estimation (ManEst). The size of the symbol for each study is scaled according to the square root of the product of the sample size and number of trials in that study. Error bars represent ± 1 SEM. See Table 17 for study abbreviations. WM = Weighted Mean.

(2014). Here we find differences between closed and open-loop conditions: there seems to be a difference between closed-loop grasping and manual estimation but the difference is in the opposite direction in open-loop conditions (see Table 18 and Figure 23). For the height-width illusion, we have even fewer data points available (see Figure 24). Therefore, the weighted means are not very informative. Ganel and Goodale (2003) reported the height-width illusion effect for the filtering condition only. For completeness, we depict in Figure 24 baseline and filtering conditions separately.

3.6.3 Discussion

We performed a literature review and compiled the results to give an overview of Garner interference in different tasks and dependent variables for all studies on this topic. Let us first summarise the findings at the level of the overall effects (i.e., weighted means).

The most important dependent variable is RT (because this is the variable that can be measured in all tasks, cf. Figure 21). For speeded-classification, results are very consistent: There is a clear Garner interference effect on RTs. For manual estimation, however, there is overall hardly any Garner interference on RTs and — most importantly — those effects are similar to the Garner interference effects found in grasping. This suggests that manual estimation and grasping may be more similar than often assumed (see also Figure 25).

For MGATime/ManEstTime (Figure 22), the Garner interference effects in manual estimation seem so unreliable that they could not be replicated even by the same authors (compare GG03 to GG14). Therefore, future research should clarify whether ManEstTime is a variable of interest for Garner interference. Also, it would need to be clarified whether ManEstTime (measured at the time of the manual estimation) is functionally comparable to a MGATime in grasping (measured at the time of maximum grip aperture).

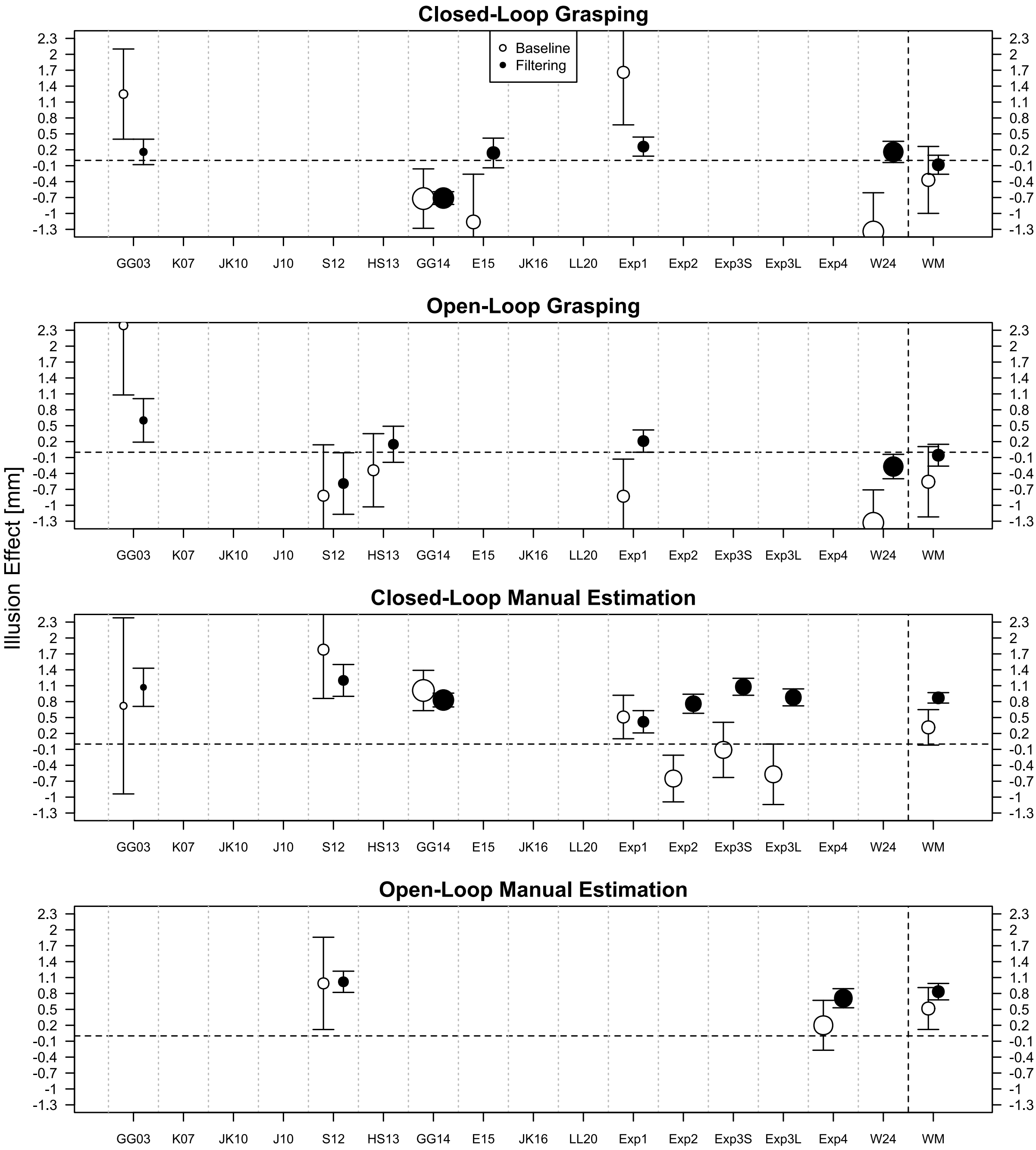
Variability-based Garner interference effects (Figure 23 and 26) shows an interesting reversal: It seems larger in closed-loop manual estimation than in closed-loop grasping, while the opposite seems to be the case for open-loop manual estimation (i.e., smaller Garner interference than in open-loop grasping).

Testing for the height-width illusion (Figure 24) shows quite variable effects, such that results are difficult to interpret. For example, the largest measured effect was in the baseline condition of open loop grasping (cf. data point GG03) and not in manual estimation. Future research should clarify how baseline and filtering conditions should be taken into account (e.g., Ganel & Goodale, 2003, analysed only the filtering condition, but did not give a rationale why one should ignore the baseline condition). Finally, none of the studies made a direct comparison between grasping, manual estimation and a classic perceptual task — which would be a good reference for such research (e.g., Franz & Gegenfurtner, 2008).

All in all, the data from all studies currently available on Garner interference in the context of the PAM show a small difference in some dependent variables, but do not provide consistent or convincing evidence for differences in manual estimation and grasping. These differences are even smaller when considering open-loop grasping. Open-loop grasping versus closed-loop manual estimation may be an unfair comparison, but the dorsal versus ventral assumption still applies here, and some studies even argued that open-loop conditions provide

Figure 24

Height-Width Illusion Effects

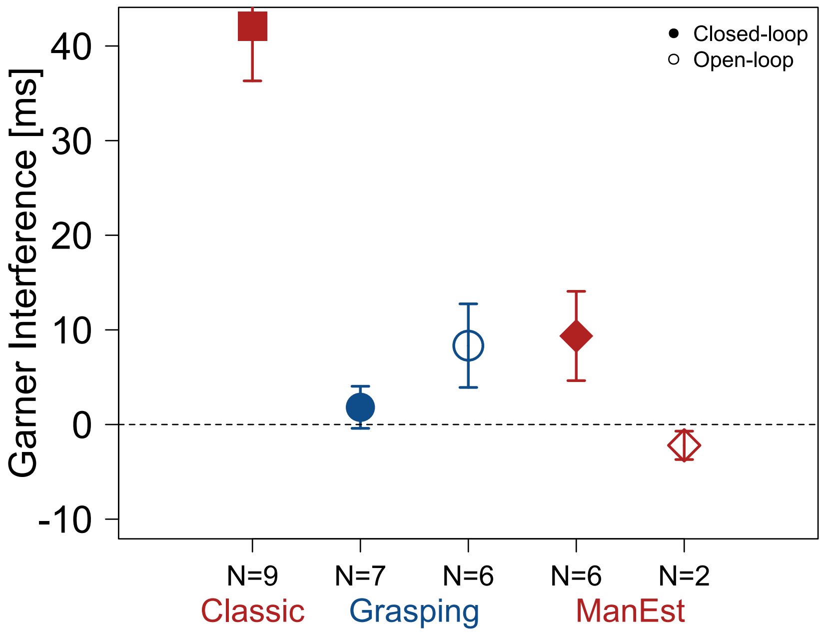


Note. The size of the symbol for each study is scaled according to the square root of the product of the sample size and number of trials in that study. Error bars represent ± 1 SEM. See Table 17 for study abbreviations. WM = Weighted Mean.

a stronger test-case for the PAM (Haffenden & Goodale, 1998; Post & Welch, 1996). Furthermore, the literature review also revealed that, while there are equally many studies investigating closed-loop and open-loop grasping, there are only two studies (including the present one) that investigated open-loop manual estimation, and future research should fill this em-

Figure 25

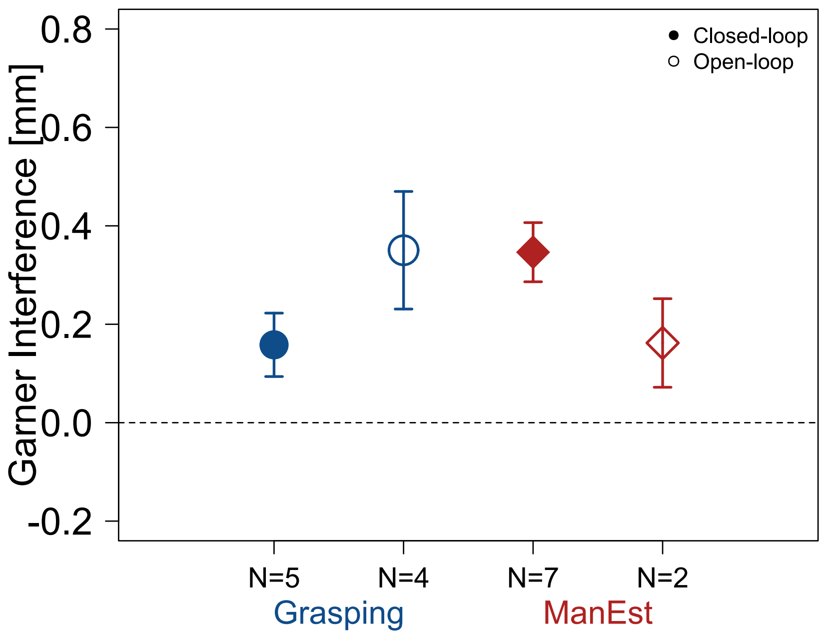
Weighted Means of Garner Interference in Reaction Time



Note. N represents the number of studies used to calculate the weighted mean. Classic = speeded-classification, ManEst = manual estimation.

Figure 26

Weighted Means of Garner Interference in Variability



Note. N represents the number of studies used to calculate the weighted mean. ManEst = manual estimation.

pirical gap. This is all the more important because our literature review suggests that there is a different pattern of results in some dependent variables between open-loop and closed-loop manual estimation, but the PAM is silent about whether open-loop versus closed-loop tasks are processed differently.

3.7 General Discussion

The presence of Garner interference in manual estimation and its absence in grasping has been used as evidence for the PAM (Goodale & Milner, 1992), the notion that the dorsal and ventral stream process visual information independently and differently for action and perception, respectively (Ganel & Goodale, 2003, 2014). However, the empirical results for manual estimation are quite unclear. This crucial and important comparison task lacks widespread and convincing empirical support. The goal of the present study was to add to the discussion with improved replications of the original study on this topic (Ganel & Goodale, 2003).

3.7.1 Is There Garner Interference in Manual Estimation?

The central question posed here was: Is there Garner interference in manual estimation? Manual estimation is a task assumed to have comparable demands as grasping, therefore this comparison is the most appropriate test for the PAM (rather than comparing grasping with speeded-classification). Reviewing the literature revealed that Garner interference in manual estimation has not often been replicated, and one study even observed a non-significant negative effect (Schum et al., 2012).

The main focus of our investigation was RT, as it is the most frequently reported dependent variable. For other variables, the results did not show a clear consensus. In Experiments 1 and 2, we tried to replicate Ganel and Goodale (2003, 2014) and were able to observe the typical results of large Garner interference in speeded-classification and small, non-significant Garner interference in grasping. However, we did not conclusively observe Garner interference in manual estimation in Experiments 1 and 2, and the descriptive size of Garner interference was $<$ 10 ms which is much smaller than the 20-30 ms Garner interference reported in previous studies (Ganel & Goodale, 2003, 2014). These results suggest that the Garner interference in RTs of manual estimation, if it is present at all, is rather small (see Figure 21). Further, the Bayesian comparisons resulted in $BF_{10} \geq 10$ across all four experiments, providing substantial-to-strong evidence that the small Garner interference in manual estimation is more similar to the Garner interference in grasping than in speeded-classification.

3.7.1.1 Relationship Between Garner Interference and Reaction Time

The results of Experiment 1 (Table 8) reveal a relationship that is not entirely unexpected: the magnitude of Garner interference seems to depend on RT. Indeed, plotting RTs as a function of Garner interference (Figure 27) indicates a strong correlation (r = 0.83): the longer the RT in a task, the larger the Garner interference (for a similar issue in the Stroop effect, see Verhaeghen & De Meersman, 1998).

Furthermore, a positive correlation between RT and the size of Garner interference was present for each individual task. This means that Garner interference seems to increase with RT in each task, so larger Garner interference would be expected for longer RTs regardless of whether that task is grasping, manual estimation or speeded-classification. In light of this result, the assumption that grasping and manual estimation have similar task demands may not be reasonable. This might be a more parsimonious explanation for some studies reporting differences in Garner interference in these tasks, than attributing the processing of these tasks to the dorsal and ventral streams.

3.7.2 Does Decision Amplitude Affect Garner Interference?

To explain our results of very small Garner interference for manual estimation in Experiments 1-2, we considered whether the decision amplitude may be modulating the Garner interference effect. Hesse and Schenk (2013) pointed out that presence or absence of Garner interference in RTs is problematic for evaluating processing differences in tasks, because one could modulate Garner interference within the same task by changing time constraints or decision amplitude.

While Hesse and Schenk (2013) demonstrated this only for speeded-classification, we extended their reasoning to manual estimation in Experiment 3 and compared a short and long decision amplitude condition. While we did not observe the expected dissociation (Garner interference larger for short condition than for long condition), overall RTs were longer for the short amplitude condition than for the long amplitude condition, suggesting that participants took more time in the short amplitude condition, because their decision was made before movement onset. This result, however, is somewhat inconclusive with regards to our original question. We could not find evidence to support the idea that not replicating the Garner interference in manual estimation was due to differences of set-up (distance/decision amplitude) between our study and Ganel and Goodale (2003). Notably, Garner interference in RTs of the manual estimation tasks were remarkably consistent across Experiments 1-4 and had a size of about 6 ms (albeit not consistently significantly different from 0).

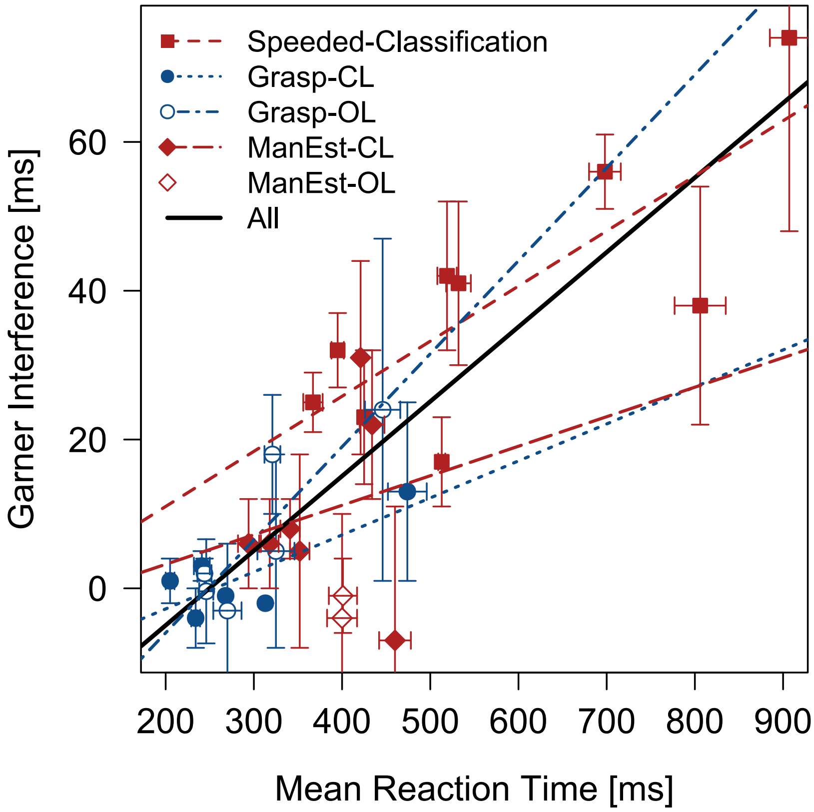
3.7.3 Is Response Variability a Better Measure for Garner Interference?

In response to the critique by Hesse and Schenk (2013) on using RTs, Ganel and Goodale (2014) demonstrated that Garner interference is also present in the variability of the grip aperture during manual estimation, but not in grasping. This variability-based Garner interference is assumed by Ganel and Goodale (2014) to be more robust than simple RT to show differences between the baseline and filtering conditions.

In our experiments, we also tested for variability-based Garner interference in manual estimation and grasping. The results suggest that, while RT effects of Garner interference seem to be unreliable, variability-effects seem to be small, but rather consistently observable in both grasping and manual estimation. In Experiment 1, both types of grasping and manual estimation had a similar Garner interference in the variability, with manual estimation showing the smallest effect. In Experiments 2-3, we found a numerically consistent and statistically significant Garner interference effect in the variability for manual estimation. In Experiment

Figure 27

Garner Interference as Function of Mean Reaction Time



Note. Each point represents mean ± standard error of one study from Table 17. Regression lines depicting Garner interference as a function of mean reaction time are plotted for each task individually as well as for all tasks together. No regression line is plotted for open-loop manual estimation since there are only two studies with this task. ManEst = manual estimation, CL = closed-loop, OL = open-loop.

4, we found a small and statistically not significant variability-based Garner interference in open-loop manual estimation.

A recent related study (Warnecke, 2024) looked at Garner effects in closed and open-loop grasping, with a large sample size and large number of trials per participant for increased precision. The results for variability-based Garner interference in closed-loop grasping were in line with our Experiment 1: a large effect (see also Figure 23 and comparable in magnitude to the effect in manual estimation, and also statistically significant (likely due to the increased precision).

Since variability-based Garner interference was identified and presented as a relevant dependent variable of interest only later, in Ganel and Goodale (2014), many of the other studies on Garner interference did not adopt this analysis. For our literature review, we obtained data of the other studies, and present the values of variability-based Garner interference for the first time. These results (see Table 18, Figures 23 and 26) revealed that variability-based Garner interference was overall largest in open-loop grasping — which cannot easily be accommodated by the PAM.

To summarise, RT results for a perception-action dissociation regarding Garner interference are somewhat inconclusive because there seems to be no clear Garner interference effect in manual estimation. On the other hand, variability-based Garner interference shows consistent effects in manual estimation. However, similar effects in grasping were present in Experiment 1 and studies like Warnecke (2024) (see Tables 9 and 18, and our literature review in Section 3.6). This discrepancy is even more prominent in open-loop conditions because the largest effects were obtained where none were expected (grasping), and vice-versa (manual estimation, see Figure 23). Future research should investigate this difference between open-loop and closed-loop conditions and whether this variable can be established as providing strong support for the PAM.

3.7.4 Is Garner Interference Present in Ventrally-Processed Unusual Grasping?

We have so far focused on right-handed precision grasping, as this is assumed the prototypical task for which the dorsal stream is responsible (Gonzalez et al., 2008). Yet, besides the central claim of the PAM regarding Garner interference in manual estimation, but not grasping, there are further predictions that are not supported by empirical evidence. Briefly, they concern situations that use some sort of grasping, but in rather unusual conditions like grasping 2D objects (as opposed to 3D), grasping with a tool, grasping with the left (or non-dominant) hand, or in an awkward manner not involving the thumb and index finger, but rather the thumb and ring finger. Under these conditions, it is assumed by the PAM, that "the grasp is more deliberate and less practiced" and that "cognitive supervision of the grasp would recruit ventral stream processing" (Gonzalez et al., 2008, p. 629). Consequently, it is expected that the representations underlying these unusual grasping conditions are more holistic than analytical. Hence, Garner interference should be observable in these tasks. In the following, we will summarise relevant results for grasping 2D objects (Freud & Ganel, 2015) as well as left-handed, awkward, and tool grasping (Eloka et al., 2015; Janczyk et al., 2010).

3.7.4.1 Grasping 2D Objects

Freud and Ganel (2015) investigated grasping 2D objects and found variability-based Garner interference (0.99 ± 0.25 mm), but the Garner interference in RTs did not reach significance (12 ± 9 ms). The result for RT in a recent replication by Löhr-Limpens et al. (2020) in open-loop grasping was similar (-1 ± 5 ms; they used a mirror-set-up such that participants saw a 2D object, but felt a physical 3D object when they made a grasp toward it), but the variability-based Garner interference (0.41 ± 0.30 mm) in their single-task condition was much smaller than in Freud and Ganel (2015) and not significant. Freud and Ganel (2015) hypothesized that grasping 2D objects may involve interactive dorsal and ventral processing leading to a lack of Garner interference in RTs. However, the same logic can be used to explain a lack of Garner interference in RTs in 3D grasping (assumed only dorsal processing), especially given that we found similar variability-based Garner interference in grasping (assumed only dorsal processing) and manual estimation (assumed only ventral processing) in Experiment 1. In addition, pointing movements to 2D objects with the computer mouse, a task arguably not very akin to right-handed precision grasping, was not susceptible to Garner interference, while the same stimuli yielded Garner interference in a perceptual task (Janczyk et al., 2013).

3.7.4.2 *Awkward, Left-handed, and Tool Grasping*

Gonzalez et al. (2006, 2008) presented evidence that awkward, unskilled grasping (i.e., between thumb and ring finger) and left-handed grasping were sensitive to effects of visual illusions, while right-handed precision grasping was immune to them. This was interpreted as further evidence that certain actions are under ventral control. However, Janczyk et al. (2010) investigated these "ventrally-processed actions" using Garner interference. Right-handed participants grasped objects in baseline and filtering conditions with their left hand, with an awkward grasp, and with a tool (pliers) across a series of three experiments. Garner interference was numerically small and not statistically significant in any case (left-handed grasping: 1 ± 9 ms, awkward grasping: -2 ± 13 ms, tool grasping: 11 ± 10 ms), even though these supposedly "ventral actions" should involve processing the objects in a holistic manner resulting in Garner interference. In a subsequent study, participants even performed left-handed awkward grasps (i.e., between thumb and ring finger of left hand) and still Garner interference was small (2 ± 7 ms) and not significant (Eloka et al., 2015).

Overall, these results stand at-odds with the predictions of the PAM. The weighted means for "unusual grasping" are depicted by hollow symbols in Figure 21, and are very similar to "normal grasping". This further shows that the picture of ventral versus dorsal processing for perception versus action with regard to Garner interference is not clear or consistent.

3.7.5 Consequences for the Perception-Action Model

We have shown that evidence from Garner interference in support of the PAM seems weaker and more inconclusive than previously assumed. As mentioned in the Introduction, Garner interference is only one of three lines of evidence from healthy participants suggested to show a dissociation between visual processing for perception and action. The other two lines are visual illusions and Weber's law. However, presumed perception-action dissociations for these cases have also not been entirely convincing, and recent studies (Bhatia et al., 2022; Kopiske et al., 2016) have described these problems.

Taken together, the results from behavioural experiments showing perception-action dissociations in healthy humans are mixed and not as clear-cut as previously believed. With two out of three lines of evidence unclear, it became increasingly important to examine the third line of evidence based on Garner interference. We observed similar issues and most importantly, empirical inconsistencies. Given this state, all three major lines of evidence in favour of the PAM seem inconclusive currently. Further investigation is required to claim strong support for the PAM from behavioural perception-action dissociations.

3.7.6 Outlook and Conclusions

3.7.6.1 Future Directions

Our investigation into Garner interference and the PAM revealed inconsistencies and open questions. Here we briefly summarise the issues that should be the basis of future studies to advance this field.

First, not many studies included a manual estimation task. Future research should focus on the critical comparison between grasping and manual estimation in Garner interference experiments, rather than taking for granted that manual estimation shows Garner interference. Using a speeded-classification task does not help here, because it is more or less resolved and clearly shows Garner interference. Subsequent studies should also use open-loop manual estimation, which only one other study (Schum et al., 2012) and our Experiment 4 employed so far. Open-loop conditions might be more favourable for Garner interference to occur in manual estimation, given the mechanisms suggested by Hesse and Schenk (2013). Also, Haffenden and Goodale (1998) argued that open-loop conditions would be more convincing in grasping because participants could not make any online adjustments based on visual feedback – at least for variables like MGATime and the variability of MGA. Finally, the dependent variables of interest should be clarified. For example, while Ganel and Goodale (2003) reported ManEst-Time, they did not report those values for their subsequent higher-powered study (Ganel & Goodale, 2014, we reanalysed these data and included those results in our Figure 22).

Lastly, the question remains whether Garner interference in manual estimation and grasping can be influenced by decision amplitude, as has been shown for speeded-classification (Hesse & Schenk, 2013). While we obtained some evidence for RTs being affected by decision amplitude in Experiment 3, we did not see a clear dissociation between long and short conditions in terms of Garner interference. We also did not find a significant Garner interference effect in Experiment 4 where we decreased the response amplitude even further. Answering this open question would also help to resolve whether RTs are suitable to test for Garner interference at all (Hesse & Schenk, 2013).

3.7.6.2 Conclusions

The idea that Garner interference is present in certain tasks like manual estimation, while visuomotor tasks like grasping do not show Garner interference (Ganel & Goodale, 2003, 2014), is often cited as supportive evidence for the idea of two separate visual streams (PAM Goodale & Milner, 1992). We showed that this claim lacks empirical support, with only very few studies having investigated manual estimation. In four experiments, we observed that the Garner interference in manual estimation is much smaller than previously reported, and more similar to grasping than often assumed. Compiling the results from all available studies on Garner interference in a literature review did not reveal consistent evidence for a dissociation between manual estimation and grasping, and consequently, perception and action.

3.8 Appendix to Section 3

3.8.1 Power Analyses

Here we describe and calculate the statistical power for Experiments 1-3 from previous studies on Garner interference.

3.8.1.1 Power for Garner Interference in Speeded-Classification in Experiment 1

Ganel and Goodale (2003) reported in their speeded-classification task shorter RTs for the baseline than for the filtering condition. The mean Garner effect was M_{SC} = 23 ms with $t(11) = 2.49$ and n = 12 (paired t-test). We calculate SEM and SD using:

$$SEM = \frac{M}{t} = \frac{23\ ms}{2.49} = 9.24\ ms \tag{16}$$

$$SD = SEM \times \sqrt{n} = 9.24\ ms \times \sqrt{12} = 32\ ms \tag{17}$$

The effect size Cohen's d_z (for repeated-measures) is then:

$$d_z = \frac{M_{diff}}{SD_{diff}} = \frac{23\ ms}{32\ ms} = 0.72 \tag{18}$$

For our Experiment 1, this results in a power of 1 – β = .96, with d_z = 0.72, n = 24 and α = 0.05 for a one-tailed, paired t-test (all power-analyses were calculated with the package 'pwr' in R).

3.8.1.2 Power for Garner Interference in Manual Estimation in Experiment 1-2

Similar to above, Ganel and Goodale (2003) reported in their manual estimation task shorter RTs for the baseline than for the filtering condition: Mean difference M_{ME} = 31 ms (digitised from their Figure 3), n = 8 and $t(7) = 2.39$. This gives SEM = 13 ms and SD = 37 ms, and further, Cohen's d_z = 0.84. Note that this effect was even larger than the effect obtained in speeded-classification. This leads one to expect a Garner interference effect in manual estimation that is about as large as the effect in speeded-classification, given that they are both ventral tasks and assumed to be processed similarly (holistically).

However, in Ganel and Goodale (2014) , the effect size in manual estimation was much smaller: M_{ME} = 22 ms, n = 40, SEM = 10 ms, SD = 63 ms, Cohen's d_z = 0.35. We therefore list the power values for different effect sizes ranging from 0.84 (Ganel & Goodale, 2003) to 0.35 (Ganel & Goodale, 2014) in Table 19. Note that in Ganel and Goodale (2014) the task was not speeded (Table 11), which is different from Ganel and Goodale (2003). One estimate of the effect size could be the average from the Ganel and Goodale studies, resulting in Cohen's d_z = 0.60, for which we have a power of 1 – β = .89 with n = 24. For Experiment 2 (where we doubled the number of trials), the power will be even larger.

Table 19

Power Values for Different Cohen's d_z in Manual Estimation in Experiment 1

Cohen's d_z	**Value Obtained From**	**Power (one-Tailed)**
0.35	Manual Estimation (Ganel & Goodale, 2014)	.51
0.40		.60
0.45		.69
0.50		.77
0.55		.83
0.60	Mean of Ganel and Goodale (2003, 2014)	.89
0.65		.93
0.70	≈ Speeded-classification (Ganel & Goodale, 2003)	.95
0.75		.97
0.80		.98
0.85	≈ Manual Estimation (Ganel & Goodale, 2003)	.99

3.8.1.3 Power for Difference Between Manual Estimation and Grasping in Experiment 1

We want to determine the power to detect a larger Garner interference in RTs (filtering - baseline) of manual estimation than in grasping for our repeated-measures design in Experiment 1. Because Ganel and Goodale (2003) used an independent-measures design with different samples of participants for grasping and manual estimation, we need to transform the Cohen's d to a repeated-measures Cohen's d_z (see below).

For manual estimation, Ganel and Goodale (2003) found a mean Garner effect on RT of M_{ME} = 31 ms (digitised from their Figure 3) with n_{ME} = 8 and $t_{ME}(7)$ = 2.39. For grasping, Ganel and Goodale (2003) reported only numerical values for "time to complete grasping" but not for RTs (p. 665). Therefore, we used the reported values for "time to complete grasping" as a substitute, $M_{G_{complete}}$ = -3 ms, n_G = 12, $t_{G_{RT}}(11)$ = 0.3. Note that this substitute slightly overestimates the SEM (due to more noise from the movement in "time to complete grasping" than in RT) and therefore slightly *underestimates* the power. As before, we can calculate SEM and SD:

$$SEM_{ME} = \frac{M_{ME}}{t_{ME}} = \frac{31\ ms}{2.39} = 13\ ms \tag{19}$$

$$SD_{ME} = SEM_{ME} \times \sqrt{n_{ME}} = 13\ ms \times \sqrt{8} = 37\ ms \tag{20}$$

$$SEM_G = \frac{M_{G_{complete}}}{t_{G_{RT}}} = \frac{-3\ ms}{0.3} = 10\ ms \tag{21}$$

$$SD_G = SEM_G \times \sqrt{n_G} = 10\ ms \times \sqrt{12} = 35\ ms \tag{22}$$

Next, we can calculate the pooled SD (pSD) for grasping and manual estimation:

$$pSD = \sqrt{\frac{(n_{ME} - 1) \times SD_{ME}^2 + (n_G - 1) \times SD_G^2}{n_{ME} + n_G - 2}} = 35.5\ ms \tag{23}$$

Garner interference in manual estimation RT was M_{ME} = 31 ms and in grasping RT it was $M_{G_{RT}}$ = -1 ms. The effect size Cohen's *d* (for independent measures and between-design) is then:

$$d = \frac{M_{diff}}{pSD} = \frac{31\ ms - (-1\ ms)}{35.5\ ms} = 0.90 \tag{24}$$

We need to convert this *d* to d_z in order to calculate the power for our repeated-measures design. This conversion can be done using Formula 12 of Morris and DeShon (2002):

$$d_z = \frac{d}{\sqrt{2 \times (1 - r)}} \tag{25}$$

where *r* is the correlation between the two measures (this relationship is also stated in Cohen, 1988, p. 46, for the simplest case of *r* = 0).

This leaves us with the task to estimate the correlation. Only one study (Ganel & Goodale, 2014) besides our Experiment 1 investigated grasping and manual estimation in a repeated-measures design. Unfortunately, the values required to calculate the correlation are not reported in that paper and the data are not openly available. Therefore, we calculate possible values of power using n = 24, and α = .05 for a one-tailed paired t-test by varying the value of *r* from 0 to 0.9 (Table 20).

Table 20

Cohen's d_z and Power Values for Different Correlations in Experiment 1

Cohen's *d*	Correlation (*r*)	Cohen's d_z	Power (one-Tailed)
0.90	0.0	0.64	.92
0.90	0.1	0.67	.94
0.90	0.2	0.71	.96
0.90	0.3	0.76	.98
0.90	0.4	0.82	.99
0.90	0.5	0.90	1.0
0.90	0.6	1.01	1.0
0.90	0.7	1.17	1.0
0.90	0.8	1.43	1.0
0.90	0.9	2.02	1.0

Thus, even with a conservative estimate of *r* = 0, we obtain for our Experiment 1 a power of 1-β = .92 to find a larger Garner interference (i.e., one-tailed test) in the RTs of manual estimation than in grasping. Note, that this high power will still be an underestimate as some correlation is likely (e.g., in our Experiment 1, we found *r* = 0.36).

3.8.1.4 Power Analysis for Experiment 3

We want to determine the statistical power to detect a larger Garner interference effect in the short amplitude condition than in the long amplitude condition (for RTs of manual estimation in our repeated-measures design). Such an experiment has not been performed before with manual estimation. Therefore, we needed to estimate the to-be-expected effect sizes from other tasks. For this, we used the results obtained in the speeded-classification task by Hesse and Schenk (2013), for the long condition in their Experiment 1 and for the short condition in their Experiment 2. Note that in Ganel and Goodale (2003) the Garner interference effect size in speeded-classification was smaller than in manual estimation (d_z = 0.72 vs. d_z = 0.84, respectively, cf. Experiment 1). As above, we will first calculate Cohen's *d* for an independent-measures design, and then convert it to d_z to calculate power for our repeated-measures design.

For the short condition, Hesse and Schenk (2013) reported a mean Garner effect of M_S = 25 ms with n_S = 16 and t_S(15) = 2.5. In the long condition, they found M_L = 6 ms (values were given for differences in MT = 6 ms and RT + MT = 12 ms, therefore RT = 6 ms), n_L = 24 and t_L(23) = 1.35. This gives SEM, SD and pooled SD, using the same formulas as above:

$$SEM_S = \frac{M_S}{t_S} = 10\ ms \tag{26}$$

$$SD_S = SEM_S \times \sqrt{n_S} = 40\ ms \tag{27}$$

$$SEM_L = \frac{M_L}{t_L} = 4\ ms \tag{28}$$

$$SD_L = SEM_L \times \sqrt{n_L} = 22\ ms \tag{29}$$

$$pSD = \sqrt{\frac{(n_L - 1) \times SD_L^2 + (n_S - 1) \times SD_S^2}{n_L + n_S - 2}} = 30.3\ ms \tag{30}$$

The effect size Cohen's *d* (for independent-measures design) is then:

$$d = \frac{M_{diff}}{pSD} = \frac{25\ ms - 6\ ms}{30.3\ ms} = 0.63 \tag{31}$$

Again, we need to convert this Cohen's *d* to Cohen's d_z for a repeated-measures design. Therefore, we calculate possible values of power using n = 32, and α = .05 for a one-tailed paired *t*-test by varying the value of the correlation *r* from 0 to 0.9 (Table 21).

Thus, even with a conservative estimate of *r* = 0, we obtain for our Experiment 3 a power of 1-β = .79 to find a larger Garner interference in the short condition of manual estimation than in the long condition. Note, that this power will still be an underestimate as some correlation is likely (e.g., in our Experiment 3, we found *r* = 0.04).

Table 21

Cohen's d_z and Power Values for Different Correlations in Experiment 3

Cohen's *d*	**Correlation (*r*)**	**Cohen's d_z**	**Power (one-Tailed)**
0.63	0.0	0.44	.79
0.63	0.1	0.47	.83
0.63	0.2	0.50	.86
0.63	0.3	0.53	.90
0.63	0.4	0.57	.94
0.63	0.5	0.63	.97
0.63	0.6	0.70	.99
0.63	0.7	0.81	1.0
0.63	0.8	0.99	1.0
0.63	0.9	1.40	1.0

3.8.2 Comparison of Methods to Determine Movement Onset and Offset

Ganel and Goodale (2003) did not mention details on the methods and criteria used to determine the RT (movement onset in grasping and manual estimation, see Experiment 1) and ManEstTime (movement offset in manual estimation). Ganel and Goodale (2014) did describe these methods (but see Table 11). While we do not expect large differences in the results with their criteria (henceforth GG14 criteria) and our criteria (see Experiment 1), we here compare results using both methods. Ganel and Goodale (2014) determined RT or movement onset as "the time point when the aperture between index finger and thumb increased by more than 0.1 mm for at least 50 ms" (p. 5) and ManEstTime or movement offset as "the time point when the aperture between finger and thumb changed by not more than 0.2 mm for at least 100 ms" (p. 5). Table 22 lists the results of Experiment 1 and 2 with both our criteria and GG14 criteria. The results are quite comparable.

Table 22

Comparison of Results Using Different Movement Onset and Offset Criteria

Experiment	Variable (unit)	Task	Our Criteria	GG14 Criteria
1	RT (ms)	CL	-4 ± 4	-3 ± 5
1	RT (ms)	OL	0 ± 7	1 ± 9
1	RT (ms)	ME	5 ± 13	7 ± 12
1	ManEstTime(ms)	ME	42 ± 25	22 ± 18
1	SD_{ManEst} (mm)	ME	0.21 ± 0.15	0.07 ± 0.16
2	Illusion Baseline (mm)	ME	0.51 ± 0.41	0.77 ± 0.43
2	Illusion Filtering (mm)	ME	0.42 ± 0.21	0.47 ± 0.23
2	RT (ms)	ME	8 ± 4	7 ± 4
2	ManEstTime(ms)	ME	17 ± 9	17 ± 7
2	SD_{ManEst} (mm)	ME	0.31 ± 0.09	0.27 ± 0.10
2	Illusion Baseline (mm)	ME	-0.65 ± 0.44	-0.52 ± 0.46
2	Illusion Filtering (mm)	ME	0.76 ± 0.18	0.71 ± 0.18

Note. CL = closed-loop grasping, OL = open-loop grasping, ME = manual estimation, SD_{ManEst} = Variability-based Garner interference in ME.

4. Size Resolution

Abstract

In a study comparing resolution of size in perception and action (Ganel et al., 2012), it was reported that actions like grasping are more accurate at discriminating small size differences than perceptual judgements. This inference was based on a significant difference between grip apertures in grasping to small and large objects on one hand, and a poor perceptual judgement accuracy (59%) on the other hand. This result was also interpreted as a perception-action dissociation, lending support to the influential Perception-Action Model (PAM; Goodale & Milner, 1992), the idea that visual perception and visuomotor actions are guided by separate and independent pathways, the ventral and dorsal cortical streams, respectively. However, the conclusions of Ganel et al. (2012) are based on an unfair comparison of different measures: grip apertures versus judgement accuracy. We show that this comparison leads to invalid results, and propose a method to calculate the same metrics in both perception and action tasks: classification accuracy. We present two experiments with improved design and increased power, and demonstrate that classification accuracies in action are not better than perception, contrary to Ganel et al. (2012). We also include manual estimation, a task that is assumed by the PAM to be based on perceptual representations yet has comparable task demands to grasping. We find that manual estimation has a similar accuracy to grasping. We then convert the results of three studies with similar designs into classification accuracies, and using a meta-analysis, quantitatively compare their results. We find that classification accuracies across multiple studies are lower in grasping than perceptual judgement, but similar to manual estimation. Thus, performing an appropriate comparison between perception and action results in no perception-action dissociation. We therefore suggest that size resolution in perception and action should not be considered as providing evidence for the PAM.

4.1 Introduction

When we want to pick up an object, we can simply reach toward it and grasp it successfully, even without explicitly knowing the exact dimensions (say, in cm) of the object. Likewise, we seemingly have no problem grasping objects, even when we are not able to distinguish their sizes reliably. But does it necessarily follow from this observation, that grasping is more accurate at discriminating sizes compared to judging?

Ganel et al. (2012) investigated this question with two discs of diameters 40 mm and 40.5 mm respectively, by comparing perceptual judgements and grip apertures in grasping these objects. They found that although participants performed poorly in judging the size of the objects (59% correct), their grip apertures for the smaller and larger objects were significantly different. Thus, they concluded that grasping is more accurate at discriminating object sizes and has better resolution of size than visual perception.

Ganel et al. (2012) considered their result as being consistent and well-explained by the Perception-Action Model (PAM; Goodale & Milner, 1992). The PAM assumes that visual information is processed differently in two separate cortical streams. Visual perception (object recognition and identification) is assumed to be processed in the ventral stream and visually-guided actions like grasping are assumed to be processed in the dorsal stream. Furthermore, the computations in the ventral stream seem to rely on relative metrics compared to absolute metrics in the dorsal stream (Milner & Goodale, 1995). Ganel et al. (2012) also suggest that "[t]his view provides an appealing account for the dissociation found between perception and action in Experiment 1" (p. 6).

Although few studies (Ganel et al., 2012; Göhringer et al., 2019; Heath et al., 2022) investigated size resolution in perception and action, there is a large body of literature on such perception-action dissociations, or such demonstrations of a difference in performance between perception and action. Perception-action dissociations are thought to provide support for the PAM, because the different representations in the ventral versus dorsal streams are interpreted as the cause fo the observed behavioural differences.

We start by describing perception-action double dissociations in patients that first led to the conception of the PAM, and then go on to briefly review different experimental paradigms which seemingly demonstrated a dissociation in behaviour between perception and action in healthy humans, but have been shown to be weaker than originally assumed. Then, we summarise the studies investigating size resolution, and show that the apparent difference in size resolution of perception and action results from an unfair comparison of different measures, and describe how to calculate the same metric (accuracy) in both. We then present two experiments examining the size resolution of perception and action, where we calculate accuracies and find that the resolution in grasping is in fact not better than perception. Finally, we aggregate the results from existing studies on size resolution in a meta-analysis to better estimate and assess differences between perception and action.

4.1.1 Perception-Action Dissociations

The PAM, when it was first proposed (Goodale & Milner, 1992), could provide a neat explanation of the behavioural deficits in patients with brain lesions. Most famously, patient D.F. developed lesions largely localised to her ventral stream following carbon monoxide poisoning. While her perception was impaired such that she could not report the orientation or shape of objects (visual form agnosia), she could successfully shape her fingers to the orientation and size of grasped objects. Conversely, optic ataxics like patient R.V., who had lesions to the dorsal stream, showed the opposite pattern: spared perception but impaired visuomotor ability.

However, it was shown that the patient data were not as clear-cut as originally assumed (e.g., Himmelbach et al., 2012), and could be explained by alternative theories (Schenk et al., 2011). This led to a need for studies demonstrating perception-action dissociations in the behaviour of healthy humans. Subsequently, apparent perception-action dissociations were demonstrated in several experimental paradigms. Here, we focus on the paradigms that were considered the strongest contenders for evidence supporting the PAM, and inspired the most subsequent research. These paradigms are namely visual illusions, Garner interference and Weber's law. However, mounting contradictory evidence in these paradigms has cast doubt on the validity of the initial claims of perception-action dissociations, which brought attention to size resolution as a paradigm that may potentially provide more unambiguous evidence for such dissociations. Below, we describe briefly each of the three paradigms.

Aglioti et al. (1995) reported a perception-action dissociation in healthy humans that gained much attention. They showed that visual illusions like the Ebbinghaus illusion influenced perception but not grasping. However, this result was quite controversial and inspired many studies (Franz & Gegenfurtner, 2008; Franz et al., 2000; Haffenden & Goodale, 1998; Haffenden et al., 2001) with inconsistent conclusions. This debate culminated in a multi-lab registered report (Kopiske et al., 2016) that concluded similar and correlated effects of visual illusions on perception and action (which were also contested, see Kopiske et al., 2017; Whitwell & Goodale, 2017). This suggested common representations for perception and action in the visual system, weakening support for the PAM.

Weber's law, a fundamental psychophysical principle, was inferred to be violated in grasping by Ganel et al. (2008). The standard deviation (SD) of the grip aperture was assumed as a proxy for the just-noticeable-difference (JND), and found to not increase with object size. Bhatia et al. (2022) reported that using the SD in place of the JND was problematic, because it did not account for the non-linear grasping response function. Considering this non-linearity and appropriately calculating the JND, Bhatia et al. (2022) showed that grasping does follow Weber's law, similar to perception, and that there seems to be no evidence for a perception-action dissociation.

Ganel and Goodale (2003) showed that actions like grasping were unaffected by changes in irrelevant stimulus features, but perception tasks would suffer interference from them. This was demonstrated with a Garner paradigm, with perception being reported to suffer from Garner interference and grasping being immune to it. Recently, Bhatia et al. (2025) performed a series of replications and a meta-analysis of several studies, concluding that Garner interference can be observed in both perception and action.

Thus, perception-action dissociations previously reported have not held up to scrutiny and seem to be weaker than originally assumed. In the present study, we examine the evidence from size resolution, reported by Ganel et al. (2012), which may have the potential to provide support for a perception-action dissociation. Results from studies investigating size resolution in perception and action are summarised below.

4.1.2 Previous Work on Size Resolution in Perception and Action

4.1.2.1 Ganel et al. (2012) and Inferring Good Size Resolution in Grasping

Ganel et al. (2012) reported a perception-action dissociation in the resolution of object size. They used discs of diameters 40 mm and 40.5 mm as stimuli, thus a size difference of just 0.5 mm. Consequently, participants' perceptual judgements (when discriminating the size of the discs) had a low accuracy of about 59% correct. However, participants also grasped one of the discs within the same trial. The mean maximum grip aperture (MGA; standard measure used in grasping, see Ganel et al., 2012; Jeannerod, 1984) for the larger disc was significantly larger than the MGA for the smaller disc, and this difference was about 0.5 mm, the true size difference between the discs. Based on this result, Ganel et al. (2012) claimed that grasping has better size resolution than perception. Moreover, their within-trial design allowed for a comparison of the MGAs on trials where the perceptual judgement was correct versus incorrect.

They found that even when participants could not correctly judge which disc was larger or smaller, their MGAs differed significantly for the two discs. They concluded that the accuracy in grasping was independent of perception (Ganel et al., 2012, p. 4).

Ganel et al. (2012) conceded that the results of their first experiment might have been an artefact of comparing continuous measures of grip aperture (MGA) with dichotomous measures of perceived size (accuracy). To address this issue, in a second experiment, Ganel et al. (2012) asked participants to manually estimate the size of the target disc and indicate this estimate with their index finger and thumb. This task, manual estimation, is assumed by the PAM to be a perceptual, ventral-stream-driven task (Haffenden & Goodale, 1998). Within the same trial, participants also made perceptual judgements about the size (they indicated which disc was smaller/larger). Again, the perceptual judgement accuracy was low, about 63% (albeit slightly higher than in Experiment 1). Ganel et al. (2012) suggested that the better accuracy in Experiment 2 might be a consequence of both tasks (perceptual judgement and manual estimation) relying on "a common perceptual resource" (Ganel et al., 2012, p. 5). However, there was a significant difference between the manual estimates for the larger and smaller discs only for those trials where participants made the correct perceptual judgement. Thus, they concluded that even with a continuous measure in a perceptual task (manual estimation), there was poor visual resolution of size in perception, because of the dependence on the accuracy of the perceptual judgement (which was low).

Taken together, Ganel et al. (2012) contrasted the relatively poor perceptual accuracy with a significant 0.5 mm difference between small and large MGAs in grasping to conclude that grasping has better size resolution than perception.

But, inferring the discrimination power (or sensitivity) based on significant or non-significant differences is a well-known fallacy (Franz & von Luxburg, 2015; Meyen et al., 2022, 2024). This means that even if there is a significant difference between MGAs for small and large objects, using just the MGA value from one trial to figure out whether it was in response to the small or large object might nevertheless result in poor accuracy. For example, Franz and von Luxburg (2015) convincingly demonstrate that, for reaction times, a statistically significant difference can actually result in classification accuracies (predictions based on those reaction times) that are close to chance (50%). Similarly, a statistically significant difference between MGAs does not necessarily imply good size resolution in grasping.

In order to actually investigate the size resolution in grasping and manual estimation, we need to calculate the classification accuracies based on the MGAs or manual estimates. This way we can determine how accurately the object size can be predicted based on the measured MGA or manual estimate. Further, this provides a comparable measure to the perception task. How can a classification accuracy (dichotomous) be calculated from MGAs/manual estimates (continuous)? This requires dichotomisation of the continuous responses (MGAs/manual estimates).

Dichotomising Continuous Measures. Let us consider grasping data from one participant who grasped small and large discs. There are multiple trials with a single MGA value for each trial. We also know whether the MGA in a single trial was in response to a small or large disc presented in that trial (let us call this the true label). Now, let us assume that we did not know the true labels; how would we then categorise the measured MGA on a single trial as small or large? One way is to simply split the data at a certain MGA value (criterion), such that any trial with MGA less than the criterion is classified as ″small″ and any trial with MGA greater than the criterion as ″large″. For each trial, the classification is compared to the true label. If they match, the classification was correct, otherwise incorrect. This results in a classification accuracy. One could also use sensitivity or d' for this purpose; for simplicity, we will use accuracy or % correct (see Equation 35 for how to convert between these measures). We now also have the same measure (accuracy) for all tasks: grasping, manual estimation (the procedure described here can also be applied to manual estimates) and perceptual judgement.

Obviously, the classification accuracy will depend on the choice of criterion. This raises the question of which criterion is the most appropriate to use. Göhringer et al. (2019) used one such criterion for a dichotomisation analysis, in an experimental design almost identical to Ganel et al. (2012), and reported classification accuracies for grasping. Below we explain the reasoning behind their choice and why it is not realistic.

4.1.2.2 Göhringer et al. (2019) and the Choice of Criterion for Dichotomisation

Göhringer et al. (2019) replicated the experimental design of Ganel et al. (2012) in separate experiments. The most important difference to Ganel et al. (2012) was that they dichotomised the MGAs in grasping and calculated classification accuracies. Instead of calculating a single accuracy based on a pre-determined criterion, they considered all possible criteria (all possible values of MGA) for dichotomising the data and calculated the corresponding accuracies. Then, they chose the criterion that achieved the highest accuracy.

This method is in a way like cheating to get the best possible accuracy. Consider the following analogy with test scores: a student takes 10 tests on some subject with slightly different questions in each test, gets 10 different scores but only the highest score among those tests is reported as the final grade. This high score would not be representative of the student's knowledge of that subject. Test scores are calculated based on performance on a particular set of questions from within a fairly broad curriculum. Students take a test and their scores are calculated based on their performance. But in the current situation, a student answers multiple tests (each with a different set of possible questions), and scores are calculated for each test. Then, the maximum score they achieved in any of these tests is taken as their final score. In some of the tests, the student might be able to guess the answers correctly, achieving a higher score randomly. This would lead to an artificially high score on those tests. But this score would not reflect a fair evaluation of that student's knowledge on the subject. Rather, such tests would determine the maximum possible score a student *could* achieve. Similarly, this dichotomisation method does not produce a realistic or to-be-expected classification accuracy; rather, it produces the maximum possible accuracy (upper bound on accuracy) that can be achieved by any classifier (Franz & von Luxburg, 2015). In machine learning, this is called the ′training accuracy′ (James et al., 2013), while Göhringer et al. (2019) dubbed it ′optimal cut-off accuracy′ or OC%.

Nevertheless, Göhringer et al. (2019) correctly reasoned that if the accuracy upper-bound in grasping was lower than in perceptual judgement, then the to-be-expected accuracy in grasping would be even worse. Despite inflating the accuracy in grasping with this method, they found consistently higher accuracies for perceptual judgement than grasping across three experiments. Therefore, they provided evidence that the maximum possible accuracy in grasping is not better than perceptual judgement.

What is the Appropriate Criterion for Dichotomisation? In order to determine a realistic, to-be-expected grasping accuracy, we apply an ideal observer analysis, assuming optimal use of the information contained within the MGAs. It has been shown that the statistically-optimal criterion to use in our experimental situation (equal trials for small and large discs, assumed normally distributed data) is the median of the data (Franz & von Luxburg, 2015; Meyen et al., 2022). Meyen et al. (2022, 2024) successfully used the median-split dichotomisation to calculate classification accuracies from reaction times in unconscious priming and implicit learning paradigms. However, to our knowledge, no other study used the median-split to dichotomise MGAs in grasping.

4.1.3 Overview of This Study

The purpose of the current work is twofold: we want to add empirical data on size resolution in perception and action, and assess the currently available evidence by comparing the results of the previous studies on this topic in a meta-analysis.

First, we present two experiments which were replications of Ganel et al. (2012). In both experiments, we aimed to improve the experimental design as well as the analysis methods. For example, we used a repeated-measures design with the same participants performing all tasks: perceptual judgement, grasping and manual estimation. In our second experiment, we also improved the power by almost doubling the sample size used by the previous studies on the topic. We also improved the analysis by applying the median split dichotomisation to calculate classification accuracies. We thus directly compared accuracies in the tasks to evaluate size resolution.

Next, we reanalysed the existing studies on size resolution and combined their results in a meta-analysis. Using the meta-analysis, we aim to quantify the evidence from all the studies investigating size resolution in perception and action. Since those studies either did not calculate classification accuracies for grasping and manual estimation (Ganel et al., 2012; Heath et al., 2022), or used a dichotomisation method that overestimated accuracy (Göhringer et al., 2019), we first reanalysed the data of these studies by obtaining the trialwise data or using methods to calculate back the accuracy from just the reported statistics (Meyen et al., 2022). Though there are few studies available for the meta-analysis, our results will show that classification accuracies of size discrimination in grasping and manual estimation are rather similar, and not better than the performance in the perceptual judgement task.

4.2 Experiment 1

This experiment was conducted as a proof-of-concept for the slightly altered study design compared to Ganel et al. (2012), that is, separate blocks for each task. Ganel et al. (2012) had asked participants to perform two tasks in succession on the same trial (in response to the same stimuli). Participants were shown two discs and they judged the size (whether the central disc was larger or smaller than the disc in the periphery) and then grasped the central disc (or vice-versa, order was counterbalanced). Such a design can be problematic because there might be some interactions between dorsal stream and ventral stream processing of the stimuli (especially since participants know while judging the size that they have to grasp that stimulus next, or vice versa), or influences from one task to the next (Schenk & Milner, 2006). Because we wanted to investigate the size resolution in each task as classification accuracy and make pairwise comparisons, we implemented a blocked design: each block consisted of 128 trials of the same task - either grasping, manual estimation or perceptual judgement. This way, we cannot analyse the data in the same way as Ganel et al. (2012) did, by separating trials based on correct or incorrect perceptual judgement (see also Section 4.8.4), but we can avoid issues of interactive processing within the dorsal and ventral streams.

Another advantage of using the blocked design is that we do not need to present both discs simultaneously during grasping or manual estimation (because only one disc needs to be grasped or estimated in a single trial). This should prevent participants from comparing disc sizes simultaneously which might recruit ventral stream processing due to relative size comparison (Milner & Goodale, 1995).

4.2.1 Method

4.2.1.1 Transparency and Openness

Data and analysis scripts of all experiments are available at OSF (https://osf.io/4k9fg/?view_only=0cfed0c19f45478889ca267570987df6). Data collection took place in 2024. Data of all experiments were analysed and figures were created using R, Version 4.1.1. (R Core Team, 2021) and the package "plotrix" (Lemon, 2006).

4.2.1.2 Participants

Fourteen participants took part in the experiment who were students and members of a practical course at the University of Tübingen. They were not naive to the purpose of the study and had knowledge about the stimuli used. One student was left-handed and excluded from further analysis, but allowed to participate in the experiment for course requirements. The final sample therefore included thirteen right-handed participants (8 women, 5 men, age range = 19-26 years, mean age = 21 years). The study was approved by the ethics committee of the University of Tübingen and was conducted in accordance with the principles of the Declaration of Helsinki.

4.2.1.3 Stimuli

The stimuli used were identical to those used by Ganel et al. (2012) and Göhringer et al. (2019): circular discs with diameters 40 mm and 40.5 mm, with a thickness of 2 mm. They were made of aluminium and one side was sanded to prevent light reflections from influencing size judgements. Two exemplars of each disc size were used, for a total of four discs of two different sizes (Ganel et al., 2012).

4.2.1.4 Apparatus and Set-Up

The experiment was performed at a table on which an LCD monitor (screen diagonal: 54.6 cm; Samsung Syncmaster2233, Samsung group, Seoul, South Korea) was placed with the screen facing up, while participants sat at a height-adjustable chair. The monitor was used as an environment for the experiment to display instructions, start location and stimulus positions. The participant's head was positioned with a chin rest to prevent large deviations in viewing distance and angle. Stimulus presentation was controlled via liquid-crystal shutter goggles (PLATO goggles, Translucent Technologies Inc., Toronto, Ontario, Canada; see Milgram, 1987). An Optotrak Certus (Northern Digital, Waterloo, Ontario, Canada) recorded kinematic data and was used to calculate reaction times (RTs) and grip apertures. The Optotrak data was recorded at 200 Hz sampling frequency via infra-red light-emitting diodes attached to the nails of the finger and thumb of the participant's right hand using adhesive putty (UHU-Patafix, UHU GmbH, Bühl, Germany). Custom-built buttons were provided for participants' responses, digitised with a DT9812 box (EconSeries Data-Translation/Acquisition circuit, Measurement Computing Corporation, Georgetown, MA, USA). Matlab (Mathworks, Natick, MA, USA) was used for stimulus presentation with the Psychophysics Toolbox (Brainard, 1997; Kleiner et al., 2007) and the Optotrak Toolbox by V. H. Franz (http://www.ecogsci.cs.uni-tuebingen.de/OptotrakToolbox).

4.2.1.5 Procedure

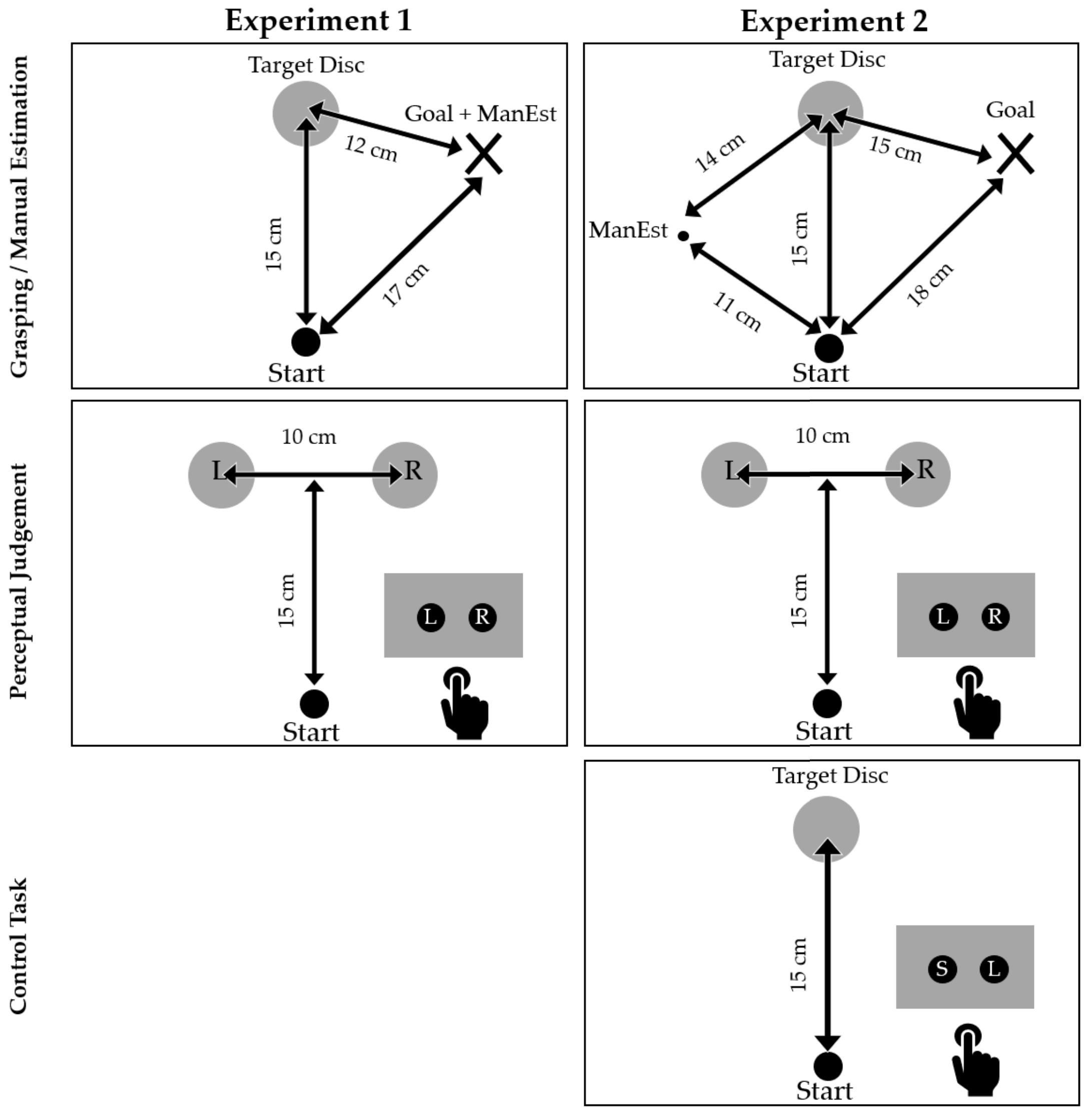
All participants were tested for visual acuity (Bach, 1996) using the Freiburg Vision Test (FrACT) before the experiment. Only participants with a visual acuity score of logMAR $<$ 0.3 were allowed to participate in the experiment. This strict threshold was based on the World Health Organisation definition of no visual impairment (World Health Organisation, 2019, 9D90 Vision impairment including blindness), and used to ensure that participants had sufficient visual acuity to detect differences between the size of the two discs (0.5 mm).

All participants performed three tasks: perceptual judgement, grasping and manual estimation. All tasks were performed closed-loop, that is, with full visual feedback throughout the task. Before each task, participants could familiarise themselves with the procedure with 8-10 practice trials. Each task was split into four blocks of 32 trials each, with a total of 128 trials per task. The order of the tasks was fully counter-balanced. Participants were instructed to be as accurate as possible in all tasks. The viewing distance for the discs was approximately 40 cm (measured from the chin rest, same distance as Ganel et al., 2012). The set-up and locations of the object from the participant's viewpoint are depicted in Figure 28. The shutter goggles prevented participants from seeing the stimulus (or the experimenter placing the stimuli) before the trial began. After the experimenter placed the stimulus at a specified location, the trial began as the shutter goggles turned transparent.

In the *perceptual judgement* task, two discs of different sizes were presented. Participants

Figure 28

Experimental Set-Up (Participant's View) for Experiments 1-2



Note. In Experiment 1, the position where the manual estimate was to be indicated and the position where the disc was to be returned after grasping was the same, denoted by a cross and labelled 'Goal + ManEst'. For Experiment 2, the the ManEst and Goal positions were separated for participant comfort, and because some participants' Optotrak markers were not visible in some positions. Goal was denoted by a cross and ManEst by a filled circle. These labels were shown for the practice trials but during the experiment only the cross and circle were visible. In the standard perceptual judgement task (middle panel), participants were asked to judge which disc was larger (or smaller, counter-balanced), and asked to respond with button press 'L' for the left disc, and 'R' for the right disc. In the control perceptual judgement task (only Experiment 2), participants were asked whether the presented disc was smaller or larger than the previously presented discs by button press, with 'S' for smaller and 'L' for larger.

had to respond which disc was larger, or which disc was smaller (separate blocks, fully counterbalanced). They could respond with the buttons labelled as 'left' or 'right', to indicate the left or right disc as the smaller (or larger) disc. The goggles turned opaque after 3,000 ms or if a button press was registered, whichever occurred earlier. Positions of the discs (including exemplars) were fully counterbalanced.

In the *grasping* task, participants kept their index finger and thumb pinched together at the start position, and were presented with one disc (randomised - either 40 mm or 40.5 mm in diameter) that they had to grasp with their index finger and thumb (precision grip), and place at a specified location to their right labelled as 'Goal'. The goggles turned opaque after 3,000 ms. In some trials, participants had problems with the grasp (collided with the object or dropped it after grasping), or could not complete the task before goggles turned opaque, or position information was missing from Optotrak diodes, and these trials were deleted and repeated at a random time later.

In the *manual estimation* task, participants began the trial similar to grasping with their finger and thumb pinched together at the start position. One disc was presented and participants had to indicate the diameter of the disc with their index finger and thumb. The manual estimate was performed at a location labelled 'ManEst' to the right of the disc. After indicating their manual estimate, participants were asked to hold their manual estimate and confirm completion of their manual estimate with a button press with their left hand. Then they had to grasp the disc and place it at the 'Goal' position (same as 'ManEst' location). The grasping after the manual estimation is a standard practice in an attempt to ensure equivalent haptic feedback in the grasping and manual estimation tasks. The goggles turned opaque after 3,000 ms. Trials where participants had problems with the post-estimation grasp (collided with the object or dropped it after grasping) or could not complete the task before goggles turned opaque, were deleted and repeated at a random time later in the block. Trials (repeated randomly later) where the participant's aperture velocity at the time of button press was too high (aperture was not stable and changing a lot), meaning that the participant did not synchronise indication of the estimate with the button press were deleted. Trials with missing position information at the time of indicating the size estimate were also deleted and repeated.

4.2.1.6 Dependent Variables

RTs were measured in each task to identify and exclude trials with anticipatory (too early, RT $\leq$ 100 ms) responses. In the perceptual judgement task, RTs were calculated as the time between the goggles turning transparent and the button press. In grasping and manual estimation, RT was measured as the time between goggles turning transparent and participant's hand leaving the start position (movement onset). This was determined using a velocity criterion: it was the first time point when either the finger or thumb marker's velocity exceeded 0.025 m/s (see also Bhatia et al., 2025).

Grip apertures were recorded for grasping and manual estimation. In grasping, the maximum grip aperture was recorded as the maximum distance between index finger and thumb during the movement. In manual estimation, the size estimate was measured as the distance between index finger and thumb at the time point of the button press (indicating completion of manual estimation). Accuracy in perceptual judgement was calculated by comparing participants' responses to the presented stimulus.

4.2.1.7 *Analyses*

All results will be reported as mean ± standard error.

Median Split Dichotomisation The finger apertures in grasping (MGA) and manual estimation (size estimates) were dichotomised to obtain classification accuracies. This was done using the procedure described in Section 4.1.2.1 with the median of the data set as the criterion.

***t*-tests to Check for Differences** To establish whether the accuracy in each task was better than random guessing (or chance level, 50% correct), one-sided *t*-tests were performed. Note that Ganel et al. (2012) did not test whether accuracies were different from chance. Pairwise comparisons were also performed (two-sided paired *t*-tests) between tasks to check for differences in accuracies of the tasks. Again, these tests were not conducted by Ganel et al. (2012) because the measures in the tasks were not comparable. We used $\alpha = 0.05$ for all tests.

Equivalence Tests to Check for Equivalence We wanted to statistically demonstrate equivalence within each task to chance level, as well as equivalence between tasks. For this we employed the two-one-sided-*t*-test procedure (TOST, Lakens et al., 2018). The equivalence margin was set to 5%, meaning that values within ±5% of the test value would be considered equivalent to the test value. This means that an accuracy with a 90% confidence interval contained within [45% 55%] would be considered equivalent to 50%, and accuracy differences between tasks with 90% confidence intervals within [-5% 5%] would be considered equivalent to 0%.

We pre-registered sequential equivalence margins of ±10%, ±5% and ±1%, moving on to the narrower margin if the previous one was significant. We adopted this procedure because we could not estimate the effect size from previous studies, and therefore, might lack power for narrower margins. Here, we had sufficient power for ±5% but not 1%. In Experiment 2, we pre-registered only ±5%.

4.2.2 Results

Outliers were few and led to no removals in perceptual judgement or grasping, and less than 0.5% of trials were removed in manual estimation.

The results of the finger aperture responses are shown in Figure 29, and the comparison of accuracies in the three tasks is depicted in Figure 30.

The difference in the size estimates in manual estimation of the large and small discs was 0.01 ± 0.20 mm ($t(12) = 0.06$, $p = .952$). In grasping, the MGA difference between the large and small discs was 0.36 ± 0.19 mm ($t(12) = 1.93$, $p = .078$). However, as explained above, we want to focus on comparing the accuracies in the tasks rather than the apertures.

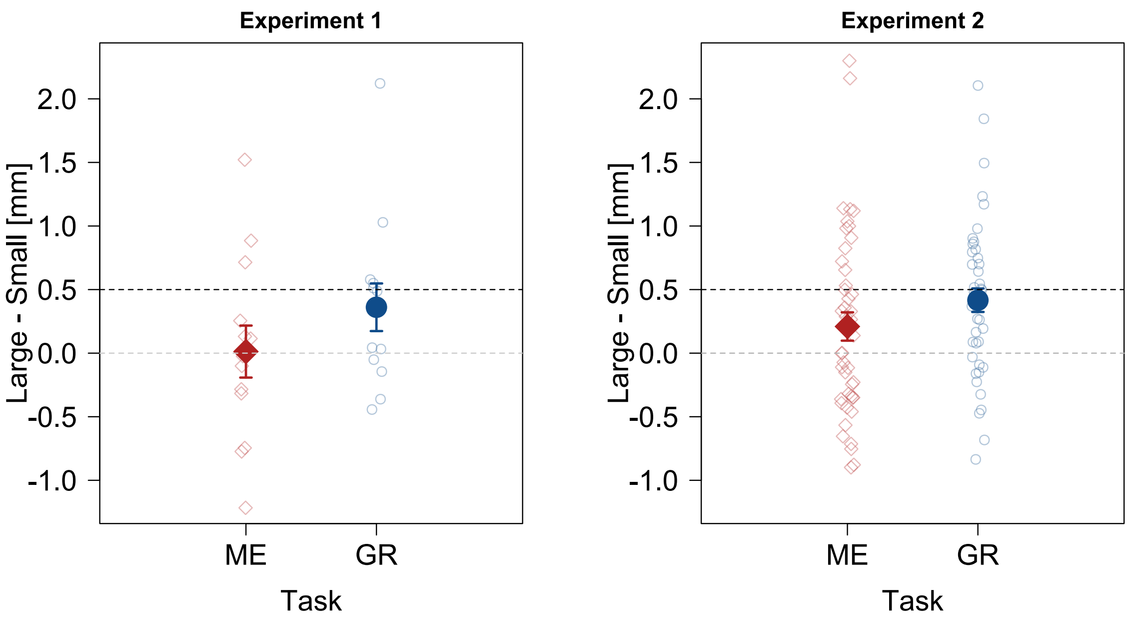
4.2.2.1 *Accuracy Differences*

The mean accuracy in the perceptual judgement task was 73.6 ± 2.5%, and was significantly better than chance-level (50%), $t(12) = 9.59$, $p < .001$. The classification accuracy based on the median-split method in grasping was 52.0 ± 1.3%, and was not significantly better than 50%, $t(12) = 1.57$, $p = .072$. In manual estimation, the accuracy was 49.1 ± 1.5% and also not significantly better than 50%, $t(12) = -0.62$, $p = .726$.

We also made pairwise comparisons between task accuracies. Perceptual judgement accuracy was significantly better than grasping, difference = 21.5 ± 2.8%, $t(12) = 7.76$, $p < .001$, as well as significantly better than manual estimation, difference = 24.5 ± 3.1%, $t(12) = 7.79$, $p < .001$. Difference between grasping and manual estimation was 2.9 ± 1.8%, and not significantly different, $t(12) = 1.63$, $p = .130$.

Figure 29

Differences in Finger Apertures to Large and Small Discs



Note. The difference in finger apertures (MGA in grasping and size estimate in manual estimation) between the large and small discs. The dark dashed line represents the true size difference between the discs, that is, 0.5 mm. Hollow symbols represent individual participants and the filled symbols represent the average of all participants. Error bars represent ± standard error. ME = manual estimation, GR = grasping.

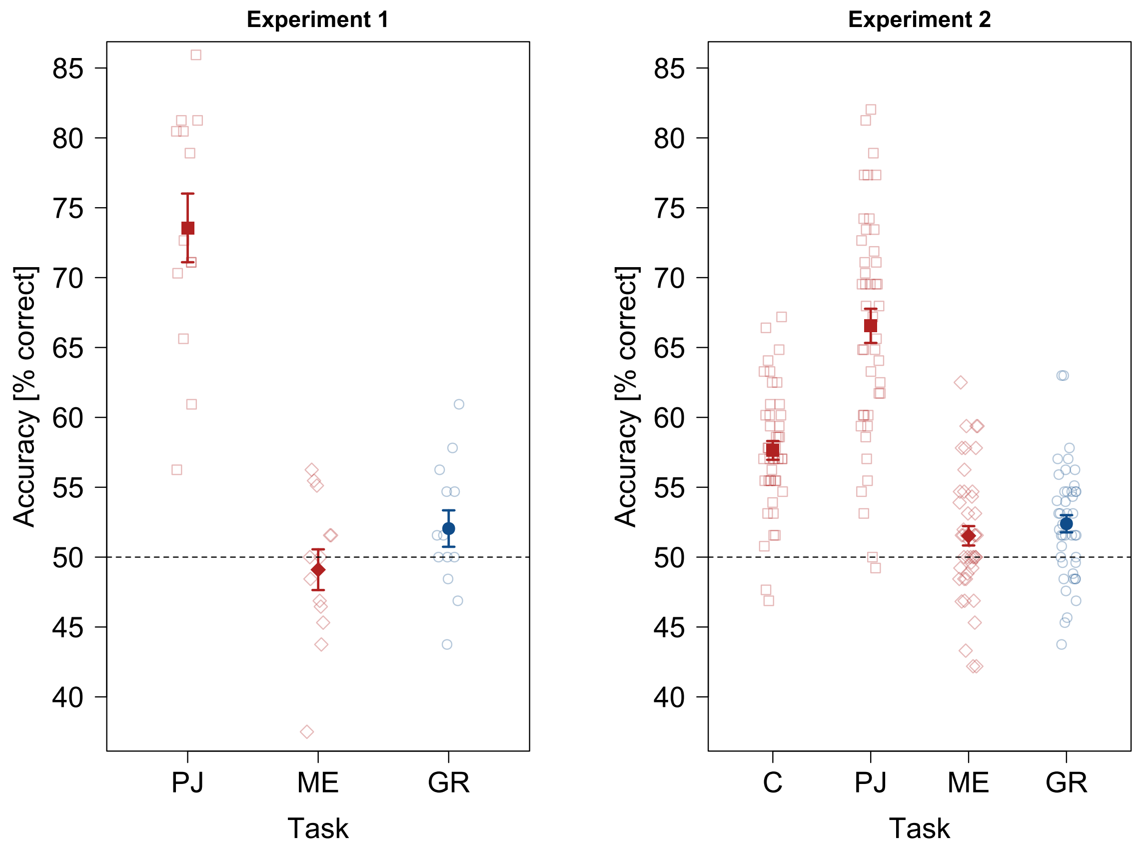
4.2.2.2 *Accuracy Equivalence*

We also formally tested if accuracies were equivalent to 50% using equivalence tests (TOST) with an equivalence margin of ±5%. As expected, the equivalence test for perceptual judgement accuracy was not significant, $t(12) = 7.56$, $p = 1$. The equivalence test for grasping accuracy was significant, $t(12) = -2.27$, $p = 0.021$. The equivalence test on manual estimation accuracy also resulted in a significant effect, $t(12) = 2.81$, $p = .008$. This means that the accuracies in grasping and manual estimation are not more extreme than [45% 55%].

Regarding the pairwise comparisons, a non-significant result was obtained for the comparison between perceptual judgement and grasping, $t(12) = 5.96$, $p = 1$, and between perceptual judgement and manual estimation, $t(12) = 6.20$, $p = 1$. The comparison between grasping and

Figure 30

Comparison of Accuracies in Different Tasks



Note. Accuracies obtained for each task. The accuracy for the perceptual judgement task was calculated directly from the participants' responses. For grasping and manual estimation, this was calculated using the median split. Hollow symbols represent individual participants and the filled symbols represent the average of all participants. Dark dashed line represents chance level accuracy (50%). Error bars represent ± standard error. C = control perceptual judgement, PJ = perceptual judgement, ME = manual estimation, GR = grasping.

manual estimation also resulted in a non-significant equivalence test, $t(12) = -1.14$, $p = 0.139$, and the 90% confidence interval [-0.28 6.17] just overlapped with the equivalence margin of 5%.

4.2.3 Discussion

In this experiment, we replicated the experiment of Ganel et al. (2012) with an improved design (individual blocks for each task) and a new analysis method (dichotomising grasping and manual estimation responses using median split). Accuracy in the perceptual judgement task was 73.6%, which was considerably higher than the accuracy reported by Ganel et al. (2012, 60.7%, average of both their experiments). The accuracy in grasping was 52%, and in manual estimation, the accuracy was 49%. In our meta-analysis in Section 4.7, we will show that these results are quite consistent with the results of the previous studies (cf. Figure 32).

We compared whether the accuracies were better than random guessing (50%). Grasping and manual estimation were within ±5% of chance level, but perceptual judgement was significantly better. This result contradicts the conclusion of Ganel et al. (2012) that grasping has better resolving power than visual perception. Participants having such high accuracies in perceptual judgement suggests that they had enough information to distinguish between the two disc sizes. We speculate three possible explanations for this result: First, the participants of this experiment were students of a seminar and had full knowledge about experiment design, hypotheses and disc sizes. That is, they were not naive. This additional knowledge might have provided an advantage to their performance in the perceptual judgement task. Both Ganel et al. (2012) and Göhringer et al. (2019) had naive participants in their experiments. Second, the grasping and manual estimation tasks were performed with only one disc presented, while both discs were presented for the perceptual judgement task. Participants' high accuracies might be the result of being able to compare both discs simultaneously during this task. Ganel et al. (2012) and Göhringer et al. (2019) presented both discs during the perception task, but also during the grasping/manual estimation tasks. Third, the participants were asked to emphasise the accuracy of their responses, and to judge/grasp/estimate (the size of) the discs as accurately as possible. Therefore, we did not want to create a speeded task and allowed participants 3,000 ms of stimulus viewing time. However, Ganel et al. (2012) only allowed 2,000 ms while Göhringer et al. (2019) allowed 2,500 ms. The longer presentation time might have also contributed to better accuracies, especially in the perceptual judgement task.

To address these design issues and to increase statistical power for our pairwise comparisons (grasping and manual estimation), we performed a second experiment with a larger sample of naive participants.

4.3 Experiment 2

The results of Experiment 1 were promising and provide a baseline for the expected accuracies in the different tasks. In the second experiment, we increased the power with a larger sample size and addressed several potential issues that were identified in the previous experiment.

First, the participants had no knowledge about the experiment design or disc sizes (fully naive). Second, we included an additional control task: perceptual judgement with one presented disc. Here participants had to answer via button press if the presented disc was larger or smaller than the average of the previously presented discs. The performance of participants in this task would clarify if high accuracies in the perceptual judgement task with two discs arise due to participants comparing both discs simultaneously, as opposed to only one disc in the grasping and manual estimation tasks. Third, we increased the sample size to $n = 48$ participants, which is considerably larger than the other studies on this topic (Ganel et al., 2012, $n \leq 25$; Göhringer et al., 2019, $n \leq 30$; Heath et al., 2022, $n = 20$).

4.3.1 Method

4.3.1.1 Transparency and Openness

Data and analysis scripts of all experiments are available at OSF (https://osf.io/4k9fg/?view_only=0cfed0c19f45478889ca267570987df6). Data collection took place in 2025. This experiment was pre-registered at AsPredicted (https://aspredicted.org/jnyz-7zg3.pdf).

4.3.1.2 Participants

Fifty-eight right-handed participants took part in the experiment who were fully naive with respect to the purpose and stimuli used in the experiment. Three initial participants were excluded from the analysis because more than 50% trials in grasping or manual estimation had missing marker information and were repeated. To improve this, minor changes were made to the positions in the experimental set-up (see Figure 28). Six further participants were excluded because more than 25% (32 trials per task) had to be repeated due to errors (see Section 4.2.1.5), and one more participant was excluded because they misunderstood the perceptual judgement task. The final sample consisted of 48 participants (23 women, 24 men, 1 non-binary person, age range = 18-39 years, mean age = 25 years). The study was approved by the ethics committee of the University of Tübingen and was conducted in accordance with the principles of the Declaration of Helsinki.

In Experiment 1, each participant performed 128 trials per task. This was more than the trials used by the other studies (see Table 26). In Experiment 2, we further increased the power by using a large sample size of n = 48 participants. This value was much larger than other studies used, and almost double the amount used by Ganel et al. (2012).

4.3.1.3 Procedure and Analyses

Most details regarding stimuli, set-up, tasks and analyses were identical to Experiment 1. Only changes from the previous experiment are described here.

We reduced the stimulus presentation time to 2,000 ms to be consistent with Ganel et al. (2012). The major change was the addition of a second perceptual judgement task. In the standard perceptual judgement task, participants are shown both discs and are asked to respond via a button press which disc is smaller/larger. This task may have an advantage over grasping/manual estimation where only one disc is presented, because participants may perform better when simultaneously comparing both discs. This hypothesis was supported by the high accuracies (> 70%) in Experiment 1 in this task. Therefore, in Experiment 2, we added a perceptual judgement task with only one presented disc in each trial as a control (in the following, we will refer to this task as the control task). This task was always performed as the last task of the experiment, to prevent participants from potentially realising that there are only two possible disc sizes. Participants were presented a single disc in the same configuration as the grasping and manual estimation tasks and were asked to judge its size with a button press (left for smaller, right for larger, see Figure 28). Participants were asked to judge if the presented disc was smaller or larger than essentially the average of the previously presented disc sizes. Again, participants were not informed that there were only two possible sizes. Here, we expect lower accuracies because participants have to judge the size of one disc without being able to see a comparison disc. This also makes the task more consistent with grasping and manual estimation.

Small changes were made to the experimental set-up that are depicted in Figure 28, right panel. The purpose of these changes was to minimise data loss due to the Optotrak markers being obstructed during the movement. The distance between the start position and the target disc was always 15 cm, as in Ganel et al. (2012). In addition, participants were asked to fill out a questionnaire at the end of the experiment about their strategy during the tasks (see Section 4.9.2 Appendix for the questions included).

The same statistical analyses as in Experiment 1 were conducted. Similar to the standard perceptual judgement task, we compared accuracies in the control task to 50% and made pairwise comparisons to the other tasks. Statistical tests used were t-tests and equivalence tests, with $\alpha = 0.05$ and an equivalence margin of 5%.

4.3.2 Results

Outliers were few and led to no removals in perceptual judgement or the control task, and less than 0.5% of trials were removed in grasping and manual estimation.

Differences for the MGA and manual estimates are depicted in Figure 29, and the accuracies of all tasks are shown in Figure 30.

The MGAs in response to the small and large discs differed by 0.38 ± 0.09 mm ($t(47) = 4.31$, $p < .001$), and the manual estimates differed by 0.18 ± 0.11 mm ($t(47) = 1.67$, $p = .102$), which are similar to the results reported by Ganel et al. (2012). However, as argued above, these values cannot be compared to the perceptual judgement task. In order to compare the size resolution in the different tasks, we calculated the classification accuracies using median split dichotomisation.

4.3.2.1 Accuracy Differences

The results here are quite consistent with Experiment 1: the accuracy in the standard perceptual judgement task (with two discs) was 66.9 ± 1.2% and significantly better than chance, $t(47) = 14.11$, $p < .001$. Classification accuracy in grasping was 52.1 ± 0.6% and also significantly better than chance, $t(47) = 3.50$, $p < .001$. Manual estimation was very similar to grasping and classification accuracy was 51.4 ± 0.7% and also significantly better than chance, $t(47) = 2.09$, $p = .021$. The control perceptual judgement task accuracy was 57.8 ± 0.7%, and was numerically similar to Ganel et al. (2012, 58.7 ± 4%), but it was significantly better than chance, $t(47) = 11.86$, $p < .001$.

The pairwise comparisons were also qualitatively identical: Standard perceptual judgement accuracy was significantly better than grasping, difference = 14.8 ± 1.3%, $t(47) = 11.02$, $p < .001$, as well as significantly better than manual estimation, difference = 15.6 ± 1.2%, $t(47) = 12.58$, $p < .001$. Difference between grasping and manual estimation was 0.7 ± 0.8%, and not significantly different, $t(47) = 0.92$, $p = .363$.

As exploratory analyses, we made pairwise comparisons between the control task and the other three tasks. The standard perceptual task was significantly more accurate than the control task (difference = 9.2 ± 1.4%, $t(47) = 6.67$, $p < .001$), but the control task was significantly more accurate than grasping (difference = 5.7 ± 1.0%, $t(47) = 5.80$, $p < .001$) and manual estimation (difference = 6.4 ± 0.8%, $t(47) = 7.66$, $p < .001$).

4.3.2.2 *Accuracy Equivalence*

The equivalence tests to check whether accuracies were equal to 50% were also consistent with previous results: Both perceptual judgement tasks were not significant (standard: $t(47) = 9.94$, $p = 1$, control: $t(47) = 4.22$, $p = 1$). On the other hand, a significant result was obtained for both grasping ($t(47) = -4.88$, $p < .001$) and manual estimation ($t(47) = -5.56$, $p < .001$). While the accuracies in the perceptual task fall beyond the equivalence bounds [45% 55%], the accuracies for grasping and manual estimation are not more extreme than this interval. In fact, our results would support even stronger conclusions: the 90% confidence interval for grasping is [51.1% 53.1%] and for manual estimation [50.3% 52.5%].

The pairwise comparisons provided further insights, with the most important result being the significant equivalence test between accuracies of grasping and manual estimation, $t(47) = -5.42$, $p < .001$ and the 90% confidence interval [-0.6% 2.0%] supporting an even tighter equivalence interval of ±2%. None of the other equivalence tests were significant (grasping vs. standard perceptual judgement: $t(47) = 7.31$, $p = 1$, manual estimation vs. standard perceptual judgement: $t(47) = 8.54$, $p = 1$, control vs. standard perceptual judgement: $t(47) = 3.03$, $p = 1$).

4.3.3 Discussion

We conducted an improved version of Experiment 1 to test for differences in size resolution in perception and action, with almost twice the number of participants as the original study (Ganel et al., 2012, n = 22 in Experiment 1 and n = 25 in Experiment 2) on this topic.

Our results were quite conclusive: the perceptual judgement tasks had much higher accuracies than grasping and manual estimation, and these were also significantly above chance. Grasping and manual estimation accuracies were close to 50% (51-52%), even though they were also significantly better than chance due to the high precision and large sample size. Based on these results, there is no evidence for superior size resolution in grasping than perception. Crucially, grasping and manual estimation (assumed to be a perceptual task), were very similar (difference of 0.7 ± 0.8%) and an equivalence test supported an equivalence interval as tight as ±2%, although we only pre-registered an equivalence interval of ±5%.

In short, we investigated size resolution with the appropriate metric of classification accuracy and calculated and compared it across perception and action tasks. Doing this, we find no evidence for a perception-action dissociation between appropriately matched tasks like grasping and manual estimation.

So far, we presented evidence from our own studies by calculating the classification accuracies. The other studies on this topic either did not calculate classification accuracies (Ganel et al., 2012; Heath et al., 2022), or used a different method to arrive at the classification accuracies (Göhringer et al., 2019). In the following sections, we evaluate these different studies by reanalysing their data to calculate classification accuracies, and then perform a meta-analysis to aggregate the available evidence.

4.4 Reanalysis of Göhringer et al. (2019)

Göhringer et al. (2019) performed a replication of Ganel et al. (2012) across three experiments. We thank Frederic Göhringer for kindly sharing the full, trialwise data from their three experiments with us.

The full data allowed us to perform a reanalysis and obtain an estimate for the classification accuracy in grasping using the median split method. Göhringer et al. (2019) had used a dichotomisation method that provides the maximum possible accuracy that can be achieved by any classifier. Obviously, this method gives an overly optimistic estimate for the classification accuracy. What would be the to-be-expected grasping accuracy, had they used the median split dichotomisation? Using the full data, we were able to calculate this value for their three experiments.

4.4.1 Method

Göhringer et al. (2019) performed three experiments with 29, 26 and 30 participants respectively. In Experiment 1, they replicated the design of Ganel et al. (2012), but could not replicate the results. Thus, they carried out Experiment 2, with a slight change in the set-up (they noticed that a pole that marked the starting position was obstructing participants' movement and shortened its height). Here, they could replicate the results of Ganel et al. (2012). In Experiment 3, participants performed both closed-loop grasping (full vision throughout the movement) and open-loop grasping (no vision after movement onset). For further details, we refer to the original publication.

The finger apertures in grasping (MGA) were dichotomised to obtain classification accuracies using the median split method in the same way as described in Experiments 1-2.

4.4.2 Results

The classification accuracies in grasping using the upper-bound method as well as the median split are depicted in Figure 31. The mean ± SEM of the grasping accuracies for Experiments 1 and 2 were 52.5 ± 0.8% and 52.7 ± 1.2% respectively. For Experiment 3, the accuracy in closed-loop grasping was 51.7 ± 1.1% and in open-loop grasping it was 51.0 ± 1.1%.

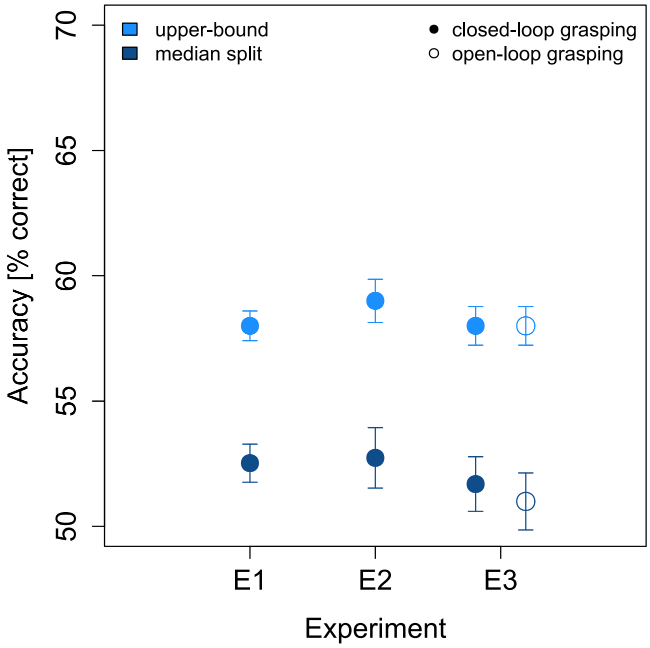
4.4.3 Discussion

We reanalysed the data from Göhringer et al. (2019) to obtain an estimate for classification accuracies in grasping using the median-split method. As expected, the median split accuracies were lower than the upper-bound accuracies, and quite close to 50% (chance-level or random guessing). The average of the three experiments was 52%, which is almost identical to the classification accuracy we obtained for grasping in Experiments 1-2.

Fortunately, we could obtain the full trialwise data of Göhringer et al. (2019) for the reanalysis. However, we do not have access to the trialwise data of the other studies on this topic, Ganel et al. (2012) and Heath et al. (2022). Nevertheless, we can still estimate classification accuracies in grasping and manual estimation from these studies using the reported summary statistics, that is, reported t and F values. For this, we use the formulae derived by Meyen

Figure 31

Reanalysis of Göhringer et al. (2019) Using the Median Split Method



Note. Comparison of classification accuracies in grasping using the median-split method and the upper-bound method. The x-axis represents the three experiments from Göhringer et al. (2019).

et al. (2022). The formulae employ a parameter named q^2, which we can estimate from the trialwise data of Göhringer et al. (2019) for grasping. Furthermore, we also use the data collected in our Experiments 1-2 for estimating q^2 in manual estimation (for which we do not have access to trialwise data from any previous study). The next section describes the details of this estimation.

4.5 Estimation of q^2 for Reanalysis Using Summary Statistics

In this section, we describe how we estimated the parameter q^2 from the trialwise data of Göhringer et al. (2019). This would allow us to to calculate back the median split classification accuracies from just the reported summary statistics from Ganel et al. (2012) and Heath et al. (2022), which we describe in Section 4.6.

The parameter q^2 (see Meyen et al., 2022), is the ratio of between-participant versus within-participant variance in the MGAs or manual estimates (Meyen et al., 2022, used it for reaction times). We use the formulae reported in Meyen et al. (2022, 2024) for this estimation.

4.5.1 Method

We use the following formula from Meyen et al. (2024, equation 6) to estimate q^2 from the trial-by-trial data of Göhringer et al. (2019) and the data of Experiments 1-2:

$$\hat{q}^2 = \frac{N \cdot SE^2 - \frac{4}{K}\hat{\sigma}_\epsilon^2}{\hat{\sigma}_\epsilon^2} \tag{32}$$

In Equation 32, N is the number of participants, K is the total number of trials, SE is the standard error of the effects (differences in MGAs, $MGA_{large} - MGA_{small}$) and $\hat{\sigma}_\epsilon^2$ is the estimated trial-by-trial variance, computed by pooling the variance of MGAs for each participant $\times$ condition (small or large).

4.5.2 Results

We computed estimates for the variance ratio q^2 using Equation 32. The estimated q^2 values are listed below in Table 23. For our reanalysis, we will use the mean of the values (excluding open-loop grasping in Experiment 3 of Göhringer et al., 2019, because the value might be different due to task differences).

Table 23

Estimates of q^2 from Göhringer et al. (2019) and our Experiments 1-2

Study	Experiment	Closed-loop Grasping	Manual Estimation
Göhringer et al. (2019)	Experiment 1	-0.002	-
Göhringer et al. (2019)	Experiment 2	0.022	-
Göhringer et al. (2019)	Experiment 3	0.043	-
Our study	Experiment 1	-0.004	0.049
Our study	Experiment 2	-0.002	0.014
	Mean	0.011	0.032

Note. q^2 from open-loop grasping of Experiment 3 of Göhringer et al. (2019) were excluded, because the reanalysed studies only used closed-loop grasping. Despite q^2 being a ratio of variances (squared value), it can sometimes be negative due to measurement error (Meyen et al., 2024). Excluding such negative values may introduce bias, therefore we will include those negative values in the mean calculation.

4.5.3 Discussion

Using the formulae from Meyen et al. (2022, 2024) and the full, trialwise data from Göhringer et al. (2019) and our own experiments, we estimated the parameter q^2 which is the variance ratio. We estimated q^2 = 0.011 for grasping and q^2 = 0.032 for manual estimation.

In the next secton, we will use this value for reanalysing and computing median split accuracies from the other studies (Ganel et al., 2012; Heath et al., 2022) for which we do not have the trialwise data.

4.6 Reanalysis of Ganel et al. (2012) and Heath et al. (2022)

After obtaining an estimate for the variance ratio q^2, we can use the formula from Meyen et al. (2022) to calculate back the median split accuracies from the other two studies on size resolution in perception and action, Ganel et al. (2012) and Heath et al. (2022), for which the trialwise data is not available.

4.6.1 Method

We used Equations 33 and 34 (Meyen et al., 2022, Equations 9 and 10, Supplement C) to estimate the sensitivity d' and its standard error using the reported t and F values from Ganel et al. (2012) and Heath et al. (2022).

$$d'_{estimated} = t \cdot \sqrt{\frac{q^2 + \frac{4}{K}}{N}} \cdot \sqrt{\frac{2}{N-1}} \cdot \frac{\Gamma\left(\frac{N-1}{2}\right)}{\Gamma\left(\frac{N-2}{2}\right)} \tag{33}$$

$$SE_{estimated} = \sqrt{\frac{q^2 + \frac{4}{K}}{N}} \cdot \sqrt{\frac{2}{N-1}} \cdot \frac{\Gamma\left(\frac{N-1}{2}\right)}{\Gamma\left(\frac{N-2}{2}\right)} \cdot \sqrt{\left(1 + \frac{2 \cdot t^2}{N-1}\left(\frac{\Gamma\left(\frac{N-1}{2}\right)}{\Gamma\left(\frac{N-2}{2}\right)}\right)^2\right)\left(\frac{N-1}{N-3} - t^2\right)} \tag{34}$$

Then we transformed the sensitivity d' to accuracy(% correct) using Equation 35 (Meyen et al., 2022, Supplement C).

$$Accuracy = \Phi\left(\frac{d'}{2}\right) \tag{35}$$

In Equations 33 - 35, N and K represent number of participants and trials respectively, t is the t-value for the comparison between conditions (=$\sqrt{F}$ for repeated-measures designs, Meyen et al., 2022), q^2 is the variance ratio we calculated in Section 4.5.2, Γ is the gamma function and Φ is the cumulative normal distribution.

To calculate the corresponding median split accuracies, we can use the values from Ganel et al. (2012) and Heath et al. (2022) listed in Table 24.

Table 24

Values for Reanalysis Using Summary Statistics

	Ganel et al. (2012)		**Heath et al. (2022)**	
	Grasp	**ME**	**Grasp**	**ME**
N	22	25	20	20
K	96	96	80	80
t			6.79	0.88
F	13.04	4.16		

Note. N = number of participants, K = number of trials, t = t-value, F = F-value, ME = manual estimation.

4.6.2 Results

Using Equations 33 - 35 and the values from Table 24, we estimated the median split accuracies for Ganel et al. (2012) and Heath et al. (2022). These accuracies are listed in Table 25 and depicted in Figure 32 for a comparison with our own results.

Table 25

Median Split Accuracies for Ganel et al. (2012) and Heath et al. (2022)

Task	Ganel et al. (2012)	Heath et al. (2022)
Perceptual Judgement	60.7 ± 0.8%	55.0 ± 1.5%
Grasping	53.4 ± 1.1%	57.1 ± 1.7%
Manual Estimation	52.1 ± 1.1%	51.1 ± 1.3%

Note. Values represent mean ± standard error. Perceptual judgement accuracy for Ganel et al. (2012) was averaged across the two experiments. Combined standard errors for this were calculated by pooling the variances.

4.6.3 Discussion

We applied the reanalysis method proposed by Meyen et al. (2022) to estimate median split accuracies for grasping and manual estimation from Ganel et al. (2012) and Heath et al. (2022). The advantage of this reanalysis is that we now have the same measures (accuracy or % correct) from each task which can be directly compared.

The choice of q^2 value may influence the results of the reanalysis, and it may be biased by our own experiments. We therefore performed the reanalysis using extreme values of q^2 to investigate the variation in the results. These results are discussed and described in the Appendix (Section 4.9.1).

Having converted the results of all the previous studies to the same metric (classification accuracies using median split dichotomisation), we can now combine these results in a meta-analysis.

4.7 Meta-analysis of Studies on Size Resolution

We collected and reanalysed the results of (to our knowledge) all the studies so far that investigated size resolution in perception and action, following the design of Ganel et al. (2012). In addition to the two experiments of Ganel et al. (2012), there are three experiments from Göhringer et al. (2019) and one from Heath et al. (2022), as well as the two experiments reported above. In Sections 4.4-4.6, we reanalysed the data so that the results from all these studies would be in the same metric: classification accuracies calculated from a median split dichotomisation.

Even with only eight data points, we believe that a meta-analysis will be helpful to *estimate* the differences in classification accuracies between grasping and perception tasks. This is because the information provided by single studies is limited. By combining and weighting (by sample size) the results of all the studies, we can better estimate the differences in size resolution between perception and action.

4.7.1 Method

We focused on accuracy as the dependent variable available in all tasks. We used the results of the reanalysis of Göhringer et al. (2019) from Section 4.4 and Ganel et al. (2012) and Heath et al. (2022) from Section 4.6.

The weighted mean (WM) was calculated by weighting the results of each experiment by the sample size in that experiment and taking the average across studies. We also calculated the SEM of the WM by weighting variances by the sample size and then taking the square root.

4.7.2 Results and Discussion

Table 26 shows an overview of the details of the different studies on size resolution and Figure 32 shows the classification accuracies for different tasks in the experiments of these studies.

Table 26

Sample Size and Number of Trials in Studies on Size Resolution

Study	Code	Experiment	Judge		ManEst		Grasp	
			N	K	N	K	N	K
Ganel et al. (2012)	Ga12	1	22	96			22	96
		2	25	96	25	96		
Göhringer et al. (2019)	Gö19	1	29	96			29	96
		2	26	96			26	96
		3	30	72			30	72
Heath et al. (2022)	H22	1	20	80	20	80	20	80
Current Study	B25	1	13	128	13	128	13	128
		2	48	128	48	128	48	128

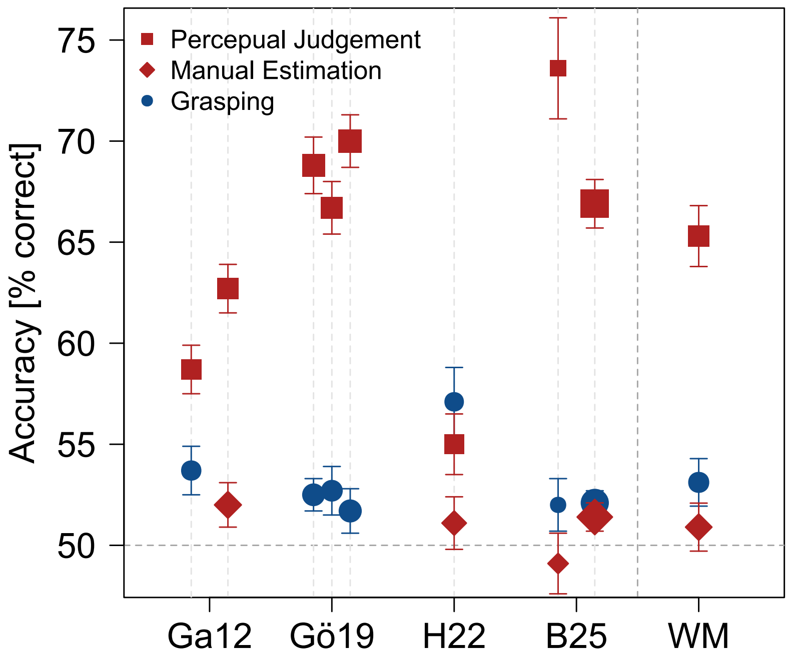
Note. Code represents the abbreviation used in x-axes of Figure 32. N = number of participants, K = number of trials per task per participant, ManEst = manual estimation, Judge = perceptual judgement.

The weighted mean ± weighted SEM of the accuracy for the perceptual judgement task is 65.3 ± 1.5%, for grasping, it is 53.1 ± 1.2% and for manual estimation, 50.9 ± 1.2% (see Figure 32). The accuracies of grasping and manual estimation are also quite consistent across studies, while perceptual judgement shows higher variability.

Therefore, based on the currently available evidence, the accuracy in perceptual judgement is better than grasping and manual estimation, which are rather similar to each other. These results do not support a perception-action dissociation regarding the size resolution of grasping and perception as inferred by Ganel et al. (2012).

Figure 32

Meta-Analysis of Studies on Size Resolution



Note. Comparison of classification accuracies from Ganel et al. (2012), Göhringer et al. (2019), and Heath et al. (2022) and the two experiments reported here. Grey dotted lines correspond to individual experiments from each study. The point sizes are scaled by the sample sizes of the experiments. Ga12 = Ganel et al. (2012), Gö19 = Göhringer et al. (2019), H22 = Heath et al. (2022), B25 = experiments reported here, WM = weighted mean.

4.8 General Discussion

In the current study, we investigated the resolution of size in perception and action using three tasks: grasping, manual estimation and perceptual judgement. A series of studies (Ganel et al., 2012; Göhringer et al., 2019; Heath et al., 2022) previously investigated this question and came to inconsistent conclusions because they used different methods to measure size resolution. The original study by Ganel et al. (2012), for example, measured accuracy (in % correct) in the perceptual judgement task and compared this to the effects on MGA in grasping, or manual estimates, and concluded that grasping has better size resolution than perception. Göhringer et al. (2019) suggested to calculate classification accuracies in all tasks for a fair comparison and used the upper-bound on accuracy that can be achieved by any classifier (Franz & von Luxburg, 2015). Most recently, Heath et al. (2022) contrasted the size resolution in perception and action by directly comparing the differences in finger apertures (MGA vs. manual estimates) in grasping versus manual estimation.

We showed that the original method of Ganel et al. (2012) runs into a well-known fallacy described by Franz and von Luxburg (2015), where a significant difference between MGAs for small versus large objects, is inferred as ’good’ size resolution, or more generally, that a significant difference is used to infer accurate classification or good discrimination. We instead suggested to calculate classification accuracies, similar to Göhringer et al. (2019), but using an optimal classifier: the median split (Franz & von Luxburg, 2015; Meyen et al., 2022). The classification accuracies from this method correspond to an ideal observer analysis - it results in the accuracy that would be achieved, had participants made optimal use of the information contained in their MGAs or manual estimates to classify object sizes.

In two experiments with improved design and statistical power, we show that the classification accuracies in grasping are not better than perceptual judgement. Indeed, they are much worse. The accuracies of manual estimation are comparable to grasping accuracies and differ by about ±2%. Further, we reanalysed the results of the previous studies, and using a meta-analysis, we aggregated the evidence from the currently available data on size resolution. Based on appropriate methods, replications and meta-analyses, our results do not provide support for a perception-action dissociation in size resolution.

4.8.1 Size Resolution in Grasping is Not Better Than Perception

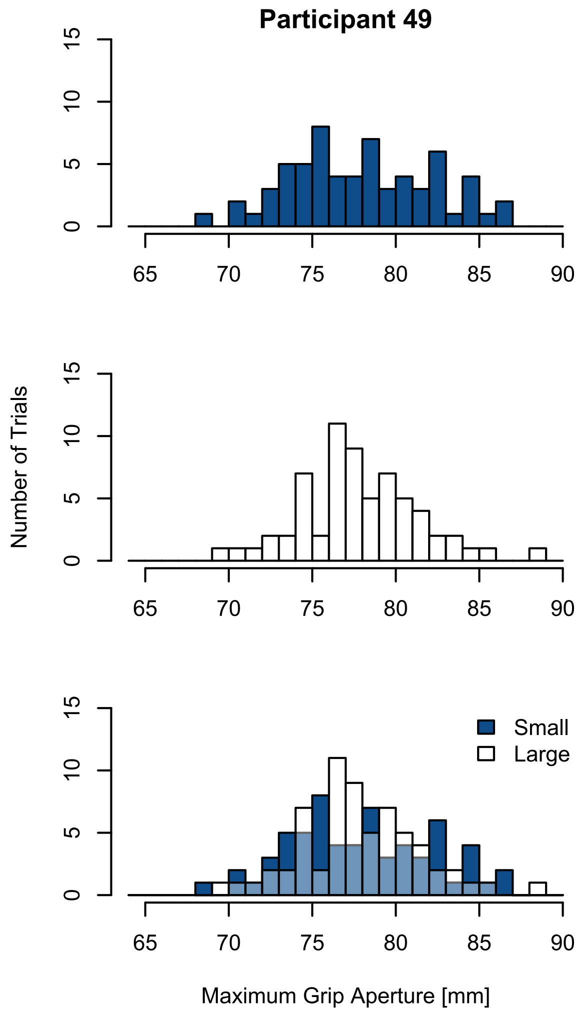
In our experiments as well as in the meta-analysis, we found that the accuracies in perceptual judgement are far better than in grasping. Further, the accuracies in manual estimation, also a perceptual task in the framework of the PAM, are very similar to grasping (51% vs. 53%). This might seem like a counter-intuitive result, given that all studies found a significant difference between the means of the MGA to small and large objects. Even though the grip aperture scales to object size, the distributions of the grip apertures are so noisy and overlapping, that classification on their basis is poor. As Franz and von Luxburg (2015) showed, a significant difference can result even when the underlying discrimination performance is low. This means that a significant difference in MGAs can be consistent with poor size resolution.

The reason for this is that the distributions of the MGAs for the small object and the large object heavily overlap. With such overlapping distributions (see Figure 33 for the data from one representative participant), if a single trial is picked out and that single MGA value is used to predict the size of the to-be-grasped object, it would be quite inaccurate. It is similar (indeed, slightly worse) for manual estimates - it is difficult to say whether a single manual estimate of 42 mm was rather in response to the 40 mm object or the 40.5 mm object.

Schenk and Milner (2006) tested size discrimination using a slightly different design in patient D.F., who suffered damage to her ventral stream and has been shown to have impaired perceptual abilities. They reported that D.F. had better perceptual performance (measured as d' and % correct) than grasping performance in a shape discrimination task (concluded to be based on size processing). Thus, even a neuropsychological patient with limited ventral stream processing like D.F. demonstrated better size discrimination via perceptual reports than based on grip apertures in grasping. This again demonstrates that classification on the basis of grip apertures is quite poor, likely due to the overlapping distributions.

Figure 33

Distributions of Maximum Grip Apertures to Small and Large Objects



Note. Histogram showing the distribution of Maximum Grip Apertures (MGAs) to the small and large objects for one representative participant. Note the heavily overlapping distributions in the bottom panel.

4.8.2 Is Manual Estimation a Perceptual Task?

Our meta-analysis (see Figure 32 and Section 4.7) suggests that manual estimation has the lowest accuracy (and therefore, worst size resolution) among the different tasks we investigated. According to the PAM, manual estimation is assumed to rely on perceptual representations and is assumed to be processed in the ventral stream. The average accuracy in manual estimation is 51% and very close to 50%, which is what would be expected if participants randomly indicated some estimate for the presented object, regardless of its size. This pattern is evident in all the studies we looked at, including our two experiments. Manual estimation was also very similar to grasping (53%). On the other hand, the meta-analysis also revealed that the accuracy in perceptual judgement (65%) is better than grasping and manual estimation. Thus, two tasks that are assumed by the PAM to be perceptual differ in their performance. This pattern is similar to the one that has been found in Garner interference (Bhatia et al., 2025), with manual estimation showing a Garner interference effect that is about the same as grasping, but much smaller than in a classic perception task. This inconsistency within the PAM should be resolved before inferences about perception and action can be made, for example, whether the size resolution of actions is better than perception, because the current state suggests that the answer depends on which perception task is considered.

4.8.3 Information Loss or the Cost of Dichotomisation

By dichotomising MGAs from multiple trials of a participant to a single value of classification accuracy, much of the information in the MGAs is discarded or unused. Indeed, Cohen (1983) showed that dichotomising a continuous variable could result in a loss of statistical power equivalent to discarding about 38% of the data. This decrease occurs because "[d]ichotomisation results in the systematic loss of measurement information" (Cohen, 1983, p. 252). It may then be argued that MGAs may contain more information about the disc sizes that is lost as a side-effect of the median split. However, the same argument holds for perceptual judgement: it is plausible that participants have internally more information about the disc sizes than is reflected in their judgement accuracy, but they are forced to give a binary response (smaller or larger), thus the dichotomisation reduces the richness of their responses (Meyen et al., 2022, Supplement G). We propose that, by also dichotomising MGAs, researchers should ensure equal grounds for a fair comparison between perception and action.

4.8.3.1 Comparing Grip Apertures With Continuous Perception Measures

Since dichotomisation leads to loss of information in the measurement, an alternative strategy for a fair comparison could be to measure a continuous variable from the perceptual task, and compare that with continuous MGA in grasping. This would require a different perceptual task than perceptual judgement like a perceptual adjustment task (e.g., Ganel et al., 2008), where participants adjust the size of a disc until it matches the size of the presented disc. Using perceptual adjustment creates an additional problem that the adjustment disc must be presented digitally (so that its size can dynamically change with participants' responses, e.g., on a computer screen as a 2D object), while the standard disc is a real, 3D object. There is currently some debate about whether 2D objects presented virtually elicit similar (dorsally-guided) grasping responses as real, 3D objects (Freud & Ganel, 2015; Ganel et al., 2020; Ozana & Ganel, 2017; Ozana et al., 2018). Thus, the stimuli presented in the grasping and perception tasks would be different and inequivalent, leading to potentially problematic inferences.

Another possibility for a continuous measure from a perceptual task is manual estimation, with the manual size estimates being comparable to the MGA in grasping. In fact, Heath et al. (2022) did exactly that: They performed a replication of Ganel et al. (2012) and compared the MGAs to the small and large objects in grasping to the manual estimates in manual estimation. They found that the MGA for the larger object was larger than the MGA for the smaller object, but the manual estimates did not differ for the small and large objects. Thus, Heath et al. (2022) concluded that "visual information mediating pantomime-grasps provides decreased resolution power" (p. 26; they refer to manual estimation as "pantomime grasping"). However, comparing effects on MGAs and manual estimates directly requires a slope-correction, which has been extensively discussed in the context of effects of visual illusions (Franz, 2003; Kopiske et al., 2016, see also Figure 1). Therefore, the conclusions of Heath et al. (2022) may not be valid.

To avoid this problem, d' values may be computed for both tasks, similar to what Schenk and Milner (2006) did. This way, a continuous measure can be obtained for both tasks and compared. The problem is that statistical tests cannot be applied because a single d' is obtained. For example, in Experiment 2, we obtained a d'_{MGA} = 0.069 in grasping, d'_{ManEst} = 0.024 in manual estimation, d'_{PJ} = 0.876 in perceptual judgement and $d'_{Control}$ = 0.392 in the control task. These values tell the same story as the classification accuracies: grasping and manual estimation are similar with grasping being slightly better, but perceptual judgement, even with one disc in the control task, has far better size resolution than grasping.

4.8.4 Correct Versus Incorrect Trials Analysis

All the previous studies on this topic, starting with Ganel et al. (2012), had a design where participants judged the size of the stimulus and grasped it within the same trial. They achieved this by asking participants to perform the two tasks sequentially with a short interval (500 ms) in between, and counterbalanced the order of the tasks. This allowed the other studies to report an analysis of the difference in MGA for the small and large object, separately for those trials where participants made the correct perceptual judgement, and incorrect trials. Ganel et al. (2012) and Heath et al. (2022) observed that the large-small MGA difference was statistically significant in both correct and incorrect trials, concluding that "accuracy of grasping is independent of the accuracy for visual perception" (Ganel et al., 2012, p. 4). The results of this analysis were inconsistent across the three experiments of Göhringer et al. (2019).

In our experiments, we implemented a blocked design, with each task performed by participants in a separate block. This meant that we could not analyse the MGAs from the correct and incorrect perceptual judgement trials because there was no mapping between the trials. However, we will argue that the correct versus incorrect trials analysis described above is problematic and is not a necessary analysis to investigate the size resolution in the different tasks.

The main problem with this analysis is that such within-trial grasping and perceptual judgement tasks might not be instances of exclusive dorsal stream or ventral stream processing, respectively. Because participants are aware that they should perform the two tasks in quick succession, it is difficult to rule out if hybrid and interactive processing in both dorsal and ventral streams may be occurring (e.g., Freud & Ganel, 2015; Ganel et al., 2020). Ganel et al. (2020) suggested that several factors could contribute to such interactive processing, including requirements of the specific task. For example, participants could start planning their grasping movement while making the perceptual judgement, or start comparing the two object sizes during the grasping movement, and these processes (presumably relying on distinct representations in the ventral and dorsal streams) might interact with each other. Schenk and Milner (2006) suggested that, in a similar experimental design with patient D.F., "the information processed during the motor preparation phase was then able to influence her verbal report" (p. 1502). A blocked design can avoid such potential interactions.

With the blocked design, we can isolate performance in each task, and investigate which task demonstrates better or worse size resolution. Furthermore, during grasping and manual estimation, participants only need one disc. Therefore presenting only one disc in the blocked design for these tasks mimics a natural situation for these tasks and may reduce effects of relative size processing occurring from the comparison of the two discs and assumed to be the domain of the ventral stream (for a related discussion in visual illusions, see Franz et al., 2000).

4.8.5 Accuracy of the Perceptual Judgement Task

Figure 32 reveals a discrepancy between the results of the studies: the accuracy in the perceptual judgement task has a high variability. Ganel et al. (2012) and Heath et al. (2022) observed rather low accuracies (59% and 55% respectively), while Göhringer et al. (2019) as well as the experiments in this study reported rather high accuracies (≥65%). One possible reason that we tried to address in Experiment 2 was presenting one disc versus both discs for the perceptual judgement task. Presenting only one disc did lead to lower accuracies (58% vs. 66% in Experiment 2), but since the other studies always used two discs, it does not explain the inter-study variability in the accuracy of perceptual judgement (e.g., between the results of Ganel et al., 2012; Göhringer et al., 2019).

Differences in the stimuli might be one reason: Ganel et al. (2012) and Göhringer et al. (2019) and our experiments used discs but Heath et al. (2022) used rectangular blocks of length 40 mm and 40.5 mm, with a height and width of 10 mm each. The accuracy in this task with discs might not be comparable to rectangular blocks, because the blocks have other size dimensions (in addition to the to-be-grasped dimension) that could confuse the participants (e.g., introducing Garner interference effects between the length and width of the rectangles, Garner, 1970). Even though the other dimensions of the rectangular blocks are kept constant across trials (arguably a baseline condition, but the other dimensions are different in magnitude than the target dimension), an interference-like effect may still occur (in comparison to a situation where the dimensions are equal in magnitude, e.g., using cubes of side 40 mm and 40.5 mm). This is because length and width of rectangles have been shown to be integral dimensions, meaning they are often not processed independently (Felfoldy, 1974). Because Garner interference is much larger in perception (Bhatia et al., 2025) than grasping, it would explain the lower accuracy in the perception task.

Even so, Ganel et al. (2012) and Göhringer et al. (2019) and the present experiments used comparable stimuli of the same dimensions, and yet reported different results of accuracy. Below, we speculate possible reasons that might explain this difference in accuracy.

As mentioned in Section 4.2.3, the stimulus presentation time used by Ganel et al. (2012) and Göhringer et al. (2019) differed by 500 ms, with Göhringer et al. (2019) using a longer presentation time. Having more time to look at the stimulus and respond might have increased participants' accuracies. Our first experiment had an even longer presentation time (3000 ms) and thus, even higher accuracies. However, in Experiment 2, we matched the presentation time to Ganel et al. (2012) and still observed higher accuracies.

Another aspect that might influence the accuracies is the viewing distance and angle of the discs. Ganel et al. (2012) presented both discs simultaneously but they were not equidistant to the participant: one disc was in the center and the second disc was 10 cm to the left or right and further back (cf. their Figure 1 and description on p. 3). The difference in viewing angle and distance between the two discs might explain a worse accuracy than comparing the discs essentially side-by-side (see Figure 28). However, Göhringer et al. (2019) replicated what Ganel et al. (2012) did, and still reported higher accuracies. Nevertheless, comparable viewing angles and distances for both stimuli would result in fewer confounds. Future studies might clarify the source of these differences when controlling for the stimulus positioning.

4.8.6 Conclusions

The initial report that grasping has superior size resolution to visual perception (Ganel et al., 2012) was seen as further support for the Perception-Action Model. However, this result was based on problematic analyses that compared accuracy in one task to aperture differences in another. Here, we show how to appropriately investigate size resolution in these tasks by calculating the classification accuracies, so that the same metric can be compared in all tasks. Our replications and meta-analysis reveal that the classification accuracies in grasping are much worse than perceptual judgement, but comparable to manual estimation (also a perceptual task). These results suggest that the size resolution in grasping is not better than in perception, and as such, do not provide any evidence for a perception-action dissociation. Thus, claims about different processing in these tasks relying on ventral or dorsal stream need to be re-assessed.

4.9 Appendix to Section 4

4.9.1 Manual Estimation Accuracies with Different q^2 Values

The results of our reanalysis of Ganel et al. (2012) and Heath et al. (2022) from summary statistics depends on the estimation of a parameter, the variance ratio q^2. We estimated this value for grasping from the trialwise data of Göhringer et al. (2019), and for grasping as well as manual estimation from our own data.

As a sanity check, we performed the reanalysis with a range of q^2 values, including those obtained from our own experiments and some extremely low and high values, to ensure that our results were not overly biased by our choice of q^2. The results are listed in Table 27.

Meyen et al. (2022, 2024) used a benefit-of-the-doubt approach, and chose higher values of q^2 (than estimated from some representative studies) in order to favour the claim of original studies on priming and contextual cueing. We can also apply a similar benefit-of-the-doubt approach, but we would have to favour higher accuracies for grasping and lower accuracies for manual estimation (perception), because Ganel et al. (2012) originally claimed that the size resolution of grasping was better than perception. To show the variation in the results of the reanalysis with the choice of q^2, we report below the accuracies for both grasping and manual estimation from Ganel et al. (2012) and Heath et al. (2022), but with a wide range of q^2 values. We chose the extremely low and extremely high values based on Figure 3 of Meyen et al. (2024), where the highest q^2 was greater than 0.15 and lowest was about -0.05. We chose q^2 = 0.2 as an extremely high value and q^2 = -0.04 as an extremely low value. Being a squared quantity, q^2

should be positive and using q^2 = -0.05 did not give meaningful results for Ganel et al. (2012), therefore we used q^2 = -0.04.

Even with the extremely high q^2, the grasping accuracies are not better than in perceptual judgement (65% from the meta-analysis). Even with extremely low q^2, manual estimation results were not considerably worse than what the meta-analysis showed (51%).

Table 27

Results from Ganel et al. (2012) and Heath et al. (2022) Using Different q^2 Values

q^2	**Obtained From**	**Ga12 Grasp**	**H22 Grasp**	**Ga12 ManEst**	**H22 ManEst**
-0.040	Extremely low	50.6 ± 0.2%	52.9 ± 0.7%	50.3 ± 0.2%	50.4 ± 0.5%
0.011	Reanalysed Mean Grasp	**53.4 ± 1.1%**	**57.1 ± 1.7%**	51.8 ± 1.0%	50.9 ± 1.1%
0.032	Reanalysed Mean ManEst	54.0 ± 1.3%	58.3 ± 1.9%	**52.1 ± 1.1%**	**51.1 ± 1.3%**
0.200	Extremely high	57.2 ± 2.4%	64.2 ± 3.4%	53.9 ± 2.1%	51.9 ± 2.3%

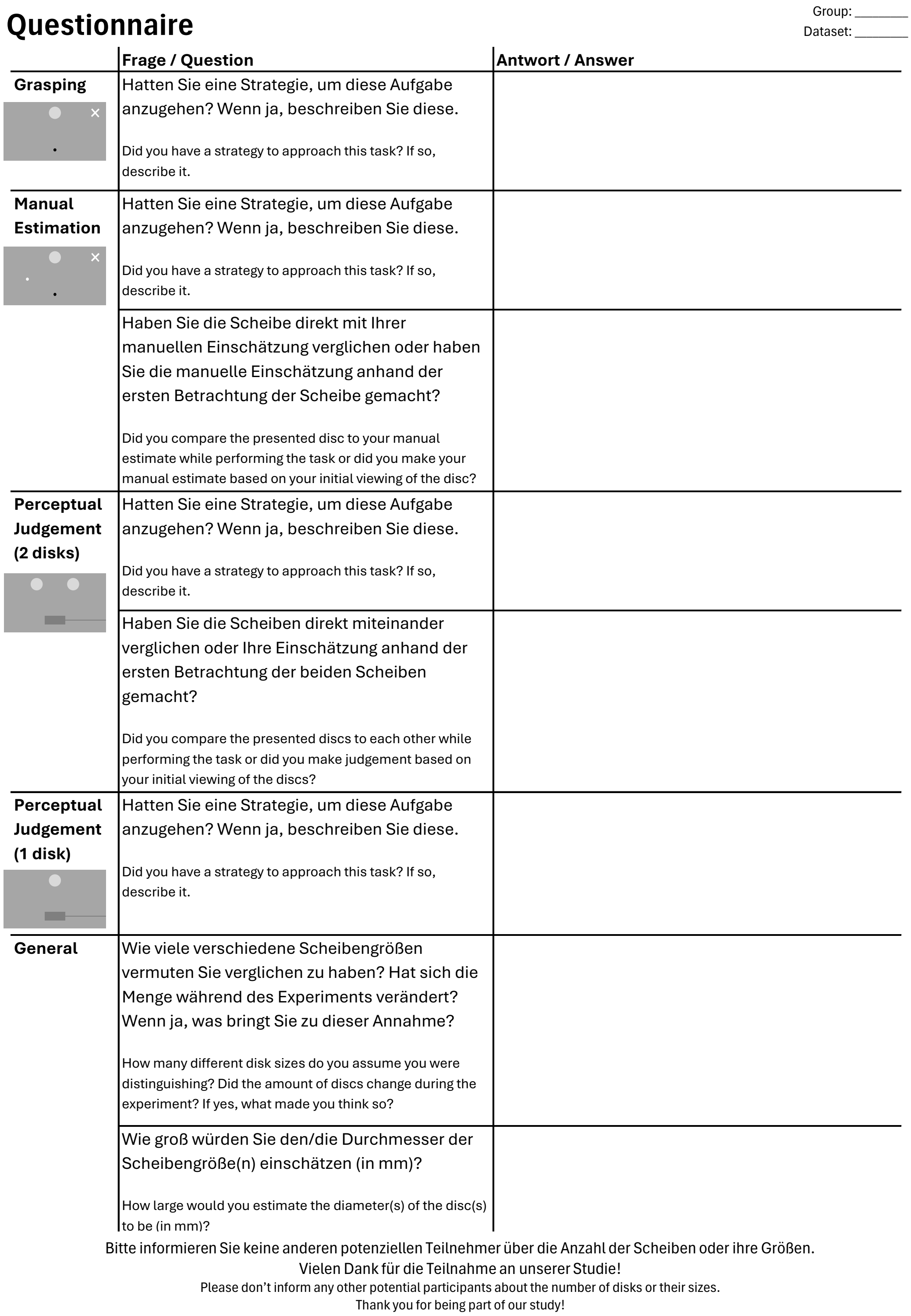
Note. The reanalysis of Ganel et al. (2012) resulted in errors with $q^2 <$ -0.04, so we here report the values with q^2 = -0.04 for this study. Values represent mean ± standard error. Bold values represent those used in the meta-analysis. Ga12 = Ganel et al. (2012), H22 = Heath et al. (2022), ManEst = manual estimation.

4.9.2 Questionnaire for Experiment 2

Figure 34 shows a copy of the questionnaire provided to participants of Experiment 2 to fill out at the end.

Figure 34

Questionnaire for Participants at the End of Experiment 2



Questionnaire

Group: ________
Dataset: ________

	Frage / Question	Antwort / Answer
Grasping	Hatten Sie eine Strategie, um diese Aufgabe anzugehen? Wenn ja, beschreiben Sie diese. Did you have a strategy to approach this task? If so, describe it.	
Manual Estimation	Hatten Sie eine Strategie, um diese Aufgabe anzugehen? Wenn ja, beschreiben Sie diese. Did you have a strategy to approach this task? If so, describe it.	
	Haben Sie die Scheibe direkt mit Ihrer manuellen Einschätzung verglichen oder haben Sie die manuelle Einschätzung anhand der ersten Betrachtung der Scheibe gemacht? Did you compare the presented disc to your manual estimate while performing the task or did you make your manual estimate based on your initial viewing of the disc?	
Perceptual Judgement (2 disks)	Hatten Sie eine Strategie, um diese Aufgabe anzugehen? Wenn ja, beschreiben Sie diese. Did you have a strategy to approach this task? If so, describe it.	
	Haben Sie die Scheiben direkt miteinander verglichen oder Ihre Einschätzung anhand der ersten Betrachtung der beiden Scheiben gemacht? Did you compare the presented discs to each other while performing the task or did you make judgement based on your initial viewing of the discs?	
Perceptual Judgement (1 disk)	Hatten Sie eine Strategie, um diese Aufgabe anzugehen? Wenn ja, beschreiben Sie diese. Did you have a strategy to approach this task? If so, describe it.	
General	Wie viele verschiedene Scheibengrößen vermuten Sie verglichen zu haben? Hat sich die Menge während des Experiments verändert? Wenn ja, was bringt Sie zu dieser Annahme? How many different disk sizes do you assume you were distinguishing? Did the amount of discs change during the experiment? If yes, what made you think so?	
	Wie groß würden Sie den/die Durchmesser der Scheibengröße(n) einschätzen (in mm)? How large would you estimate the diameter(s) of the disc(s) to be (in mm)?	

Bitte informieren Sie keine anderen potenziellen Teilnehmer über die Anzahl der Scheiben oder ihre Größen.
Vielen Dank für die Teilnahme an unserer Studie!
Please don't inform any other potential participants about the number of disks or their sizes.
Thank you for being part of our study!

5. Discussion

> Inference that could be called trustworthy would require merging information from multiple studies and lines of evidence.
>
> Amrhein et al. (2019, p. 264)

In this thesis, the evidence for perception-action dissociations was critically evaluated in three different behavioural experimental paradigms: Weber's law, Garner interference and size resolution. Based on cumulative evidence from replications and aggregated evidence from meta-analyses, we conclude that the perception-action dissociations in these paradigms are much weaker than initially assumed (cf. Ganel & Goodale, 2003; Ganel et al., 2008, 2012). Consequently, the results from these studies and similar studies on these topics can no longer be counted as support for the PAM. In the subsequent sections, the implications for the PAM and other related theories on perception and action are discussed, followed by a discussion of metascience tools that contributed to the progress made in this debate about PAM. We end with a summary and outlook for future research.

5.1 Is There Evidence for Perception-Action Dissociations?

Perception-action dissociations are observed differences in performance between perception and action tasks. They are often considered evidence in support of the PAM, which postulates that perception and action are processed in different ways in the ventral and dorsal streams and rely on separate representations of object features (Goodale & Milner, 1992). The PAM was initially proposed on the basis of perception-action double-dissociations in patients with lesions to the ventral or dorsal stream. In response to criticism against relying solely on evidence from neuropsychological patients (Schenk, 2010; Schenk et al., 2011), there was a call for demonstrating evidence of such perception-action dissociations in the behaviour of healthy humans. The most widely-studied yet also most controversial evidence for this came from Aglioti et al. (1995), who reported that grasping was not affected by the Ebbinghaus illusion, but perception was. The controversy was somewhat resolved by a multi-lab registered replication (Kopiske et al., 2016), which concluded that the Ebbinghaus illusion has similar effects on grasping and perception. Evidence from other lines, claiming that grasping violates Weber's law or that grasping is immune to Garner interference, gained traction and were highly influential (Ganel & Goodale, 2003; Ganel et al., 2008). Later, it was also shown that grasping has apparently better size resolution than perception (Ganel et al., 2012). These studies, along with evidence from the neuropsychological patients, were seen as converging evidence for the PAM.

In recent years, several studies were published that reported contradictory evidence and cast doubt on the apparent perception-action dissociations in Weber's law (Löwenkamp et al., 2015; Utz et al., 2015), Garner interference (Hesse & Schenk, 2013; Löhr-Limpens et al.,

2020) and size resolution (Göhringer et al., 2019). Informative debates ensued (e.g., Bruno et al., 2016; Ganel & Goodale, 2014; Ganel et al., 2020; Uccelli et al., 2021), but no resolution or consensus could be reached via individual studies that were either pro or contra the PAM. Our investigation into these three paradigms attempted to streamline the literature and provide an overview of various studies through improved methods, replications and meta-analyses (see also Section 5.4).

In each paradigm we investigated, large effects and strong evidence for perception-action dissociations were originally reported (Ganel & Goodale, 2003; Ganel et al., 2008, 2012). However, our comprehensive analysis of these paradigms revealed little evidence for perception-action dissociations across the many studies on those topics. This contradiction arose due to different reasons: In Weber's law, suboptimal analysis methods that disregarded features of grasping were used, and applying the appropriate analysis method found no difference between perception and action with regard to Weber's law, across several representative studies (Bhatia et al., 2022). In Garner interference, mounting replication failures suggested that the initially demonstrated perception-action dissociation was not robust, and a meta-analysis of 15 studies revealed no difference in the Garner interference effects between perception and action (Bhatia et al., 2025). In size resolution, incompatible dependent variables measuring different aspects of perception and action were originally compared. Converting them to the same metric resulted again in no difference between perception and action across several studies (see Section 4). Thus, the results reported here cast doubt on three further experimental paradigms assumed to provide evidence for the PAM. Putting these results together with past research, the currently available data from visual illusions, Garner interference, Weber's law and size resolution provide insufficient evidence for perception-action dissociations, and consequently, the PAM.

5.1.1 Is Manual Estimation a Perceptual/Ventrally-Guided Task?

The PAM assumes that manual estimation is a perceptual/ventrally-guided task. Based on studies with lesion patients (e.g., patient D.F. who had lesions to large parts of the ventral stream, had perceptual deficits and could not scale her manual estimates to object size, see Figure 2A of Goodale & Milner, 1992), it is assumed that manual estimation is anatomically processed in the ventral stream. Based on purported perception-action dissociations between grasping and manual estimation from behavioural experiments (Ganel & Goodale, 2003; Ganel et al., 2008, 2012; Goodale, Jakobson, & Keillor, 1994; Haffenden & Goodale, 1998), it is assumed that the representations of object features (e.g., size) are functionally different for these two tasks. A further assumption in the PAM framework is that grasping and manual estimation have similar task demands (e.g., because the same effectors are used, see also Ganel & Goodale, 2003).

Initial studies on Garner interference, Weber's law and size resolution reported different effects for grasping and manual estimation (interpreted as perception-action dissociations): larger Weber constant in manual estimation than grasping (Ganel et al., 2008), larger Garner interference effects in manual estimation than grasping (Ganel & Goodale, 2003) and worse size resolution in manual estimation than grasping (Ganel et al., 2012). The results reported in this thesis from new experiments and meta-analyses paint a different picture: Garner interference (see Figures 25–26 and Bhatia et al., 2025), Weber constants (Figure 9 and Bhatia et al., 2022) and size discrimination accuracies (see also Figure 32) in grasping versus manual estimation are surprisingly similar.

These results are surprising within the PAM framework because of assumptions associating manual estimation to the ventral stream. But, given the motor aspect of manual estimation, and other investigations into manual estimation, the results are rather consistent. For instance, Cesanek and Domini (2018) showed that adaptation of grasping transferred to manual estimation, suggesting shared mechanisms and overlapping control systems for these tasks.

Based on these results, we suggest that there is currently no evidence for a dissociation between grasping and manual estimation, and thus, no evidence for different representations of object features for grasping versus manual estimation. There is no contradiction to the PAM here if the auxiliary assumption that manual estimation is a ventrally-guided task is discarded. Importantly, this would not necessarily falsify or disprove the PAM - rather, it could be compatible with the existence of a dissociation between grasping and a different perceptual task (other than manual estimation), that is sufficiently comparable to grasping. In order to provide evidence for the PAM, subsequent research would therefore need to demonstrate the perceptual/ventral nature of a task other than manual estimation, establish the equivalence of task demands in this task to those in grasping, and finally, show a dissociation between this new task and grasping.

5.2 Other Theories Explaining Perception and Action

5.2.1 Separate Representations Model Versus Common Representation Model

So far, what we have been referring to as 'PAM' is sometimes called 'strong PAM' by some authors (Franz et al., 2001; Grünbaum, 2017). This 'strong PAM' assumes that object features like size and orientation are computed twice by independent processes in separate streams. In contrast, 'weak PAM' allows for interactions and cross-talk between the streams, such that perceptual and motor representations of object features may influence each other (Franz et al., 2001). Further, Franz et al. (2001) among others, have argued for a 'Common Representation Model' (CRM), where a single representation of object features is used for both perception and action. Since these competing models were defined first to explain the effect of visual illusions on grasping and perception, let us take an example from visual illusions to clarify and contrast the model predictions. CRM predicts a similar illusion effect in grasping and perception, weak PAM predicts a smaller illusion effect in grasping than perception, while strong PAM would predict no illusion effect in grasping (see also Franz et al., 2001, Table 1). Based on these, we can formulate general predictions for the other paradigms (Weber's law, Garner interference and size resolution) and these are listed in Table 28.

We can then compare the results from our experiments to the predictions in Table 28 to decide which model's predictions best fit the data. In Weber's law, the Weber constants for grasping were greater than 0 and in the expected range for size perception (0.02-0.06, see Figure 9). Furthermore, we found similar values of the Weber constant for manual estimation. But,

Table 28

Predictions From the Competing Models

Model	Weber's Law	Garner Interference	Size Resolution
Strong PAM	k_G = 0 & $k_G < k_P$	GI_G = 0 & $GI_G < GI_P$	$\%_G >$ 50% & $\%_P < \%_G$
Weak PAM	$k_G < k_P$	$GI_G < GI_P$	$\%_P < \%_G$
CRM	$k_G = k_P$	$GI_G = GI_P$	$\%_G = \%_P$

Note. We use the generic term 'perception' here because studies used different tasks to investigate perception, for example, perceptual adjustment, speeded-classification, perceptual judgement and manual estimation. The PAM assumes that all these tasks are guided by the ventral stream. PAM = Perception-Action Model, CRM = common representation model, P = measure in perception, G = measure in grasping, *k* = Weber constant, GI = Garner interference Filtering - Baseline, % = classification accuracy for discriminating object size.

the Weber constant for perceptual adjustment seems slightly larger (see Figure 9 and McGraw & Whitaker, 1999; McKee & Welch, 1992). The picture is similar in Garner interference (see Figure 25 and 26): grasping shows a small Garner interference effect that is similar to manual estimation but much smaller than speeded-classification. Therefore, the results from different *assumed* perceptual tasks do not match: we find no dissociation between grasping and manual estimation but a clear dissociation between classic perceptual tasks (perceptual adjustment, speeded-classification) and grasping. In size resolution also the same pattern emerges: similar classification accuracies for grasping and manual estimation but far *better* (counter-intuitively to the theory) accuracies in perceptual judgement. The problem here is that classic perceptual tasks often have quite different task demands and effectors than grasping (Franz et al., 2001; Ganel & Goodale, 2003), and it is difficult to assess if dissociations in performance are observed due to differing representations in the two tasks, or occur simply due to the incomparable nature of the tasks. If we accept the assumption of the PAM that manual estimation is a ventrally-guided task (but see Section 5.1 for reasons why this assumption may not be valid), then our data best fits the CRM: in both grasping and manual estimation, we find Weber's law with similar Weber constants, similar effects of Garner interference, and similar accuracies in resolution of object size.

5.2.2 Digits in Space or Double-Pointing Model

The PAM (strong and weak) and the CRM assume that grip aperture in grasping is based on size of the target object (based on extensive work by Jeannerod, 1984, 1999). Smeets and Brenner (1999) proposed a different model which they call 'Digits in Space' Model, which instead assumes that grip aperture in grasping is based on position information. Essentially, they argued that a grasp is based on independent pointing movements by the index finger and thumb (double pointing) toward suitable positions on the target object. Evidence for position information guiding grasping comes from studies on prism adaptation (Schot et al., 2014, 2017; Smeets et al., 2023), where independent adaptations of the finger and thumb have been shown. Further, as described in Section 2.6.2.2, this model could provide an explanation of why grasping seemingly violated Weber's law (Ganel et al., 2008): Weber's law holds only for properties that have magnitude and if grasping relies on positions (do not have magnitude), then Weber's law would not be expected (Smeets & Brenner, 2008). However, we suggested that the absence of Weber's law in grasping was rather due to a methodological issue in the calculation of the JND (Bhatia et al., 2022). When the JND was appropriately estimated in grasping, Weber's law was present (see Figure 9).

What about Garner interference and size resolution? Could the results from these paradigms be reconciled with the Digits in Space Model? In the majority of studies on grasping, the stimulus size and positions often coincide: manipulation of the object size also changes the grip positions (Smeets & Brenner, 2019), making inferences difficult. A similar problem is also present in Garner interference and size resolution: because size and positions co-vary, models assuming that grasping is based on size or positions would predict similar outcomes. The current results from Garner interference and size resolution cannot answer whether grasping relies on size or position information, and they were unfortunately also not designed to test this. Beyond prism adaptation, researchers would need to develop experimental designs in which size and positions could be independently varied, in order to test the Digits in Space Model against others that assume grasping is based on size.

5.3 Reference Frames, Metrics and Processing Modes in the Two Streams

The PAM characterises ventral versus dorsal stream processing along some existing functional dichotomies (e.g., see Table 2 of Schenk & McIntosh, 2010). Here, we focus on three such axes, namely, reference frames (egocentric vs. allocentric), metrics (absolute vs. relative) and processing mode (analytic vs. holistic). That the two streams differ along these axes has been used to explain various observed perception-action dissociations.

Milner and Goodale (1995) argued that interacting with objects would require egocentric reference frames and absolute metrics, because the visuomotor system needs to compute object properties with respect to the effector (egocentric coordinates) and requires precise information about those object properties (e.g., position or size; absolute metrics). On the other hand, perception would need to rely on relations between different objects, and object recognition would require viewpoint-invariant representations - thus, allocentric coordinates and relative metrics. According to this view, actions like grasping would be based on a veridical representation of object size, and thus not be affected by visual illusions (e.g., Aglioti et al., 1995). Furthermore, Ganel et al. (2008, 2012) suggested that such a view could also explain why grasping apparently violated Weber's law, and why the resolution of size in grasping is superior to perception. Goodale, Milner, Ganel and colleagues thus argued for different metrics and reference frames in the two streams based on these results.

However, Schenk (2006) showed that patient D.F.'s behaviour depended on whether allocentric or egocentric information was provided during a task, rather than the task itself. He argued that tasks and spatial information are often confounded such that perceptual tasks use allocentric information (e.g., the perception task in Section 4 and Ganel et al., 2012) while visuomotor tasks rely on egocentric information (e.g., the grasping task in Section 4 and Ganel et al., 2012). Schenk (2006) demonstrated that D.F.'s performance in perceptual and motor tasks with allocentric information was deficient compared to matched controls, but comparable to controls when egocentric information was provided in those same tasks. Thus, the purported perception-action dissociation was in fact an allocentric-egocentric dissociation, determined by task demands and not the visual stream.

Concerning processing mode, Garner (1974) regarded those stimulus dimensions that could be perceived independently as being separable and analytically processed (no Garner interference), while those dimensions that could not be decomposed into their constituents, as integral and holistically processed (Garner interference present). Ganel and Goodale (2003) used this approach and concluded that the length and width of rectangles, which were shown to be integral dimensions (Felfoldy, 1974), are processed analytically in grasping (dorsal stream, Garner interference absent) and holistically in manual estimation (ventral stream, Garner interference present). Therefore, Ganel and Goodale (2003) attributed analytical processing to the dorsal stream and holistic processing to the ventral stream.

Foard and Kemler (1984), however, demonstrated analytical processing of integral dimensions (saturation and brightness) and that the processing mode can be manipulated by factors like experimenter instructions, task demands and available processing time. This result can be corroborated by contemporary studies on Garner interference: Hesse and Schenk (2013) were able to manipulate the presence of Garner interference in the same speeded-classification task by altering the temporal profile of participants' responses (decision-amplitude hypothesis), while Löhr-Limpens et al. (2020) reported Garner interference in grasping under dual-tasking conditions (changing task demands). Moreover, Bhatia et al. (2025) analysed several studies on Garner interference and found some evidence that the overall reaction time in a task is a good predictor of Garner interference in that task. Further, Bhatia et al. (2025) speculated that Garner interference in a manual estimation task might depend on the task instructions, whether participants were asked to be fast or accurate (see also Table 11). Thus, again, it seems a more parsimonious explanation that the processing mode is a function of some combination of these factors, rather than which visual stream is active during a certain task.

Recently, Kaup et al. (2024) suggested that various dichotomies in mental representations can be mapped onto a 'modal' versus 'amodal' distinction. Modal representations are experiential and concrete, while amodal representations are symbolic and abstract. Thus, within the PAM framework, the dorsal stream operates on modal representations (veridical, egocentric, absolute and analytical) for carrying out visuomotor actions, while the ventral stream relies on amodal representations (abstract, allocentric, relative and holistic) to serve visual perception (defined as object recognition, identification and classification, see also Section 3 Introduction). The results presented here suggest that such a simple mapping might be difficult, and further suggest that the representations in the dorsal and ventral stream are rather similar, as inferred from Weber's law, Garner interference and size resolution. The question of whether these similar representations are more modal or amodal, is underdetermined by our experiments. It seems that the representational format is more likely influenced by task demands and other experimental factors, rather than the visual stream. This is not a new insight, indeed it has been a position that both proponents and opponents of the PAM can agree on - Schenk et al. (2011) concluded, "But there is common ground between us and Westwood and Goodale (2011). We both agree that the way information is used and processed in the visual brain will be shaped by the behavioural task".

5.4 Advancing Knowledge Using Metascience: Methods, Replications and Meta-analyses

Our investigations employed metascience tools like improved methods, replications and meta-analyses. We believe that this metascientific approach aided the progress in the debate on perception-action dissociations. Below, we discuss how each tool contributed to this progress and may also improve future work.

5.4.1 Improving Methods

In each of the three experimental paradigms, we critically evaluated the methods used for experiment design and data analysis. We identified suboptimal methods in all three paradigms and suggested improved alternatives, some more specific to the experimental paradigm and some more general. The quality of subsequent research may be improved if future studies consider and are aware of these observations and guidelines for experiment design and analysis methods.

First, it is sometimes necessary to transform and make corrections to the measured data, in order to perform a sensible analysis. For example, studies investigating Weber's law in grasping used the within-participant SD of the MGA as a proxy to the JND (Ganel et al., 2008). Equating the JND with the SD_{MGA} is problematic because the former is the variability at the level of the stimulus, and the latter is the variability at the level of the response. We therefore suggested a method to estimate the JND using SD_{MGA} (easily measured in grasping studies). This method involves dividing the SD_{MGA} by the local slope of the grasping response function (function relating object size to MGA, Bhatia et al., 2022). One reason why this correction is necessary is that the grasping response function is slightly non-linear (see also Appendix B of Deng et al., 2024). In other tasks like perceptual adjustment (Ganel et al., 2008), the response function is almost completely linear (see Figure 12a and b, and Bhatia et al., 2022) and no correction is needed. A similar correction (rather normalisation) was also needed for comparing the effects of visual illusions on grasping, perception and manual estimation (Franz, 2003; Kopiske et al., 2016), because the slopes of the response functions were different and therefore, could not be directly compared.

Second, performance in two tasks or conditions should be compared by demonstrating a difference in the same metric or measure, and not just demonstrating a significant effect in one task but a non-significant effect in the other (Franz & von Luxburg, 2015). For example, studies inferred better size resolution based on a significant mean difference in MGA in grasping, and worse size resolution in perceptual judgement based on a low accuracy (Ganel et al., 2012; Heath et al., 2022). Therefore, different metrics were used for the two tasks and a difference between the tasks was not shown. A similar problem is also present in studies on unconscious priming where different sensitivities are inferred for the prime and target stimuli: participants typically have low accuracy in detecting the masked, briefly-presented prime stimulus (poor, not significantly different from 50% sensitivity), but nevertheless a significant reaction time difference (priming effect) is observed in the responses to the target stimulus (inferred high sensitivity, see Meyen et al., 2022). The d' or sensitivity for both tasks however is approximately the same (Meyen et al., 2022). In size resolution, we also found that the classification accuracies in grasping were not better than in perceptual judgement, and that when the same metric is compared, no dissociation was present.

Furthermore, in Garner interference, Ganel and Goodale (2003) reported a non-significant Garner effect in grasping but significant Garner effect in manual estimation. This difference was not directly tested, and many authors have shown that a significant effect versus a non-significant effect in two quantities is not evidence of a difference between those quantities (Franz & Gegenfurtner, 2008, Appendix B; Gelman & Stern, 2006; Nieuwenhuis et al., 2011). Subsequent replications demonstrated that the difference between Garner interference in grasping and manual estimation was rather small (Bhatia et al., 2025).

Finally, co-variates and moderator variables should be appropriately considered. For example, in Garner interference, we found that the overall reaction time (average of Baseline and Filtering conditions) in a task was highly correlated with the Garner interference effect across different tasks (Filtering - Baseline, $r = 0.83$, see Section 3.7.1.1). Different overall RTs influencing the Garner effects in these tasks would be a more parsimonious explanation than assumptions regarding ventral or dorsal stream guidance.

5.4.2 Accumulating Evidence Using Replications

In 2015, the Open Science Collaboration undertook a Replication Project to determine the reproducibility rate of Psychology. Overall, their results suggested relatively low reproducibility. Of particular note was their finding that the effect sizes of the replications were about half the size of the original study. This project was a wake-up call for the field in general, and led to an increasing focus on reproducibility and transparency (e.g., Kidwell et al., 2016; Simmons et al., 2021).

Despite this, by 2021, only about 20% of psychology journals (including a random sample of journals as well as high-impact journals) had made policy changes regarding submission of replication studies (Nosek et al., 2022, Supplemental Tables 9 and 10). Thus, on the one hand, there has not been a substantial improvement in the incentives for conducting replications. On the other hand, "if an individual finding is regularly cited and used as support for theory, then there exists an implicit or explicit presumption that the finding is replicable." (Nosek et al., 2022, p. 724). Researchers therefore *assume* that highly-cited, theory-corroborating results are replicable, but violations of this assumption are difficult to evaluate because researchers are not incentivised to conduct replications. On top of this are issues of selective reporting and publication bias, leading to the phenomenon of the "winner's curse" (Amrhein et al., 2019) - with original studies reporting larger effect sizes than the replications (Open Science Collaboration, 2015). The original and initial studies on a topic are thus readily accepted into journals, but not subsequent ones, even though the original studies are not necessarily more accurate (Stanley & Spence, 2014; but see Göppert et al., 2025, for a discussion).

Given this background, it is not surprising that the original finding of Garner interference in manual estimation (Ganel & Goodale, 2003) was only demonstrated by the same authors in one other study (Ganel & Goodale, 2014). A different study, Schum et al. (2012), actually reported a non-replication of Garner interference in manual estimation, but it was only discussed in a footnote, again highlighting the general view towards (failed) replications. Garner interference in manual estimation was often cited in support of the PAM (Goodale, 2011, 2014), and replication studies employed grasping and perceptual speeded-classification but not manual estimation (cf. Bhatia et al., 2025). As described above, the replication studies may have taken the replicability of Garner interference in manual estimation for granted. Furthermore, low transparency about the methods may have deterred others (Nosek et al., 2022). For instance, Ganel and Goodale (2003) had a very brief Method section with no details about task instructions or how the dependent variables were calculated. Later, Ganel and Goodale (2014) reported these details but because a new dependent variable was proposed (response variability), it was unclear if the methodological details were still applicable to Ganel and Goodale (2003) and the original dependent variable (RT).

Our investigation into Garner interference revealed that 12 out of 14 other studies that replicated the original study (Ganel & Goodale, 2003), were only partial replications. The crucial, theory-supporting result of larger Garner interference in manual estimation than grasping was investigated by only two studies (Ganel & Goodale, 2014; Schum et al., 2012), and replicated by only one of them (Ganel & Goodale, 2014). We conducted multiple replications, all of which resulted in substantially smaller effects of Garner interference on manual estimation than previously reported (Ganel & Goodale, 2003, 2014). Thus, through replications, we revealed that a highly-cited, theory-corroborating result (Ganel & Goodale, 2003) was in fact *not* replicable (Bhatia et al., 2025).

Even today, researchers are not agreed on the degree of importance of replications (Feest, 2019; Haig, 2022; Nosek & Errington, 2020; Nosek et al., 2022; Stanley & Spence, 2014). Earp and Trafimow (2015) offer a useful outlook: "Replications do not need to be 'conclusive' in order to be informative." They introduce a Bayesian framework to model how a rational researcher's confidence in an original result should change as a function of replication attempts, with increasing replication failures decreasing confidence. Thus, mounting replication attempts can be considered as accumulating evidence in favour of or against a certain result or claim. For example, four replications (total n = 110 participants) suggesting a Garner interference effect $\leq$ 10 ms in manual estimation should decrease confidence in the original claim that the effect might be $\geq$ 20 ms (n = 8 participants). We hope that this mindset gains more popularity in future research, and that this thesis can be an example of the importance of replications for scientific progress.

5.4.3 Aggregating Evidence Using Meta-Analyses

Since the "replication crisis", several authors have also warned against taking individual, single studies too seriously (Amrhein et al., 2019; Earp & Trafimow, 2015; Nosek & Errington, 2020; Schmidt, 1992; Stanley & Spence, 2014), with Stanley and Spence (2014, p. 316) even going so far as to say that the replication crisis might only exist for those "who do not view research through the lens of meta-analysis" (but see Göppert et al., 2025, for a critical view of their conclusions). Meta-analysis, the method of aggregating similar studies like aggregating participants in a single study, is not new and can be traced back several decades (e.g., Schmidt, 1992). At best, it allows the combination of results of several studies to reveal underlying patterns. At worst, it can exacerbate the underlying issues (e.g., p-hacking, file-drawer problem, etc., Nelson et al., 2018). Other critiques of meta-analyses include the subjectivity of effect size calculations, overlap in different meta-analyses and resolution of conflicting meta-analyses. Therefore, it is decidedly not a silver bullet. Nevertheless, we believe that a meta-analysis of studies in a relatively narrow field and with relatively low heterogeneity, namely, studies investigating grasping and manual estimation in the context of the PAM, can be insightful (especially when no other meta-analyses exist).

Evidence of this insightfulness can be found in our meta-analysis of the classification accuracies in grasping, manual estimation and perceptual judgement in the (admittedly few) studies on size resolution (Section 4.7). The different studies relied on different metrics and analyses. We performed reanalyses of the data of these studies to convert the results to the same metric: classification accuracies. Figure 32 revealed that the classification accuracies in grasping and manual estimation are surprisingly consistent, while accuracy in perceptual judgement has a large variation. The former result was not obvious from the analyses typically reported in the studies, that is, aperture differences for the small and large objects. Furthermore, the large variation in perceptual judgement accuracy prompted us to consider different set-up decisions in the studies, and we identified potential conditions that might contribute to the variation, which could form the basis of future investigations on this topic.

The meta-analysis in Garner interference also proved useful, because it allowed us to demonstrate that the Garner interference in grasping and manual estimation is similar across several dependent variables. We further discovered that the height-width illusion effect differs between the Garner conditions, at least in manual estimation, with a larger effect for the filtering condition than the baseline. Such observations can inspire future research, and would have been difficult to identify without a quantitative comparison of the studies.

Regarding Weber's law, we did not perform a meta-analysis, but rather collected data from a small sample of representative studies. Here the goal was to confirm that our reanalysis method of calculating $\widehat{JND}$ (for not just our own study) led to meaningful values of the Weber constant *k*, that were within a range reported by literature reviews for size perception.

These aggregations via meta-analyses are not perfect (due to the reasons listed above) but they do allow us to rely on accumulated evidence from several studies, and therefore, make stronger conclusions than from just single studies of our own. We did try to avoid some known issues with meta-analyses in the following way: We used unstandardised, raw effect sizes to avoid issues with effect size subjectivity, and our meta-analyses were the first (to our knowledge) meta-analyses on these topics (no conflict or overlap with other meta-analyses). In each of the three domains, the original result was inferred as support for the PAM. Our meta-analyses, however, reveal that the pattern of accumulated and aggregated results do not provide evidence for perception-action dissociations in either Weber's law, Garner interference, or size resolution.

5.5 Conclusion

We investigated the evidence for the PAM with a detailed scrutiny of three behavioural paradigms thought to provide compelling support to the idea of two functionally-independent visual streams. In each case, the original studies used problematic methods or lacked empirical support. Our comprehensive investigations yielded an absence of evidence for perception-action dissociations. In fact, we found surprisingly similar effects of Weber's law, Garner interference and size resolution in both perception and action, as probed by manual estimation and grasping. Our results instead suggest that perception and action rely on a common representation of object features, and that observed behavioural dissociations are largely influenced by task-specific demands and constraints. This conclusion further weakens the empirical foundation of the PAM, rather lending to support to the idea of shared representations in the human visual system.

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