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Visual Perception of Dynamic Properties and Events: Collisions and Throws

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Prologue

The central topic of this dissertation is visual perception of dynamic events. The topic is worth of interest, as witnessed by its long tradition in the history of Experimental Psychology, starting with the seminal work of Albert Michotte (1881 - 1965) on phenomenal causality. Thus, the topic I chose is not original in itself. However, a distinctive element of novelty in my dissertation is the use of Computer Graphics techniques as a means for creating realistic experimental stimuli in psychological experiments. Besides the advantage of reducing the gap between laboratory experiments and everyday experience, this may reveal the importance of experimental variables which traditionally have been ignored in research on visual perception of dynamic events.

The reader should be informed that this dissertation is characterized by various lines of research, which are intrinsically connected with the central topic of visual perception of dynamic events. In some of the experiments, I investigate visual perception of dynamic events, whereas in others I investigate cognition of the same events. Two distinct dynamic events will be especially studied: horizontal collisions and throws. Moreover, the results of the experiments will be discussed not only in relation to their theoretical implications for psychological models, but also in relation to their potential applications to Physics education and Computer Graphics. As a result, the content of the dissertation is quite heterogeneous, but I hope to provide the reader with a broad and multidisciplinary perspective on the subject at hand.

The dissertation is composed of five chapters, which may be divided into three groups. (i) In Chapters 1-3, after a presentation of the theoretical background of visual perception of dynamic events, I investigate the influence of dynamic properties of virtual objects on visual perception of horizontal collisions. The results of this research are important for the old and still active debate on phenomenal causality. (ii) In Chapter 4 I present a research on Naïve Physics of horizontal collisions between virtual spheres differing in simulated mass and velocity. In this chapter I take a more cognitive (rather than perceptual) perspective on dynamic events, investigating how people reason about the proposed physical event. (iii) In Chapter 5, I present a research on visual perception of virtual throwing animations, which are complex and rarely studied dynamic events. This chapter stands out for its multidisciplinary nature, as in it I discuss how the results can be applied to Computer Graphics. The research presented in this last chapter has been conducted as a part of my doctorate studies when I was a visiting PhD student at the Graphics, Vision, and Visualisation Group at Trinity College Dublin, where I collaborated with Professor Carol O’Sullivan and Doctor Ludovic Hoyet, who are computer scientists working on applications of visual perception to Computer Graphics.

In more detail, in Chapter 1 I discuss the theoretical background of visual perception of dynamic events and phenomenal causality. Firstly, I focus on Michotte’s classical work. Secondly, I discuss some prominent issues which have been debated for a long time in this field of research. Lastly, I present White’s *schema-matching model* of visual perception of dynamic events, discussing its differences and similarities as compared with Michotte’s model. This chapter is intended to serve as a theoretical point of reference for the entire dissertation.

In Chapter 2 I discuss the hypothesis that visually perceived dynamic properties of objects involved in dynamic events do influence visual perception of the dynamic events themselves. Firstly, I try to confute two popular arguments against this hypothesis. Then, I highlight the evolutionary advantage of visual perception of dynamic properties, discussing their possible influence on visual perception of dynamic events. Lastly, I discuss Runeson’s *KSD model* in relation to the presented hypothesis.

In Chapter 3 I present three experiments which confirm the hypothesis discussed in Chapter 2. In particular, I show that simulated material (Experiment 1) and size (Experiments 2 and 3) of virtual objects involved in horizontal collisions strongly influence how observers perceive the event. I also discuss the theoretical implications of these findings by referring to Michotte’s and White’s models.

In Chapter 4 I present a research on Naïve Physics of horizontal collisions. Firstly, I discuss the general importance of studying Naïve Physics for improving basic education in Physics. Secondly, I present Information Integration Theory and Functional Measurement methodology as suitable tools for the assessment of students’ intuitive knowledge of physical events, evidencing their advantages over multiple-choice surveys. Lastly, I present two experiments (conducted using Information

Integration Theory and Functional Measurement) on Naïve Physics of horizontal collisions between simulated spheres differing in size, velocity, and material. The importance of the results for Physics instruction will also be discussed.

Finally, in Chapter 5 I present a research on visual perception of edited virtual throwing animations. First I discuss the relations between visual perception of dynamic events (human motion in particular) and Computer Graphics. Then, I present two experiments on observers' sensitivity to anomalies in realistic virtual throwing animations, discussing the importance of the results for videogames and movies industry.

Chapter 1

Visual Perception of Dynamic Events: a Historical-Critical Introduction

I look outside the window of my room. Inside a restful garden, a boy is playing with a ball. The boy strongly kicks the ball toward an empty bottle resting on the ground; the ball strikes the bottle, causing its fast rolling. Now the boy kicks the ball again, this time toward a small bird which immediately flies away with a sudden beating of wings. These are examples of common everyday experiences called *dynamic events*.

The following of the discussion would benefit of a clear definition of *dynamic event*. The term takes a specific meaning in Physics: " […] we may say that environmental dynamic events are occurrences involving one or more objects (or creatures) and consisting of rather abrupt changes in the kinematic state of the object(s) resulting from exertion or exchange of energy (or momentum) among the objects." (Runeson, 1983, pp. 12-13). This definition may satisfy a physicist, but the student of visual perception need a psychological, rather than physical, conceptualization of dynamic event. Runeson (ibid., p. 13) stated: "Starts, stops, bounces, collisions, catchings, hits, touches, breaks, squeezes, releases, hoists, jumps, etc., are examples of events which are usually distinguished in perception. It is important to note that these categories are not to be found among the concepts of scientific dynamics, i.e. the theory of dynamics that mankind have developed through systematic intellectual endeavours. […]. For the above reasons, it must be accepted that the field of dynamics is covered in perception by a conceptual structure which differs extensively from that of scientific dynamics." This passage should clarify that physical exchanges of energy or momentum are neither necessary nor sufficient conditions for the perception of dynamic events. It is nonetheless difficult to precisely delimit the domain of perceptual dynamics, as evidenced by the fact that Runeson only listed a number of examples without providing a real definition. Generally, researchers speak of perceptual dynamic events when *something is perceived to happen* in a scene where one or more moving objects are involved. In the following I’m going to use the term dynamic event in perceptual rather than physical sense, unless otherwise specified.

1.1 Albert Michotte (1881 - 1965): causality as a fact of perception

Early researchers in visual perception argued that we perceive dynamic events as sequences of successive and independent motions: going back to the first example, the kick, the motion of the ball, the rolling of the bottle and the flight of the bird would be processed by our visual system as independent motions. According to this theoretical position, mind would intervene in a later stage in order to create consistent and meaningful representations of the world, elaborating and unifying elementary sensations of motion into cause-effect relations. Albert Michotte (1881 - 1965), the pioneer of experimental studies on dynamic events, challenged this idea. In his most famous book, *The Perception of Causality* (1963), he argued against this elementaristic approach to visual perception. Michotte’s idea was that observers perceive dynamic events as meaningful cause-effect sequences without the intervention of mind, i.e. without the intervention of conscious interpretation and past experience. When observing dynamic events like those I previously described, our visual system would process the scene as a unified compound of functional relations, not as a meaningless amount of separate motions. We would see the boy kicking the ball and the ball causing the bottle rolling without any further cognitive elaboration of the scene. In some sense, dynamic events would be perceived as such. Michotte demonstrated that even seemingly “cognitive” properties such as causality may be processed directly in the visual system (Wagemans, van Lier, & Scholl, 2006). Note that this idea had been around for years before Michotte’s work: Gestalt psychologists like Koffka, Duncker, and Köhler believed that causal relations can be directly perceived (Bozzi, 1969). Michotte’s great achievement was to provide convincing empirical results supporting the idea.

Dynamic events constitute a substantial part of our phenomenal world. One might ask why Michotte, in the title of his seminal book, used the word *causality* instead of the term *dynamic events*. The difference between these two concepts is only superficial: dynamic events and causal impressions are intertwined concepts. When something *happens* between two or more objects in the perceived scene, these objects stand in perceived cause-effect relation. Consider the case of a billiard ball striking another stationary ball. This is a dynamic event, because observers perceive that something is happening between the two objects, i.e., they are in functional relation. At the same time, observers perceive the moving ball causing the motion of the initially stationary ball. Visual perception of dynamic events and visual perception of causality are two faces of the same coin: in the following, they will be used as interchangeable terms.

Most of Michotte's efforts were directed at demonstrating that people can perceive causal interactions in simple, abstract, and counterintuitive stimulus conditions: from a theoretical point of view, this meant to dismiss the role of past experience and to highlight the role of pure perception. In Michotte's first and most famous experiment (Michotte, 1963, pp. 19-20), observers were presented with two small squares aligned horizontally (see Figure 1 for a 3D version of Michotte's stimuli). At a point in time, one square (*A*) started moving toward the other (*B*), which was initially stationary. Upon contact, *B* started moving with the same velocity as *A*, while *A* came to a stop. The vast majority of observers described this condition saying that *A* "launched" or "kicked" *B*, that is, the motion of *A* had caused the motion of *B*. This phenomenon was called the *Launching Effect*. The finding has been important for two reasons: first, it has allowed researchers to bring the study of phenomenal causality in laboratory (initially using the ingenious apparatus of rotating disks, and more recently using computer graphics). Second, it has been the first striking demonstration that causal impressions can occur even with abstract "non-physical" objects, this suggesting that perceptual and physical causality are distinct and independent concepts each one characterized by its own rules. The latter claim was reinforced by Michotte's results on the so-called "paradoxical cases": observers perceived the Launching Effect even when the post-collision velocities of *A* and *B* were inconsistent with mechanical laws of motion. Michotte also showed that notable phenomenal features of the effect cannot be explained with reference to past experience and knowledge of physical rules: the

Launching Effect is characterized by a "radius of action"[1] (ibid., Experiment 11, p. 54), it may occur even with small temporal delays between the successive motion of the two objects (ibid., Experiment 30, p. 95), or when a spatial gap is present between them (Yela, 1952). Moreover, it is independent of the phenomenal aspect of the objects involved (Michotte, 1963, Experiments 27 and 28, p. 84; Gordon, Day, & Stecher, 1990; White, 2005).

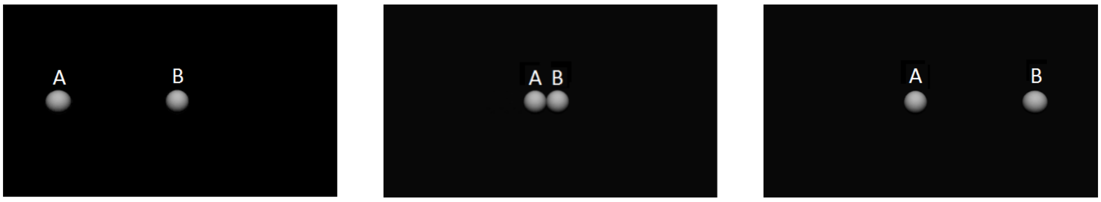

Figure 1: Three frames of an animation sequence used in our experiment (a 3-D version of Michotte's stimuli). Labels "*A*" and "*B*" are added for reference in our discussion.

1.1.1 Perceptual causality as ampliation of the movement: a limited theoretical interpretation

Michotte interpreted the Launching Effect in terms of Gestalt principles, and more specifically in terms of *ampliation of the movement*[2] from *A* to *B*: the stimulus conditions would be interpreted by the visual system as a unique motion initially carried by *A* and then transferred to *B*. This "conflict" would be resolved through the construction of a single dynamic event involving two distinct objects, one playing the role of "cause" (*A*) and the other playing the role of "effect" (*B*)[3]. Michotte argued that ampliation of the movement is the necessary and sufficient condition not only for the perception of Launching Effect, but also for the perception of all kinds of dynamic events. This restricted the range of directly perceivable events only to cases where ampliation of the motion occurred. Beside the Launching Effect, Michotte admitted no more than six directly-perceivable dynamic events: the Triggering Effect, the Entraining Effect, the Traction Effect, Launching by expulsion, Propulsion, and Animal locomotion.

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[1] "Rayon d'action" in the original French version (Michotte, 1946).

[2] "Ampliation du mouvement" in the original French version (Michotte, 1946).

[3] This theoretical interpretation is closely related to the concepts of "perceptual unification" and "good continuation", which are basic principles of Gestalt theory.

Michotte also considered other interesting events: for instance, he observed that when a projectile collides with a stationary surface, and the latter is deformed after the impact, observers may report that the projectile caused the deformation of the surface. However, consistent with his rigid theoretical interpretation, the Belgian researcher denied direct perception of causality in this condition (note that here ampliation of the movement does not occur), arguing in favor of the intervention of explicit knowledge and of conscious interpretation. Michotte's distinction between perceivable and non-perceivable dynamic events seems however somewhat arbitrary, more based on his theoretical interpretation rather than on reliable empirical evidences. Even though ampliation of the movement was the first elegant model of phenomenal causality, it led Michotte to almost ignore many interesting dynamic events occurring in everyday life which could disconfirm his theory.

1.2 Ongoing debates around visual perception of dynamic events

Surprisingly, after decades from Michotte's original work, experiments on the Launching Effect still dominate research on dynamic events[4]. In my opinion, there are two reasons for this tendency: first, the stimulus conditions corresponding to the Launching Effect are simple and easily replicable, and all the variables involved can be easily controlled by experimenters. The second reason is historical-theoretical. Two opposite factions have clashed on two interrelated topics: whether causality is directly perceived and innate, as Michotte claimed, or inferred and acquired through learning as suggested by his opponents (e.g., Gemelli & Cappellini, 1958). Due to its simplicity and popularity, the Launching Effect has been used by researchers as a ground for comparison of the opposite theoretical positions. In the following section I'm going to briefly resume the debate between followers and opponents of Michotte.

1.2.1 Perception vs. Learning of causality: an open issue

Many philosophers had debated the problem of causality and its relation with human knowledge before the publication of Michotte's experimental work (a detailed

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[4] See the following link to get an idea of the amount of published papers on the Launching Effect: http://www.yale.edu/perception/Brian/refGuides/causality.html

review in Bozzi, 1969). The stake of the dispute is high because it involves opposite conceptions about the structure of human knowledge and mind development. The British empiricist David Hume (1711 - 1776) argued that humans cannot directly perceive cause-effect relations because causality does not exist in nature. This position stems from a physicalistic and elementaristic approach to visual perception: because our visual system could only register what happens in the outer world, we could only perceive separate and independent motions. Learning would be the basis of our understanding of causality: repetitive exposure to chains of events would originate their classification in terms of cause-effect relations. Michotte's work has been a cornerstone in the debate, opening a new perspective on the understanding of cause-effect relations. The contrast between Michotte and Hume recalls the perennial debate between students believing that perception constitute an important basis of human knowledge (Michotte), and students believing that perception does not provide any form of knowledge, and that learning and past experience are fundamental in order to build conceptual structures (Hume). Also the opposed doctrines of Innatism (Michotte) and Empiricism (Hume) are involved in the debate. Despite Michotte's empirical findings seemed to bring decisive evidence in favor of his claims, the debate is far from conclusion (see Scholl & Tremoulet, 2000; Schlottmann, 2000; Saxe & Carey, 2006; White, 2006a; Rips, 2011). Michotte's experimental methods have been criticized, and his results challenged (Joynson, 1971; White, 2012). Moreover, the supposed intra- and inter-individual invariance of causal impressions has been refuted (Beasley, 1968; Schlottmann & Anderson, 1993). The difficulty of distinguishing between genuine percepts and response biases seems to be the most serious hindrance for a conclusive solution (Choi & Scholl, 2006; Schlottmann, Ray, Mitchell, & Demetriou, 2006).

1.2.2 Broadening the domain of dynamic events: the Schema-Matching model

A promising way for improving knowledge of dynamic events seems to be the use of more complex and realistic stimuli in experimental research. As in our environment many different dynamic events occur, a primary aim of research should be the simulation of the complexity and variety of everyday events in laboratory experiments. Researchers in Experimental Psychology and Computer Graphics have recently started on this path[5], using as stimuli for their experiments realistic scenarios with many objects moving in various directions. White and Milne explored visual impressions of "Pulling" (White & Milne, 1997), "Enforced disintegration", "Bursting" (White & Milne, 1999), and "Penetration" (White & Milne, 2003). Scholl and Nakayama (2002) and Choi and Scholl (2004) found that contextual dynamic events strongly influence the perception of the Launching Effect. Reitsma and O'Sullivan (2009) showed that sensitivity to physical distortions in collisions depends on the realism of the scenario, whereas Hoyet, McDonnell, and O'Sullivan (2012) replaced abstract inanimate objects with virtual human characters, studying observers' sensitivity to distortions in pushing interactions. The results of all these experiments suggest that Michotte's theoretical interpretation in terms of ampliation of motion cannot be longer sustained.

The above mentioned researchers have questioned Michotte's model of perceptual causality for its incapability of taking in to account empirical results in such complex stimulus conditions. White (2006a) proposed a *schema-matching model* based on recent research on dynamic events such as Pulling, Enforced disintegration, Bursting, and Penetration: the model predicts that the perceived scene is compared with several schemas of dynamic events stored in memory, and when a schema reasonably fits the perceived scene, the latter is interpreted according to the schema. Schemas are acquired through personal experiences of actions on objects haptically perceived, and fill out gaps in the stimulus information (ibid.). The main advantage of the model is that it accounts for the variety of dynamic events that people can perceive, because no limits are imposed on number and complexity of stored schemas. A notable feature of White's schema-matching model is the content of stored schemas: kinematic properties[6] are similar across different occurrences of the same dynamic event, and thus constitute the basis both of schema construction and matching. Consider the case of the boy kicking

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[5] This has been possible thanks also to technical advances in Computer Graphics software, which allowed researchers to increase the complexity and realism (ecological value) of the stimuli.

[6] Kinematics is the branch of classical mechanics describing the motion of objects (displacement of points in space and time). Forces, energy, momentum, and mass are not considered by Kinematics, but fall under the domain of Dynamics (see also Section 2.1 below).

the ball: the velocities of the foot and of the ball are reasonably invariant across all kicking actions, and are thus important both for construction of kicking action schemas and for recognition (schema-matching) of the same actions. In contrast, non-kinematic “featural” properties like the color and the shape of the ball are specific to the single scene, and thereby are not part of the kicking action schema.

The schema-matching model greatly differs from Michotte’s model of ampliation of the movement, because the former attributes a crucial role to learning and past experience, and admits the possibility of perceiving an indefinite number of dynamic events. It is however similar to Michotte’s model when it assumes that visual perception of dynamic events is based on kinematic information only.

1.2.3 On the desirability of further increasing the realism of the stimuli

The use of more complex and realistic stimuli has allowed researchers the development of new and more accurate models of visual perception of dynamic events, such as the schema-matching model previously discussed. Nonetheless, the stimuli used in current research still appear as highly simplified and impoverished simulations of everyday dynamic events because they are composed of monochromatic two-dimensional shapes moving on an uniform background (for a notable exception, see Reitsma & O’Sullivan, 2009 and Hoyet et al., 2012). These stimuli still look more similar to cartoons rather than to everyday events, which vice versa involve three-dimensional objects composed of different materials. The idea I’m going to deepen in the following chapter is that research would benefit of a further increase of the realism of the stimuli, which should include three-dimensional textured objects.

Chapter 2

The Influence of Perceived Mass on Visual Perception of Dynamic Events

2.1 Kinematics and Dynamics in physical and perceptual dynamic events

Physical dynamic events are characterized both by kinematic and dynamic properties. Kinematics refers to motion of objects, i.e., their displacement in space and time, whereas Dynamics refers to masses, forces, energy, and momentum. Dynamic properties are of primary importance, because exchanges of energy and momentum are usually referred to as the causes of motion. Mass of objects is also fundamental because energy, forces, and momentum all depend on it. This is quite intuitive: the mass of a hitting ball is proportional to the post-collision velocity of a struck ball. Mass has also a special status, because unlike energy, force, and momentum, it is a permanent property of objects.

A common idea of both Michotte's and White's models is that, unlike physical dynamic events, perceptual dynamic events do only depend on kinematic features of the stimulus. For instance, according to the schema-matching model, the Enforced disintegration and Bursting impressions would only depend on pre- and post-impact velocities of the cracking object and on the trajectory of its fragments after the impact (White & Milne, 1999). Non-kinematic (featural) properties would not play any role from a perceptual point of view. A logical argument for this claim is that we can directly perceive kinematic properties such as velocities and trajectories, whereas dynamic properties like mass or momentum cannot be visually perceived (cf. Runeson, 1983). White (2006a; see Section 1.2.2) stated that recognition of dynamic events is based only on kinematic features of the perceived scene, and that non-kinematic features like color and shape of the objects are "superficial properties", which do not influence perception of dynamic events.

I'm going to advance a different hypothesis, namely that non-kinematic properties such as shape and color influence perception of dynamic events when they act as perceptual cues to dynamic properties of objects, and in particular to their mass. My idea is that when these cues are available they influence perception of dynamic events. Before developing this argument in detail, it is worth examining the literature in favor of the opposite idea, i.e., that visual perception of dynamic only depends on kinematic properties of the objects involved. This idea has been accepted and is still supported by many important researchers (e.g., Michotte, 1963; Scholl & Tremoulet, 2000; White, 2006a).

2.2 Dynamic events and non-kinematic properties: a critical overview of the literature

Two main arguments are invoked in favor of independence of perceptual dynamic events of non-kinematic variables. (1) Dynamic events are perceivable even when non-kinematic properties of the stimuli are absent or greatly weakened. (2) When non-kinematic properties of the stimuli are manipulated, their influence on perceptual causality is null or negligible. I'm going to separately discuss both arguments in the following two sub-sections.

2.2.1 Discussion of Argument 1: dynamic events are perceivable even when non-kinematic properties are absent or greatly weakened

Michotte showed that the Launching Effect occurs even when *A* and *B* are small and abstract two-dimensional objects of various colors and shapes. Moreover, in his Experiment 27 (Michotte, 1963, p. 84), he showed that the effect occurs even when *A* and *B* are two blurred shadows projected on a screen. Gordon et al. (1990) showed that the Launching Effect is visible even when real moving objects are replaced with stroboscopic motion of one or both objects, and a similar finding was also reported by White (2005). The perception of causality has been systematically reported by many different researchers who used abstract and “immaterial” stimuli, where non-kinematic properties were absent or greatly weakened. There is enough evidence to conclude that non-kinematic properties of the stimuli are not necessary for the perception of dynamic events.

Even though there is compelling evidence in favor of argument 1, this does not imply, in principle, that non-kinematic properties do not influence the perception of causality in absolute sense. The experiments reported above show that perceptual causality is “flexible” and deeply rooted in our visual system, because it can occur with extremely impoverished stimulus conditions. However, the independence of perceptual causality of non-kinematic variables may be bounded to the particular stimulus conditions used in the above mentioned experiments. It has already been shown that which variables are necessary for the perception of causality depend on the stimulus conditions: after Michotte’s work, it has been generally believed that collision between two distinct objects was a necessary condition for the perception of the Launching Effect. Recent experimental findings have instead shown that when appropriate contextual events are present in the scene, the Launching Effect occurs even when *A* and *B* overlap instead than colliding (Scholl & Nakayama, 2002; Choi & Scholl, 2004) and also when one single object rather than two is presented to the observers (Bae & Flombaum, 2010). By analogy, this suggests that non-kinematic properties may not be necessary for the perception of causality as long as observers are presented with abstract two-dimensional stimuli. However, the possibility that non-kinematic variables may be important in more realistic stimulus conditions composed of realistic three-dimensional objects is open and needs empirical verification[7]. This hypothesis recalls Gibson’s critique of the use of suboptimal stimulus conditions in experimental research on visual perception (Gibson, 1979, Ch. 15).

2.2.2 Discussion of Argument 2: when non-kinematic properties are manipulated, their influence on perceptual causality is null or negligible

In Michotte’s Experiment 28 (Michotte, 1963, p. 84) observers reported the Launching Effect when *A* was a real wooden sphere and *B* was just a shadow projected on a screen. Natsoulas (1961) tested the relative contribution of kinematic (velocity

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[7] It is possible that the influence of non-kinematic variables on perceptual causality has been underestimated due to technical difficulties in building realistic simulations of dynamic events. This technical limitations can now be overcome thanks to Computer Graphics, which allows the simulation of dynamic events with realistic 3-D objects made of a specific simulated material.

ratio between *A* and *B*) and non-kinematic variables (size ratio between *A* and *B*) on the Launching Effect, and found that the effect of size ratio was very small when compared with the effect of velocity ratio, thus confirming the marginal role of non-kinematic properties. White and Milne (1999) found that Enforced disintegration and Bursting impressions mainly depend on kinematic features of the stimuli, namely pre and post-collision velocities of the cracking objects and the angle of dispersion of their fragments. They also maintained that these impressions do not depend on superficial features of the stimuli because they occur with a variety of objects with different (two-dimensional) shapes. White and Milne (2003) found that the Penetration impression mainly depends on the stopping position of the penetrating object with respect to the penetrated object. They also manipulated the shape of the penetrating object (thin and elongated rectangle, thin and elongated ellipse, thick and elongated rectangle) but found a small effect of this variable.

The absence of an effect of non-kinematic variables even when they are manipulated by experimenters, would be a compelling argument in favor of their irrelevance for perception of dynamic events. However, I do not think that the above mentioned experiments provide sufficient evidence in this sense. Michotte's experiment is the most compelling one, but note that his results were obtained with a few non-naïve participants, and they have not been replicated afterwards. The results of the other three experiments are not so clear in my opinion and need revision. In Natsoulas's (1961) experiment, observers' responses revealed that they expected *B* travelling slower when *A* was small and *B* was big, and faster in the opposite condition. In White and Milne (1999) the Bursting impression was more likely (and the Enforced disintegration impression less likely) when the shape of the stimuli recalled a sharp object popping balloon (their Experiment 2). The opposite result was obtained when the shape of the stimuli recalled a solid object breaking in consequence of a mechanical collision (Experiments 1 and 3). Finally, in White and Milne (2003) the Penetration impression was stronger when the penetrating object was a thin rectangle instead of a thin ellipse or a thick rectangle, with no difference between the last two conditions. To sum up, in all the above mentioned experiments there is a trace of an effect of non-kinematic variables (albeit small). Note also that the relative smallness of the effect may be due to the small range of variation of the variables: in all the considered experiments, manipulations of the non-kinematic variables coincided with manipulations of size and shape of simple two-dimensional objects. However, in everyday dynamic events the range of variation of non-kinematic variables is much larger, with objects differing in three-dimensional shapes and material. The conclusion that non-kinematic variables do not (or slightly) influence perception of dynamic events may thus be due to suboptimal stimulus conditions.

The discussion of both arguments 1 and 2 leads to the same conclusion. In order to test the possible influence of non-kinematic variables on visual perception of dynamic events we need to build more realistic stimuli involving three-dimensional "material" objects.

2.3 Visual perception of mass and its influence on dynamic events

In this section I'm going to deepen the hypothesis that visual perception of dynamic events depends on non-kinematic variables. More specifically, my hypothesis is that the visual system takes into account perceptual cues to mass (if available in the stimuli) when processing dynamic events. In the first sub-section I discuss the evolutionary advantage of visual perception of dynamic events, arguing in favor of the role of perceived mass. In the second sub-section I discuss visual cues to mass.

2.3.1 The evolutionary advantage of visual perception of dynamic events

An important distinction in the domain of physical dynamic events is that between mechanical events, in which energy is conserved, and non-mechanical events, in which energy is not conserved. The same distinction can be found in perceptual dynamic events: for instance, the Launching Effect is a case of perceptual mechanical event, whereas the Triggering Effect[8] is a case of perceptual non-mechanical event. Recent studies have shown that this dichotomy is embedded in our brain: Roser,

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[8] The Triggering effect takes place when, in a stimulus condition like that represented in Figure 1, the post-collision velocity of object *B* is much larger than the pre-collision velocity of object *A*. In this case, object *B* is usually interpreted as a living creature escaping from object *A*. The case of the bird flying away from the ball (see pag. 1) is a typical case of Triggering effect.

Fugelsang, Handy, Dunbar, and Gazzaniga (2009) showed that human brain expects that objects behave in accordance with mechanical laws, and when this expectation is violated specific event-related potentials (P300) are activated. Badler, Lefèvre, and Missal (2010) found that ocular movements anticipate the outcome of mechanically plausible events. The sensitivity to the difference between mechanical and non-mechanical events is evolutionary old, as shown by studies on newly hatched chicks (Mascalzoni, Regolin, & Vallortigara, 2010). Why animal visual system has evolved the ability to distinguish these two kinds of events? In natural environment, mechanical events usually involve inanimate objects, whereas non-mechanical events usually involve animate living creatures. Because the discrimination between living creatures and inanimate objects is extremely important for survival, in particular for feeding or imprinting purposes, visual system has evolved the ability to discriminate mechanical from non-mechanical events as a cue to discriminate living creatures (non-mechanical events) from inanimate objects (mechanical events)[9]. This idea has been foreshadowed by Michotte, who stated: “The phenomenal world does not consist of a simple juxtaposition of ‘detached pieces’, but of a group of things that act upon each other and in relation to each other. Thus the regulation of conduct requires a knowledge *of what things do* or *can do* and what living creatures (and ourselves in particular) can do with them.” (Michotte, 1963, p. 1). Visual perception of dynamic events is thus a fundamental step of the perception-action chain.

The crucial problem is to understand what variables are used by the visual system in everyday life in order to distinguish mechanical from non-mechanical dynamic events. As discussed in Section 2.1, the most widespread opinion among researchers is that the visual system only uses kinematic properties of the perceived scene for this purpose. Note however that mechanical laws of motion strongly depend on mass: this means that correct classification of dynamic events should rely both on kinematic properties and on perceived mass. Because of the above discussed evolutionary importance of the task, our visual system should have adapted to perform it correctly, and should thus take into account both kinematic properties and mass when

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[9] Because of the evolutionary importance of this distinction, the visual system has also evolved other ways to differentiate living creatures from inanimate objects: for instance, living creatures can be recognized from biological motions, their phenomenal aspect, and the sounds they emit.

"judging" whether a dynamic event is mechanical or non-mechanical. In my view, this is a strong argument in favor of the role of perceived mass in visual perception of dynamic events: this hypothesis needs to be empirically tested.

2.3.2 Visual cues to mass: surface properties and size

Mass can be perceived haptically, through lifting and manipulation of objects. However, because the main topic under discussion is visual perception of dynamic events, my hypothesis is that visually (rather than haptically) perceived mass influences perception of dynamic events. Even though visual perception of mass has not received much attention[10], it is nonetheless evident from everyday experience that the visual system is able of providing information concerning mass: for instance, a dark, smooth, and glossy sphere is perceived as a metal sphere, and looks heavy. This information is fundamental in order to properly guide human interactions with objects. Although research on visual perception of material is in its infancy (see Anderson, 2011), surface properties such as texture, reflectance, color, etc. are believed to provide unique information about material (see also Gibson, 1979 Ch. 2). It is reasonable to suppose that observers are able to use perceived material in order to "perceive" or "infer"[11] heaviness of objects. This idea is supported by a phenomenon called the material-weight illusion: visually perceived material influences haptically perceived heaviness (Ellis & Lederman, 1999; Buckingham, Ranger, & Goodale, 2011). Size is another cue, albeit weaker, of mass: this is witnessed by the influence of perceived size on perceived heaviness, a phenomenon called the size-weight illusion (Murray, Ellis, Bandomir, & Ross, 1999). A study on intuitive physics of collisions has shown that observers use both visually perceived material and size as cues to mass, with material playing a dominant role (Vicovaro, 2012). The main hypothesis of this work can thus be reformulated as follows: visual perception of dynamic events depends on visually perceived material, and, to a lesser extent, on size of objects.

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[10] Runeson's KSD model (Runeson & Frykholm, 1983) is, to my knowledge, the first model on visual perception of mass. See Section 2.4 for a critical discussion of the model.

[11] It can be reasonably argued that material is directly perceived by the visual system. Whether or not mass is directly perceived, or inferred through conscious or unconscious reasoning, goes beyond the scope of this work, and remains an interesting topic for future research.

2.4 The KSD model: perceiving mass from dynamic events

My hypothesis is that visually perceived mass influences perception of dynamic events. A related but in some sense opposite idea was proposed by Runeson (1983), who suggested that dynamic events are “exploited” by the visual system in order to perceive the mass of objects involved in the event. This model is called “Kinematic specification of Dynamics” (*KSD*) (Runeson & Frykholm, 1983). Consider, for instance, the collision between two objects *A* and *B*. Physically, given a pair of pre-collision velocities, the mass ratio of the two objects uniquely specifies the post-collision velocities of *A* and *B*. According to the *KSD* model, the visual system proceeds the other way round, “using” pre- and post-collision velocities (kinematic properties hereafter) of *A* and *B* in order to perceive their mass ratio. The mass ratio can be “computed” by the visual system in the following way:

$$m_a/m_b = (u_b - v_b) / (v_a - u_a) \quad (1)$$

where m_a and m_b are the masses of *A* and *B* respectively, u_a and u_b are the pre-collision velocities of *A* and *B* respectively, and v_a and v_b are the post-collision velocities of *A* and *B* respectively. Note that I used the verbs “to use” and “to compute” metaphorically: kinematic properties are part of the optic array (right part of Equation 1), and according to the *KSD* model the mass ratio (left part of Equation 1) would be directly “picked up” by the visual system without any mental calculus. Note that the *KSD* model lies within the theory of direct perception.

Empirical studies have tested naïve observers’ ability to estimate mass ratios in collision events[12]. The results suggest that mass ratios estimates are often guided by sub-optimal heuristics such as the comparison between post-collision velocities of objects. Naïve observers do not fully exploit kinematic properties contained in the optic array as specified in the right part of Equation 1 (Todd & Warren, 1982; Gilden & Proffitt, 1989). Performance gradually improves with extensive training sessions, at the end of which the majority of observers become accurate in mass ratio estimation task (Jacobs, Michaels, & Runeson, 2000). Although these results are compatible with the

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[12] The stimuli that have been used in order to test the *KSD* model are as abstract as those used by Michotte, because they are composed of simple two-dimensional shapes moving on a homogeneous background.

main tenets of the Ecological approach to visual perception[13], they suggest that perceiving mass ratio from kinematic properties of the collision is a perceptual skill that needs to be learned, and thus is not available in everyday life.

2.4.1 The *KSD* model does not adequately describe visual perception of mass in everyday life conditions

Individuals must continually estimate the mass of objects in order to properly interact with them: for instance, adequate lifting requires accurate visual estimates of mass in order to avoid injuries or wastes of energy. The main strength of Runeson's *KSD* model is that it gives the correct importance to visual perception of mass, a topic which has been neglected by many students of visual perception of dynamic events. However, there are three reasons why *KSD* model does not seem adequate for explaining visual perception of mass in everyday life conditions. First, it is unlikely that visual perception of mass is based on kinematic properties of dynamic events, simply because the majority of objects which we interact with are stationary. Thus, visual perception of mass is probably based on cues which are available for moving as well as for stationary objects: surface properties and size (see Section 2.3.2) seem to be good candidates. Second, *KSD* model only admits mass ratios perception, whereas the most important property to be perceived is absolute mass. Third, experimental results have shown that the ability of "picking up" mass ratio from kinematic properties needs to be learned, and thus individuals would need a lot of experience (and a lot of errors) before adequately interacting with objects. This does not seem a realistic description of what happens in everyday life.

To conclude, Runeson's model is formally interesting and it is likely that the visual system can directly "pick up" mass ratios from kinematic properties when other cues to mass are not available. However, the *KSD* model seems to be more valid for laboratory experiments with abstract two-dimensional stimuli than for visual perception in ecological contexts. In contrast with the *KSD* model, I propose that visual perception of mass in everyday life is primarily based on surface properties of objects and to a

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[13] The Ecological approach to visual perception admits that the visual system can perceive higher order properties (in this case dynamic properties) of the optic array, and that this sometimes requires perceptual learning.

lesser extent on their size (see Section 2.3.2). My hypothesis is that visually perceived mass influences visual perception and identification of dynamic events, whereas the opposite dependence relation is weaker, and valid mostly for laboratory experiments where surface properties and size information are artificially removed.

Chapter 3

The Influence of Simulated Material and Size on the "Launching Effect": an Empirical Study

To my knowledge, the influence of visually perceived mass of objects on visual perception of dynamic events has never been systematically tested. As a first stage of research on the topic, the Launching Effect is a suitable testing ground because size, surface properties, and velocities of the two objects involved (*A* and *B*, see Fig. 1) can be easily manipulated. Moreover, from Michotte's work onward, it has been shown that instructions of experiments on the Launching Effect can be understood by participants with a minimum amount of practice. In the three experiments that I'm going to present in this chapter, I tested whether the Launching Effect depends on material of 3-D spheres (Experiment 1), volume of 3-D spheres (Experiment 2), and area of 2-D disks (Experiment 3). The general outcome of these experiments is a confirmation of the stated hypothesis.

3.1 The "Braking threshold" and the "Triggering threshold": a theoretical introduction to the experiments

A critical variable for the perception of the Launching Effect is the ratio between the pre-collision velocity of object *A* (v_A) and the post-collision velocity of object *B* (v_B). In particular, Michotte (1963, Experiment 40, p. 109) reported that the Launching Effect leaves place to the Triggering Effect when v_B is twice v_A. *Triggering Effect* means that the post-collision motion of *B* appears self-generated, rather than generated by the collision with *A* (see also Note 8). Natsoulas (1961) also found that when v_A is three times v_B, observers have the impression of "braked launch", i.e., the impression that the post-collision motion of *B* is braked by some force, rather than exclusively generated by the collision with *A*. Even though the *Braking Effect* is not reported in most studies on perception of causality, its existence was proved by Minguzzi (1968) in an extensive series of experiments. The Launching Effect is perceived by observers as a mechanical collision (see Section 2.3.1); conversely, the

Triggering Effect and the Braking Effect are both perceived as non-mechanical collisions. When the Triggering Effect occurs, observers have the impression that the "reaction" of *B* (i.e., the post-collision velocity of *B*) exceeds the "action" of *A* (i.e., the pre-collision velocity of *A*): object *B* is perceived as self-moving, or alternatively observers perceive an external force which "accelerates" object *B*. When the Braking Effect occurs, observers have the impression that the "reaction" of *B* is too small compared with the "action" of *A*, and thus they perceive an external force which "brakes" object *B* after the collision.

In the three experiments presented below I determined a "Braking threshold" and a "Triggering threshold". The *Braking threshold* is the value of ratio v_A/v_B above which observers will perceive the Braking Effect more than 50% of the times. The *Triggering threshold* is the value of ratio v_A/v_B below which observers will perceive the Triggering Effect more than 50% of the times. When ratio v_A/v_B is below the Braking threshold and above the Triggering threshold, then observers will perceive the Launching Effect more than 50% of the times. In the experiments presented here, I tested whether these two thresholds depend on the visually perceived mass of objects *A* and *B*.

3.1.1 Prior constraints to the perception of the "Launching Effect"

As stated in the previous section, a range of v_A/v_B values correspond to the perception of the Launching Effect, i.e., all values included between the Triggering and the Braking thresholds. In contrast, physical mechanical collisions are characterized by one single v_A/v_B value which is determined by Newtonian laws of motion. This value depends on many physical variables, such as the mass of the two objects, friction, the elasticity of the collision, etc. One might ask why one single v_A/v_B value corresponds to physical mechanical collisions, whereas a range of v_A/v_B values correspond to perceptual mechanical collisions. In the following I propose a tentative answer. The stimulus conditions of experiments on visual perception of the Launching Effect (see Figure 1) do not usually provide the visual system with information about friction, the elasticity of the collision and masses of the objects involved[14]. I propose that, in the absence of such additional information on relevant physical properties, the visual system "constrains" the value of these variables within definite ranges, the upper and lower boundaries of which are probably similar to the maximum and minimum values ordinarily taken by these variables in everyday natural environment. Because the values of these variables are uncertain, various v_A/v_B ratios are thus compatible with mechanical collisions. The idea of "prior constraints" in visual perception of the Launching Effect has been foreshadowed by Michotte: in commenting the fact that when $v_A/v_B < 0.5$ the Launching Effect usually leaves place to the Triggering Effect, he noted that in nature v_A/v_B can never be smaller than 0.5, irrespectively of the masses of *A* and *B*, friction, and elasticity of the collision (Michotte, 1963, p. 111). It seems thus that the visual system "embeds" mechanical constraints when judging whether a collision is mechanical (i.e., a Launching Effect) or not.

3.1.2 The influence of visually perceived mass on the "Braking threshold" and the "Triggering threshold": experimental hypotheses

The main problem under discussion can be restated as follows: do visual cues to mass (material and size) influence the Braking and the Triggering thresholds? Note that even when the visual system is provided with information concerning the mass of the two objects, the values of friction and elasticity are still unknown, and thus many different v_A/v_B values should still produce the Launching Effect (see Section 3.1.1). However, if visual cues to mass influence the Launching Effect, the range of v_A/v_B values producing the Launching Effect should depend on the simulated mass of both objects. In mechanical collisions the mass of object *A* is inversely proportional to v_A/v_B, whereas the mass of object *B* is directly proportional to v_A/v_B, as shown by the following equation[15] (see Kittel, Knight, & Ruderman, 1973):

$$v_A/v_B = (m_A + m_B) / 2m_A \qquad (2)$$

where m_A and m_B are the masses of objects *A* and *B* respectively.

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[14] This is because the stimuli usually employed in these experiments are composed of simple shapes moving on a uniform background.

[15] Equation (2) is valid when *B* is stationary before the collision.

Correct classification of dynamic events is evolutionary important (see Section 2.3.1). I thus expect a fair degree of isomorphism between visual system and the outer world: as in mechanical collisions an increase of mass of object *A* implies a decrease in v_A/v_B, an increase of visually perceived mass of *A* should cause a shift downward of the range of v_A/v_B values originating impressions of mechanical collisions (Launching Effect), whereas the opposite should be true for the visually perceived mass of *B*. In other words, the perceived mass of *A* should be inversely proportional to the Braking and Triggering thresholds, and the perceived mass of *B* should be directly proportional to both thresholds. Moreover, because simulated material is a stronger visual cue to mass when compared with size[16] (Vicovaro, 2012; see also Section 2.3.2), I expect manipulations of simulated material (Experiment 1) to produce the greatest effect on both thresholds, and manipulations of size (Experiments 2 and 3) to produce significant but weaker effects. Conversely, if Michotte and his followers were right (see Sections 2.2.1 and 2.2.2), visual cues to mass (material and size) should not have any influence on both thresholds.

3.2 Experiment 1: the influence of simulated material on the "Launching Effect"

In the first experiment I presented the observers with virtual simulations of horizontal collisions (see Figure 1), and tested the influence of visually perceived mass of objects *A* and *B* on the Braking threshold and on the Triggering threshold. If the main hypothesis stated above is true, then perceived mass of sphere *A* should be inversely proportional to the Braking and Triggering thresholds, whereas perceived mass of sphere *B* should be directly proportional to both thresholds. I manipulated visually perceived mass of both objects by manipulating their simulated material. Because perceived material is a prominent cue to mass, its effect on both thresholds should be evident.

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[16] A small piece of iron can be much heavier with respect to a large piece of polystyrene: it is a common everyday experience to lift small but heavy objects and large but light objects.

3.2.1 Experimental setup

Participants. Fifteen students of Psychology (aged from 19 to 27, 4 males) participated in the experiment. They all had normal or corrected-to-normal visual abilities, and were paid for the participation.

Stimuli and apparatus. The stimuli were presented on a personal computer equipped with a 37.5 cm × 30 cm screen and a keyboard. Participants sat at a distance of about 50 cm from the screen, the background of which was black. Two 3-D spheres (created by 3D Studio Max) were presented at middle height of the screen. Their size, computed on the diameter of the corresponding image on the screen, was 8.7 cm[3]. At the beginning of each animation, one sphere (*A*) appeared close to the left edge of the screen and the other sphere (*B*) in the centre. Then, 170 milliseconds after the appearance of the spheres, *A* began to move horizontally from left to right towards *B*, until making contact with it. At this point, *A* came to a stop, and *B* started moving in the same direction as *A*, until stopping close to the right edge of the screen (see Figure 1). I manipulated the simulated material of *A* and *B*, according to a 3 Material *A* (polystyrene, wood, iron) × 3 Material *B* (polystyrene, wood, iron) factorial design. The spheres were created with 3D Studio Max; Photographic textures of the corresponding materials were attached on their surfaces, and their reflectances were regulated in order to increase the realism of their appearance. The spheres thus created are depicted in Figure 2. The velocity of *A* was kept the same (15.5 cm/s) across the experiment. In each of the nine experimental conditions I manipulated the velocity of *B* for determining the Braking and Triggering thresholds (see *Experimental design* below).

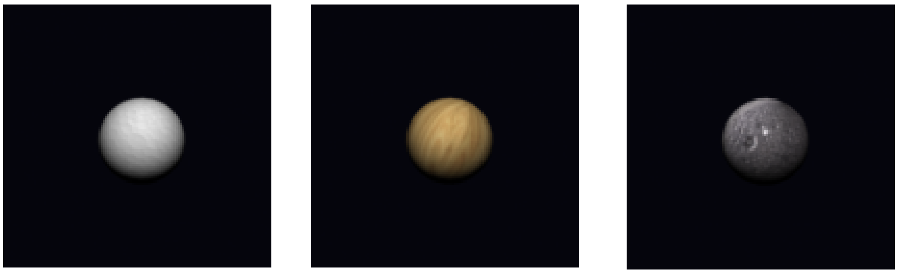

Figure 2: The three spheres used as stimuli in Experiment 1. The simulated materials are, from left to right, polystyrene, wood, and iron.

Procedure. Instructions readable on the screen informed the participants that they would be presented with two colliding spheres, which could be made of three different materials: polystyrene, wood, or iron. The participants were asked to pay attention to the post-collision velocity of the initially stationary sphere (*B*), and were informed that the initially moving sphere (*A*) was always stationary after the collision. They were asked to judge whether the post-collision motion of sphere *B* was "natural" or "unnatural" compared with the force exerted by the initially moving sphere (*A*). The instructions specified that "unnatural" could have two alternative meanings: first, that the motion of *B* was too slow compared with the force exerted by *A*, as if the motion of *B* was braked by an invisible force; second, that the motion of *B* was too fast compared with the force exerted by *A*, as if the motion of *B* was accelerated by an invisible force. In each trial the participants were allowed to view the stimulus as many times as they wanted by pressing "SPACE" on the keyboard and then, when they felt ready to respond, they had to press "N" for the "natural" response, and "Z" for the "unnatural" response. After the instructions, the participants were allowed to lift with their favourite hand and in the order they preferred three small parallelepiped blocks (42 cm^3) made of polystyrene (1.5 g), wood (29.4 g), and iron (334.3 g), whereupon they were presented with five randomly chosen stimuli to familiarize with the task. After that, additional written instructions recommended them to rely on their visual impression, and not on what they knew from experience or from learning of Physics. This was also remarked verbally by the experimenter before starting the experimental session.

Experimental design. In order to estimate individual 50% Braking and Triggering thresholds I used the standard psychophysical method of "randomly interleaved staircases" with fixed step size (Levitt, 1971)[17]. In each of the 9 experimental conditions, I manipulated the velocity of *B* (the velocity of *A* was fixed at 15.5 cm/s) such that the v_A/v_B ratio could take on 21 values from 1/3 to 3. The following series

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[17] The use of this psychophysical method is not new for studies on visual perception of collisions. It was previously used by Kaiser and Proffitt (1987) in order to test observers' sensitivity to different kinds of distortions in mechanical collisions, and by Reitsma & O'Sullivan (2009) for similar purposes. Its precursor, the method of limits, was used by Boyle (1960).

shows the sequence of all possible values of v_A/v_B: 1/3, 1/2.8, 1/2.6, …, 1/1.2, 1, 1.2, … 2.6, 2.8, 3. Both individual thresholds were estimated by generating two staircases, one "ascending" and the other one "descending". Figure 3 depicts a schema of the procedure.

(i) For the estimation of individual 50% *Braking thresholds,* the *ascending staircase* started from the velocity ratio of 1, which gave rise in most cases to a Launching impression. Every time the participant responded "natural", the velocity ratio was increased by one step (for instance, from 1 to 1.2, then to 1.4, etc.) by decreasing v_B, until the participant responded "unnatural" (she perceived a "braked launch"). At that point, the staircase changed its direction, and the velocity ratio was decreased by one step (for instance, from 2 to 1.8, then to 1.6, etc.) by increasing v_B every time the participant responded "unnatural". The staircase changed its direction whenever the participant changed her answer, and continued in that direction until the participant changed her answer again. Symmetrically, the *descending staircase* started from the velocity ratio of 3. The velocity ratio was decreased by increasing v_B as long as the participant responded "unnatural" (she perceived a "braked launch"), and the staircase changed its direction when the participant changed her response. Note that the stimuli comprised between two changes of direction constitute a "run". Both staircases were terminated after eight runs[18]. Individual 50% Braking thresholds were estimated by averaging the v_A/v_B values corresponding to the midpoints of the last four runs of the ascending and the descending staircase (ibid., p. 470).

(ii) For the estimation of individual 50% *Triggering thresholds* I applied the same procedure, but the *ascending staircase* started from the velocity ratio of 1/3, which gave rise to a Triggering impression, whereas the *descending staircase* started from the velocity ratio of 1 (Launching impression). Each staircase was increased by one step after an "unnatural" response (Triggering Effect) and decreased by one step after a "natural" response (Launching Effect). Both staircases were terminated after eight runs, and individual 50% Triggering thresholds were estimated as for individual Braking thresholds.

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[18] Because of the adaptive nature of the psychophysical method used in this experiment, there was a variable number of trials for each participant and for each staircase.

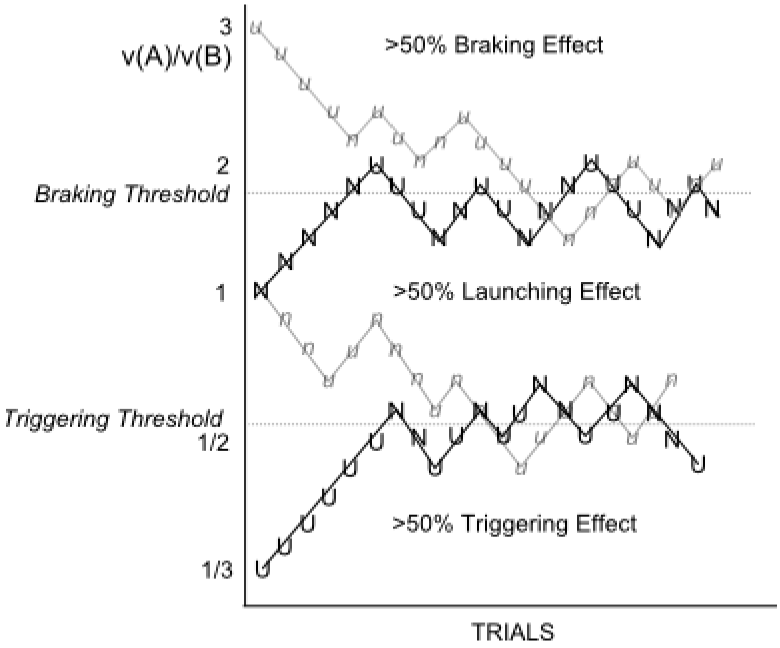

Figure 3: A schema of the method of "randomly interleaved staircases" which refers to the responses of a simulated (not real) participant. On the horizontal axis I represent the number of trials. On the vertical axis I represent the 21 possible values of v_A/v_B, corresponding to the possible steps of the staircases. Letter "U" denotes the "unnatural" response (corresponding to the Braking Effect for the first two staircases from top and to the Triggering Effect for the other two), whereas letter "N" denotes the "natural" response (Launching Effect). Gray lines and lowercase letters are used for the *descending staircases*, whereas black lines and uppercase letters are used for the *ascending staircases*. The upper and lower gray horizontal lines indicate the Braking and Triggering individual thresholds respectively (computed as indicated in the text), and divide the area of the graph into three regions, each corresponding to the indicated prevailing impression.

Note that the term "ascending" ("descending") is used in the literature (see Note 15) to indicate that the starting point of the staircase is below (above) the threshold, and so the first run of the staircase "ascends" ("descends") towards the threshold value. In the experiment presented here, the Braking threshold was always greater than 1 and smaller than 3 (see the left graph in Figure 4), so the terms "ascending" and "descending" referred to the two staircases (the former starting from 1 and the latter starting from 3) are fully appropriate. As regards the Triggering threshold, in a minority of cases (see the right graph in Figure 4) the Triggering threshold was greater than 1. In these cases, the term "descending staircase" was not appropriate because this staircase actually started from below the threshold (from 1) and "ascended" towards the threshold in the first run. This is a flaw of the experimental design which however does not seem to affect the validity of the results.

Individual Braking and Triggering thresholds were estimated in each of the 9 (3 Material A × 3 Material B) experimental conditions. In order to avoid anticipatory effects, the 36 staircases (9 experimental conditions × 2 thresholds × 2 staircases) were randomly interleaved. Participants were allowed to rest as much as they wanted after every 200 trials. The experimental session could last from 35 to 45 minutes.

3.2.2 Results and discussion

Figure 4 shows the means across participants of the Braking (left graph) and Triggering (right graph) individual thresholds, for the simulated material of sphere A (abscissa), and the simulated material of sphere B (separate lines). Both thresholds are expressed in terms of the following measure:

$$100 \times \mathrm{Log}_3(v_A/v_B) \tag{3}$$

The reason why I express the results in this way (rather than in terms of v_A/v_B) is to facilitate the comparison between the Braking and the Triggering thresholds, which, when expressed in terms of Equation (3), can both take on values from -100 (corresponding to $v_A/v_B = 1/3$) to +100 (corresponding to $v_A/v_B = 3$). When $v_A = v_B$, which is the condition optimal for the perception of the Launching Effect, Equation (3) equals 0. When v_A is three times v_B, the condition that should correspond to the maximum Braking Effect, Equations (3) equals 100. Finally, when v_B is three times v_A, the condition that should correspond to the maximum Triggering Effect, Equations (3) equals -100. These are useful reference points for evaluating the one and the other kind of threshold. Note that it is possible to transform the values resulting from Equation (3) into v_A/v_B values using the following equation:

$$v_A/v_B = 3^{\text{Equation (3)/100}} \tag{4}$$

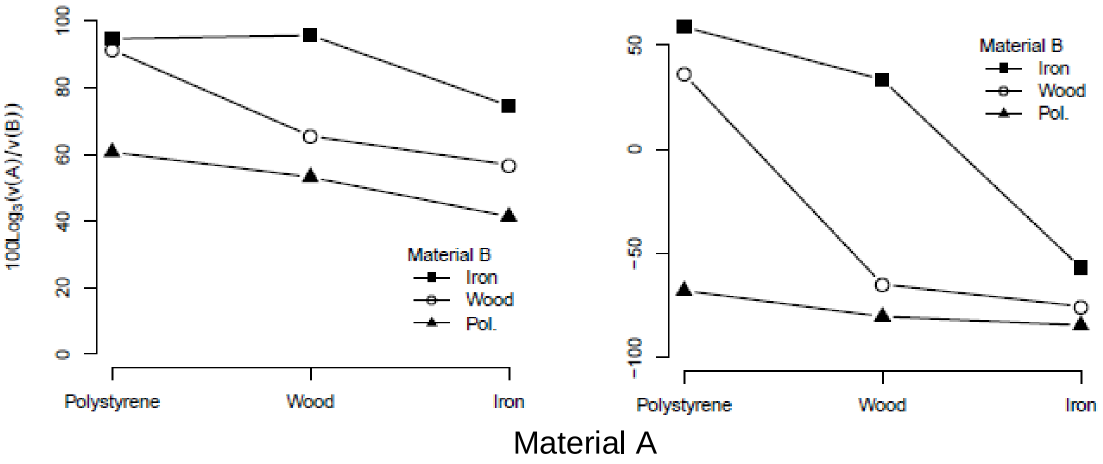

Figure 4. Mean Braking (left) and Triggering (right) thresholds for each combination of material of sphere *A* (horizontal axis) and material of sphere *B* (separate lines).

Braking threshold. A two-way within subjects ANOVA showed that factors *Material sphere A* and *Material sphere B* had significant main effects on the Braking threshold as $F(2,28) = 13.85$, $p = 6.59 \times 10^{-5}$ and $F(2,28) = 11.14$, $p = 0.00028$ respectively. Their interaction effects were marginally significant, with $F(4,56) = 2.83$, $p = 0.0329$. As shown in the left graph of Figure 4, the mean Braking threshold decreases with the simulated mass of sphere *A*, and increases with the simulated mass of sphere *B*. The interaction effects are due to the fact that when the simulated mass of sphere *A* changes from lighter to equal with respect to the simulated mass of sphere *B*, this produces a greater decrease of the mean Braking threshold compared with the other experimental manipulations. At present, this result seems difficult to explain and requires further experimental investigation.

Triggering threshold. A two-way within subjects ANOVA showed that factors *Material sphere A* and *Material sphere B* had significant main effects on the Triggering threshold as $F(2,28) = 43.24$, $p = 2.74 \times 10^{-9}$ and $F(2,28) = 73.11$, $p = 7.66 \times 10^{-12}$ respectively. Their interaction effects were also significant, with $F(4,56) = 19.61$, $p = 3.88 \times 10^{-10}$. As shown in the right graph of Figure 4, the mean Triggering threshold decreases with the simulated mass of sphere *A*, and increases with the simulated mass of sphere *B*. The interaction effects can be explained as the interaction effects which I found for the mean Braking threshold.

The results of Experiment 1 confirm my hypothesis: the perceived mass of sphere *A* is inversely related, and the perceived mass of sphere *B* is directly related, to the Braking and Triggering thresholds. As shown by Figure 4, the effect of simulated material on visual perception of the Launching Effect is not slight or marginal as hypothesized by Michotte and his followers, but very strong indeed.

Consider first the results obtained for the Braking threshold. When the simulated material of both spheres is the same, the average threshold is about 65, which means that observers tend to perceive a Braking Effect about 50% of the times when *A* is two times as fast as *B*. However, when the simulated material of sphere *A* is polystyrene and that of sphere *B* is iron, the Braking threshold is around the upper limit of the staircase, i.e., about 100. Observers tend thus to perceive a mechanical collision (Launching Effect) about 50% of the times even when *A* is three times as fast as *B*. Conversely, when the simulated material of sphere *A* is iron and that of sphere *B* is polystyrene, the Braking threshold is about 40, which corresponds to a v_A/v_B ratio of about 1.5: while in equal-material conditions this velocity ratio gives rise to an unambiguous Launching Effect, when *A* is perceived much heavier than *B* the same velocity ratio produces the impression of "braked launch" about 50% of the times.

The results for the Triggering threshold are even stronger. When the simulated material of both spheres is the same, the Triggering threshold is about -60, which means that observers tend to perceive a Triggering Effect about 50% of the times when *B* is two times as fast as *A*. However, when the simulated material of sphere *A* is polystyrene and that of sphere *B* is iron, the Triggering threshold takes on a positive value, i.e., about 60, corresponding to a v_A/v_B ratio around 2. This result is probably the most striking one, because according to the results reported by Michotte and by many other researchers, when *A* is two times as fast as *B* observers should perceive an unambiguous Launching Effect or even a slight Braking Effect. In a footnote, Michotte states that "It is even possible that some people get an impression of triggering when the speeds are equal. We have met occasional cases of this, although it has never happened when there was a descending ratio[19].” (Michotte, 1963, p. 111). The results of the present experiment show instead that when *A* is perceived much lighter than *B*, observers report a Triggering Effect about 50% of the times even when *A* is two times as fast as *B*. Conversely, when the simulated material of sphere *A* is iron and that of sphere *B* is polystyrene, the Triggering threshold is about -85, which means that observers perceive a Launching Effect about 50% of the times even when *B* is 2.6 times as fast as *A*. Note that in equal-material conditions this velocity ratio gives rise to an unambiguous Triggering Effect.

To sum up, the results of Experiment 1 suggest that Michotte’s claim that the phenomenal aspect of the objects involved does not (or slightly) influence the Launching Effect needs substantial revision. These results show that the range of velocity ratios corresponding to the Launching Effect greatly varies with the simulated material of both objects. Kinematic properties by themselves do not provide an exhaustive description of the stimulus conditions producing the Launching Effect: non-kinematic properties such as simulated material exert a prominent role on the phenomenon. In addition, the results of Experiment 1 show that the rules governing visual perception of the Launching Effect are similar to the rules of mechanics: the greater the perceived mass of object *A*, the greater the shift downward of the range of v_A/v_B values originating impressions of mechanical collisions (Launching Effect), whereas the larger the perceived mass of object *B*, the greater the shift upward of this range.

3.3 Experiment 2: the influence of size of 3-D spheres on the “Launching Effect”

The results of Experiment 1 show that manipulations of simulated material of the objects involved in a horizontal collision strongly influence visual perception of the event. In Experiment 2 I tested whether analogous effects can be obtained with manipulations of size of both objects.

As discussed in Section 2.3.2, a possible visual cue to mass is size. In nature the relation between size and mass is much weaker than the relation between material and

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[19] According to Michotte’s terminology, “descending ratio” means that $v_A > v_B$.

mass (see Note 16). However, when objects are made of the same material, or information about material is not available, it is reasonable to rely on a positive correlation between size and mass. This is consistent with the phenomenon called the “size-weight illusion” (Murray et al., 1999): when two objects of equal physical mass but of different volumes are weighed by hand, the smaller object usually feels heavier than the larger one. According to Anderson (1970), perceived volume positively correlates with expected weight, and perceived heaviness results from the subtraction between actual and expected weight. This supports the idea that the visual system uses size as a cue to mass.

If the hypothesis that visually perceived mass influences perception of the Launching Effect is correct, I should find that size of objects *A* and *B* influences the Braking and the Triggering thresholds. More precisely, and analogously to the predictions of Experiment 1, an increase of size of object *A* should cause a decrease of the Braking and Triggering thresholds, whereas an increase of size of object *B* should cause a decrease of both thresholds. I also predict that because size is a weaker cue to mass with respect to material, its effect should be weaker when compared with the effect of simulated material.

3.3.1 Experimental setup

Participants. Fifteen students of Psychology (aged from 20 to 29, 4 males) participated in the experiment. They all had normal or corrected-to-normal visual abilities, and were paid for the participation. None of them had participated in Experiment 1.

Stimuli and apparatus. The apparatus was identical to that used in Experiment 1. Two smooth, greenish 3-D spheres (created by 3D Studio Max) were presented at middle height of the screen. I manipulated their apparent size according to a 3 Size *A* (4.2, 8.4, 16.8 cm^3) × 3 Size *B* (4.2, 8.4, 16.8 cm^3) factorial design. These sizes (volumes) of the spheres are computed on the diameters of the corresponding images on the screen. The spheres thus created are depicted in Figure 5. The stimuli were identical to those of Experiment 1 in all other respects.

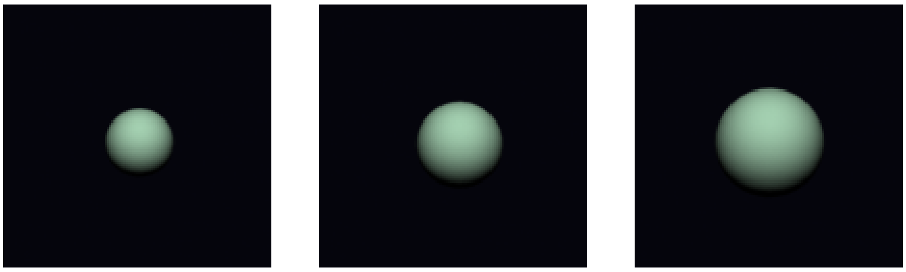

Figure 5: The three spheres used as stimuli in Experiment 2.

Procedure. The procedure was the same as that of Experiment 1, except that the instructions did not specified the material of which the spheres were made of[20]. The lifting procedure at the beginning of the experiment did not take place.

Experimental design. The experimental design was the same as that of Experiment 1.

3.3.2 Results and discussion

Figure 6 shows the means across participants of the Braking (left graph) and Triggering (right graph) individual thresholds, for the size of sphere *A* (abscissa), and the size of sphere *B* (separate lines).

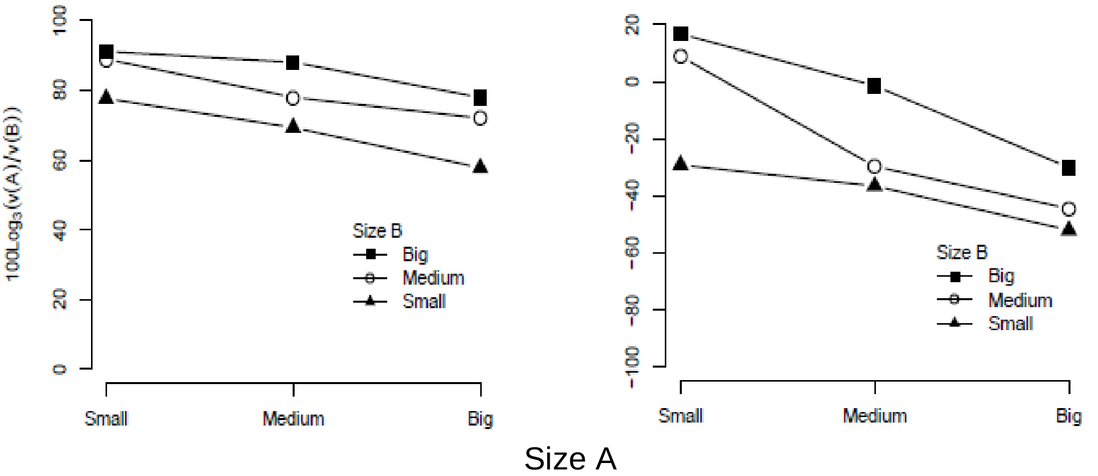

Figure 6. Mean Braking (left) and Triggering (right) thresholds for each combination of size of sphere *A* (horizontal axis) and size of sphere *B* (separate lines).

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[20] At the end of the experiment a short debriefing question clarified that the vast majority of the participants had imagined, during the experiment, that the two spheres were made of a hard material like ivory.

Braking threshold. A two-way within subjects ANOVA showed that factors *Size sphere A* and *Size sphere B* had significant main effects on the Braking threshold as $F(2,28) = 8.55$, $p = 0.00126$ and $F(2,28) = 6.93$, $p = 0.0036$ respectively. Their interaction effects were not significant, with $F(4,56) = 0.513$, $p = 0.727$. As shown in the left graph of Figure 6, the mean Braking threshold decreases with the size of sphere *A*, and increases with the size of sphere *B*.

Triggering threshold. A two-way within subjects ANOVA showed that factors *Size sphere A* and *Size sphere B* had significant main effects on the Triggering threshold as $F(2,28) = 20.38$, $p = 3.45 \times 10^{-6}$ and $F(2,28) = 12.91$, $p = 0.00011$ respectively. Their interaction effects were also significant, with $F(4,56) = 5.70$, $p = 0.00064$. As shown in the right graph of Figure 6, the mean Triggering threshold decreases with the size of sphere *A*, and increases with the size of sphere *B*. The interaction effects can be explained as the interaction effects which I found for the mean Braking threshold in Experiment 1

The results of Experiment 2 confirm that visually perceived mass influences visual perception of the Launching Effect. They also confirm that the Braking and the Triggering thresholds decrease with the size of object *A*, and increase with the size of object *B*.

Consider first the results obtained for the Braking threshold. When the size of both spheres is the same, the threshold is about 78, which means that observers tend to perceive a Braking Effect about 50% of the times when *A* is 2.4 times as fast as *B*. However, when the size of sphere *A* is small (the leftmost sphere depicted in Figure 5) and the size of sphere *B* is big (the rightmost sphere depicted in Figure 5), the Braking threshold is about 90. Observers tend thus to perceive a mechanical collision (Launching Effect) about 50% of the times even when *A* is 2.7 times as fast as *B*. Conversely, when sphere *A* is big and sphere *B* is small, the Braking threshold is about 57, which corresponds to a v_A/v_B ratio of about 1.9: while in equal-material conditions this velocity ratio gives rise to an unambiguous Launching Effect, when *A* is much bigger *B* the same velocity ratio produces the impression of "braked launch" about 50% of the times.

As for the Triggering threshold, when the size of both spheres is the same, the Triggering threshold is about -60, which means that observers tend to perceive a Triggering Effect about 50% of the times when *B* is two times as fast as *A*. However, when sphere *A* is small and sphere *B* is big, the Triggering threshold takes on a positive value, i.e., about 16, corresponding to a v_A/v_B ratio around 1.2. This means that when *A* is much smaller than *B*, even a v_A/v_B ratio slightly greater than 1 produces a Triggering Effect about 50% of the times: this confirms that size plays a prominent role in determining the range of velocity ratios producing the Launching Effect. Conversely, when sphere *A* is big and sphere *B* is small, the Triggering threshold is about -85, which means that observers perceive a Launching Effect about 50% of the times even when *B* is 2.6 times as fast as *A*: in equal-material conditions this velocity ratio gives rise to an unambiguous Triggering Effect.

3.3.3 A comparison between the results of experiments 1 and 2

The curves in both graphs of Figure 6 (Experiment 2) are flatter and closer when compared with the curves in both graphs of Figure 4 (Experiment 1). This is especially true for the graphs on the right (Triggering threshold). This indicates that, as predicted, manipulations of size of both spheres produce smaller variations of the two thresholds when compared with manipulations of their simulated material. In order to test statistically this qualitative evidence, I performed a 3-way mixed-effect ANOVA on the Braking thresholds with within-participants factors *Simulated mass sphere A* and *Simulated mass sphere B* and between-participants factor *Experimental condition*. The same statistical analysis was performed on the Triggering thresholds. Both within participants factors had three possible levels: light, medium and heavy. The between-participants factor had two possible levels: manipulations of simulated material (Experiment 1) and manipulations of size (Experiment 2). The comparison between the Braking thresholds fell short of statistical significance: the main effects of factor *Experimental condition* were only marginally significant ($F(1,126) = 3.91$, $p = 0.05$), the effects of two-factor interactions *Experimental condition* × *Simulated mass sphere*

A, *Experimental condition* × *Simulated mass sphere B* and the effects of three-factor interaction were not significant ($F(2,126) = 0.37$, $p = 0.69$, $F(2,126) = 2.15$, $p = 0.12$, $F(4,126) = 0.28$, $p = 0.89$ respectively). In contrast, the Triggering thresholds were significantly different: the main effects of factor *Experimental condition* were significant ($F(1,126) = 7.28$, $p = 0.008$), the effects of two-factor interactions *Experimental condition* × *Simulated mass sphere A* and *Experimental condition* × *Simulated mass sphere B* were significant ($F(2,126) = 7.73$, $p = 0.0007$ and $F(2,126) = 14.16$, $p = 2.84 \times 10^{-6}$ respectively), as well as the effects of the three-factor interaction ($F(4,126) = 4.49$, $p = 0.002$). Thus, the statistical analysis confirms that the Triggering threshold is more influenced by manipulations of simulated material (Experiment 1) than by manipulations of size (Experiment 2). As hypothesized, this is probably due to the fact that perceived material is a stronger cue to mass with respect to perceived size. The same trend appears also in the comparison between the two Braking thresholds, but the difference falls short of statistical significance. When the two graphs relative to the Braking threshold and the two graphs relative to the Triggering threshold are compared (Figures 4 and 6), it clearly appears that the Triggering threshold is more affected by perceived mass in both experiments. This may explain why I found a statistically significant difference between the two experimental conditions only for the Triggering threshold. At present I have no explanation of the reason why manipulations of perceived mass (simulated material or size) influence more the Triggering threshold than the Braking threshold.

3.4 Experiment 3: the influence of size of 2-D disks on the “Launching Effect”

The results of Experiment 2 show that manipulations of size of objects *A* and *B* influence the Braking and the Triggering thresholds. This is in contrast with the results obtained in a similar experiment by Natsoulas (1961), where he manipulated the size of *A* and *B* (2-D rectangles) and their velocity ratio, and asked the participants whether they perceived a “Launching Effect”, a “Braking Effect”, or a “Triggering Effect”. Natsoulas found that size of both objects had only a slight influence on the impression reported by observers, which depended almost exclusively on the velocity ratio of the two objects. My Experiment 2 and Natsoulas's experiment differ however in many respects. First, the method of construction and of presentation of the stimuli is different: Natsoulas used the method of rotating discs rather than virtual simulations. Second, the psychophysical method is different: Natsoulas used the method of "single stimuli", whereas I used the method of "randomly interleaved staircases". Third, while in my Experiment 2 the velocity ratio between *A* and *B* could take on 21 possible values between 1/3 and 3, in Natsoulas's experiment the velocity ratio was manipulated in very large steps, i.e., it could take on only five values between 1/3 and 3. Large manipulations of the velocity ratio may have overshadowed the possible effect of size in Natsoulas's experiment. The discrepancy between the results of the two experiments might thus depend on one or more of the above mentioned methodological differences. However, it is also possible that differences in the fundamental results depend on the nature of the stimuli presented to the participants: while Natsoulas (in line with Michotte's tradition) used abstract 2-D rectangles, I used more realistic 3-D spheres. It is then possible that manipulations of size are effective in producing different visual impressions of mass when the two objects are three-dimensional, but not when they are abstract 2-D shapes. This is an important issue not only for visual perception of the Launching Effect, but also for other fields of experimental psychology where it is often assumed that size of abstract 2-D shapes correlates with their perceived mass. This is a common assumption in research on Representational Momentum (e.g., Hubbard, 1997; Kozhevnikov & Hegarty, 2001), and Intuitive Physics (e.g., De Sá Teixeira, De Oliveira, & Viegas, 2008). It is thus important to test whether manipulations of area of two-dimensional shapes produce the same effect on visual perception of the Launching Effect as manipulations of volume of three-dimensional objects.

In order to test whether differences in results between my Experiment 2 and Natsoulas's experiment are due to methodological differences or rather to the "dimensionality" (2-D vs. 3-D) of the stimuli, in Experiment 3 I used the same method as in Experiment 2, but objects *A* and *B* were 2-D disks rather than 3-D spheres. If the discrepancies between my findings and Natsoulas's findings are due to methodological differences, then the results of Experiment 3 should be similar to the results of Experiment 2. If instead manipulations of area of 2-D disks are less effective than manipulations of volume of 3-D spheres in producing different visual impressions of mass, then experimental manipulations in Experiment 3 should produce less variation of the Braking and the Triggering thresholds than experimental manipulations in Experiment 2.

3.4.1 Experimental setup

Participants. Fifteen students of Psychology (aged from 19 to 34, 4 males) participated in the experiment. They all had normal or corrected-to-normal visual abilities, and were paid for the participation. None of them had participated in Experiments 1 or 2.

Stimuli and apparatus. The apparatus was identical to that used in Experiments 1 and 2. Two smooth, greenish disks (created by 3D Studio Max) were presented at middle height of the screen. I manipulated their apparent size according to a 3 Size *A* (3.15, 4.99, 7.93 cm^2) × 3 Size *B* (3.15, 4.99, 7.93 cm^2) factorial design. These sizes (areas) of the disks are computed on the diameters of the corresponding images on the screen, which were equal in all the three experiments. The disks thus created are depicted in Figure 7. The stimuli were identical to those of Experiments 1 and 2 in all other respects.

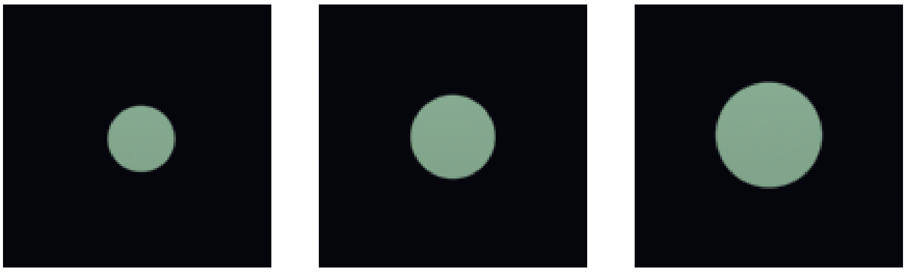

Figure 7: The three disks used as stimuli in Experiment 3.

Procedure. The procedure was the same of Experiment 2.

Experimental design. The experimental design was the same as in Experiments 1 and 2.

3.4.2 Results and discussion

Figure 8 shows the means across participants of the Braking (left graph) and Triggering (right graph) individual thresholds, for the size of sphere *A* (abscissa), and the size of sphere *B* (separate lines).

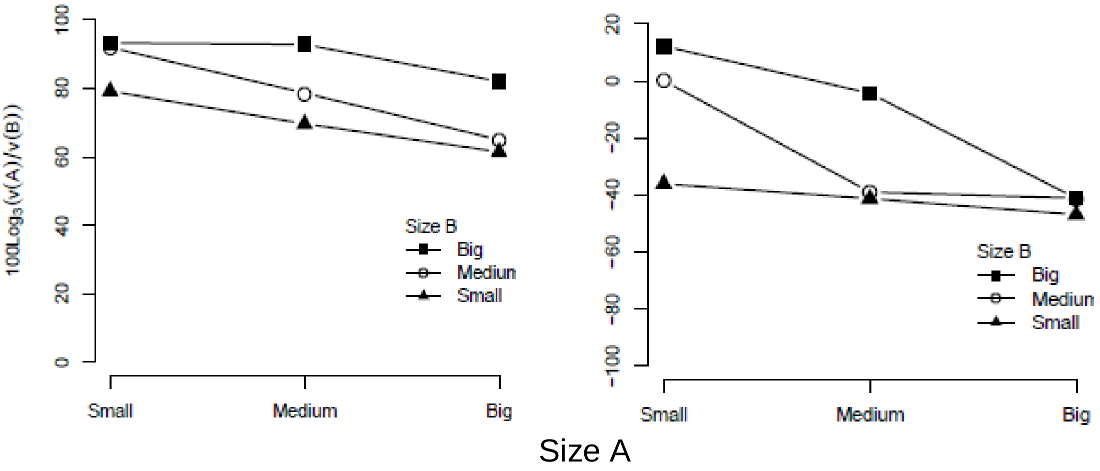

Figure 8. Mean Braking (left) and Triggering (right) thresholds for each combination of size of disk *A* (horizontal axis) and size of disk *B* (separate lines).

Braking threshold. A two-way within subjects ANOVA showed that factors *Size disk A* and *Size disk B* had significant main effects on the Braking threshold as $F(2,28) = 18.18$, $p = 8.72 \times 10^{-6}$ and $F(2,28) = 8.12$, $p = 0.0017$ respectively. Their interaction effects were not significant, with $F(4,56) = 2.27$, $p = 0.073$. As shown in the left graph of Figure 6, the Braking threshold decreases with the size of disk *A*, and increases with the size of disk *B*.

Triggering threshold. A two-way within subjects ANOVA showed that factors *Size disk A* and *Size disk B* had significant main effects on the Triggering threshold as $F(2,28) = 14.83$, $p = 4.05 \times 10^{-5}$ and $F(2,28) = 10.16$, $p = 0.00048$ respectively. Their interaction effects were also significant, with $F(4,56) = 6.93$, $p = 0.00013$. As shown in the right graph of Figure 6, the Triggering threshold decreases with the size of disk *A*, and increases with the size of disk *B*. The interaction effects can be explained as the interaction effects which I found for the mean Braking threshold in Experiments 1 and 2.

3.4.3 A comparison between the results of the three experiments

A comparison between the graphs in Figures 6 and 8 reveals the similarity between the results of Experiments 2 and 3. In order to test statistically this qualitative evidence, I performed a 3-way mixed-effect ANOVA, on the Braking thresholds with within-participants factors *Size object A* and *Size object B* and between-participants factor *Experimental condition*. The same statistical analysis was performed on the Triggering thresholds. Both within participants factors had three possible levels: small, medium and big. The between-participants factor had two possible levels: manipulations of volume of 3-D spheres (Experiment 2) and manipulations of area of 2-D disks (Experiment 3). The comparison between the Braking thresholds was not significant: the main effects of factor *Experimental condition*, the effects of two-factor interactions *Experimental condition* × *Size object A*, *Experimental condition* × *Size object B* and the effect of the three-factor interaction were not significant ($F(1,126) = 0.279$, $p = 0.60$), $F(2,126) = 0.052$, $p = 0.95$, $F(2,126) = 0.26$, $p = 0.77$, $F(4,126) = 0.22$, $p = 0.93$ respectively). The comparison between the Triggering thresholds was not significant: the main effects of factor *Experimental condition*, the effects of two-factor interactions *Experimental condition* × *Size object A*, *Experimental condition* × *Size object B* and the effect of the three-factor interaction were not significant ($F(1,126) = 0.99$, $p = 0.32$), $F(2,126) = 0.16$, $p = 0.85$, $F(2,126) = 0.07$, $p = 0.93$, $F(4,126) = 0.23$, $p = 0.92$ respectively). These statistical analyses thus confirm that manipulations of area of 2-D disks (Experiment 3) produce the same effects as manipulations of volume of 3-D spheres (Experiment 2) on the Braking and Triggering thresholds. Hence we may conclude that the discrepancy between the results of my Experiment 2 and the results of Natsoulas's experiment are due to methodological differences.

The results of Experiment 3 confirm that size is a visual cue to mass, and that it influences visual perception of the Launching Effect even when size is intended as area of 2-D shapes rather than volume of 3-D objects. I previously showed (see Section 3.3.3) that manipulations of simulated material influence more the Triggering threshold when compared with manipulations of size. A comparison between the results of Experiment 1 (graphs in Figure 4) and the results of Experiment 3 (graphs in Figure 8) confirms this trend. A statistical analysis supports this qualitative evidence, and also highlights a statistically significant difference between the two Braking thresholds. Remember that the latter difference was not significant in the comparison between the results of Experiment 1 and the results of Experiment 2. I performed a 3-way mixed ANOVA on the Braking thresholds with within-participants factors *Simulated mass sphere A* and *Simulated mass sphere B* and between-participants factor *Experimental condition*. The same statistical analysis was performed on the Triggering thresholds. Both within participants factors had three possible levels: light, medium and heavy. The between-participants factor had two possible levels: manipulations of simulated material (Experiment 1) and manipulations of size (Experiment 3). The comparison between the Braking thresholds was significant: the main effects of factor *Experimental condition* were significant ($F(1,126) = 7.75$, $p = 0.006$), the effects of the two-factor interaction *Experimental condition* × *Simulated mass sphere A* were not significant ($F(2,126) = 0.29$, $p = 0.75$), the effects of the two-factor interaction *Experimental condition* × *Simulated mass sphere B* were marginally significant ($F(2,126) = 2.50$, $p = 0.086$) and the effects of the three-factor interaction were not significant ($F(4,126) = 0.26$, $p = 0.90$). The two Triggering thresholds were significantly different: the main effects of factor *Experimental condition* were marginally significant ($F(1,126) = 3.01$, $p = 0.085$), the effects of two-factor interactions *Experimental condition* × *Simulated mass sphere A* and *Experimental condition* × *Simulated mass sphere B* were significant ($F(2,126) = 10.77$, $p = 4.79 \times 10^{-5}$ and $F(2,126) = 17.63$, $p = 1.78 \times 10^{-7}$ respectively), as well as the effects of the three-factor interaction ($F(4,126) = 3.42$, $p = 0.009$).

3.5 General discussion

The results of the three experiments presented in this chapter show that the Braking threshold and the Triggering threshold are strongly influenced by simulated material and size of objects involved in collision events. This supports the general hypothesis that non-kinematic properties of the stimulus influence visual perception of the Launching Effect. More specifically, an increase of visually perceived mass of object *A* causes a shift downward of the range of v_A/v_B values originating impressions of mechanical collisions (Launching Effect), whereas an increase of visually perceived mass of object *B* causes a shift upward of this range. This confirms the conjecture of a fair degree of isomorphism between mechanical rules of collisions and visual perception of the Launching Effect. The results also confirm that simulated material is a stronger visual cue to mass as compared with size.

In Section 2.2.2 I hypothesized that the role of non-kinematic properties in visual perception of dynamic events has so far been underestimated because of the abstractness of the stimuli used in previous experiments on the topic (e.g., Michotte, 1963; Natsoulas, 1961; White & Milne, 1999; 2003). The results of Experiment 1 show that simulated material of objects involved in collisions has a prominent influence on visual perception of the Launching Effect. For revealing the importance of this non-kinematic variable it is necessary to use realistic virtual simulation of dynamic events, where simulated material can be manipulated.

Abstractness of the stimulus conditions is nonetheless only one of the reasons why the role of non-kinematic properties has been neglected in previous research. Lack of appropriate experimental methods is another reason. The results of Experiment 3 show that manipulations of area of abstract 2-D shapes have the same effect on the Braking and Triggering thresholds as manipulations of volume of more realistic 3-D objects. The importance of size in visual perception of the Launching Effect can thus be revealed also by using simple 2-D shapes of various dimensions, provided that appropriate and rigorous psychophysical methods are employed in experiments.

3.5.1 The influence of perceived mass on the "Launching Effect": perception or cognition?

A possible objection to the results of the three experiments presented here, is that participants may have relied on their explicit knowledge of mechanical collisions, rather than their visual impressions. In other words, visually perceived mass of objects *A* and *B* would influence not visual perception of the Launching Effect, but only explicit beliefs about mechanical collisions. For instance, when the simulated material of sphere *A* is polystyrene, the simulated material of sphere *B* is iron, and the velocity ratio is unitary, observers would perceive a Launching Effect, but reported a Triggering Effect because they knew that the presented collision was not physically correct.

This objection recalls an old but still on-going debate about whether experiments on visual perception of dynamic events investigate observers' genuine visual impressions, or rather reasoning and explicit knowledge of the proposed events. In his strong critique of Michotte's work, Joynson (1971) pointed out that when naïve observers are presented with laboratory simulations of dynamic events, they may not rely on their visual impressions, but rather report what they explicitly think about the proposed stimulus condition. The problem exists not only when participants are required free verbal descriptions of their impressions (like in Michotte's experiments), but also when an "objective approach" is taken, i.e., when participants are required to choose between various alternative responses: "The procedure would still require verbal instructions, and would seem to assume that phrases such as 'perceive causality' have a plain and agreed meaning…" (ibid., p. 302). Schlottmann (2000; 2001) argued that causal perception and causal reasoning cannot be clearly distinguished in adulthood: observers' causal judgments are based more on explicit reasoning about the mechanism linking cause and effect rather than on genuine visual impressions. Schlottmann & Anderson (1993) found that ratings of causality of classic Michottean stimuli depended not only on manipulations of the stimulus conditions (velocity ratio, temporal delay, and spatial gap), but also on experimental instructions and on participants' attitude. Moreover, many experiments carried out by different researchers have shown that explicit causal judgments are prone to great individual variability (e.g., Gemelli & Cappellini, 1958; Beasley, 1968; Schlottmann & Anderson, 1993). All these findings have cast doubts on the true nature (perceptual vs. cognitive) of the Launching Effect and of other dynamic events.

Recent experiments have however supported the hypothesis that the Launching Effect is a genuine visual impression. The key idea of these experiments is to measure causal impressions "indirectly": observers are not required explicit causal judgments, but are rather required to judge "collateral" phenomena which have been shown to correlate with the Launching Effect. For instance, Scholl and Nakayama (2004) reported that observers tend to underestimate the overlap between *A* and *B* when contextual stimuli favor the perception of a Launching Effect. Buehner and Humphreys (2010) showed that objects forming a causal event appear closer in space relative to objects involved in non-causal sequences. Hubbard, Blessum, and Ruppel (2001) showed a decrease in displacement in memory of object *B* when the motion of object *A* favor the impression of launching (cf. Choi & Scholl, 2006). Because in these studies observers were not required explicit judgments of causality, the possible influence of high-level cognitive processes was greatly reduced, if not completely eliminated. That the Launching Effect is a genuine visual impression is also supported by studies showing that purely perceptual factors like grouping and context influence the phenomenon (Scholl & Nakayama, 2002; Choi & Scoll, 2004; Bae & Flombaum, 2010). These findings cannot be explained in terms of knowledge and past experience. Neurophysiological studies also provide evidence supporting that causality is embedded in our brain, and that its recognition is fast and automatic (Roser et al., 2009; Badler et al., 2010). It is thus possible to conclude that the Launching Effect cannot be explained only in terms of high-level cognitive processes[21].

3.5.2 The effect of perceived mass on the "Launching Effect" is primarily perceptual

In virtue of the discussion above, one might argue that "indirect measures" of causality should replace "direct measures"[22] because the former are less influenced by non-perceptual factors compared with the latter (see Choi & Scholl, 2006). Indirect measures such as "causal crescents" (Scholl & Nakayama, 2004) and "spatial binding" (Buehner & Humphreys, 2010) have been shown to be sensitive to the difference between unambiguous Launching Effect and non-causal motion. Note however that phenomenal causality is not a dichotomous property: unambiguous Launching Effect and non-causal motion are just the two poles of a continuum. A reliable *measure* of perceptual causality should be sensitive to subtle differences in causal impressions, providing a continuous scale of values from no causal impression at all to unambiguous Launching Effect. Unfortunately, indirect measures are not refined enough to fulfill this requirement. Further development of indirect tools is desirable (see Choi & Scholl, 2006), but at present they cannot replace "direct measures" of causality. Direct causal

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[21] This supports Michotte's interpretation of the phenomenon (see Section 1.1).

[22] Direct measures of perceptual causality refer to explicit judgments of causality in form of rating or two-alternative forced choice.

judgments, together with appropriate psychophysical methods, still appear the most refined tools for measuring causal impressions, especially when experimental manipulations produce subtle variations of the impression itself.

The problem remains, however, concerning the extent to which explicit judgments of causality may be influenced by non-perceptual factors. Even though the Launching Effect is a purely perceptual phenomenon, high-level cognitive processes [23] may intervene post-perceptually. When direct judgments of causality are required, it is possible to emphasize the perceptual component of the task by means of appropriate experimental instructions (Choi & Scholl, 2006). In the three experiments I have presented, participants were explicitly asked to rely on their visual impressions, and not on their knowledge of the simulated physical events (see Section 3.2.1). This was remarked two times (the second time verbally by the experimenter) before starting the experiment. Because all the participants were students of psychology, I think it is reasonable to suppose that they were aware of the meaning of the sentence “rely on your visual impression”. Moreover, I avoided any reference to the word “causality”, which could be misunderstood, and used more generic words such as “natural” and “unnatural”.

I can also say that, when I observed the experimental stimuli, the influence of visually perceived mass was immediate and compelling: for instance, when the simulated material of sphere *A* was polystyrene, the simulated material of sphere *B* was iron, and *B* travelled faster or as fast as *A*, the collision *looked* unnatural, i.e., the motion of sphere *B* appeared too fast compared with the force exerted by *A*. This impression was immediate and compelling. The same is true for stimulus conditions in which size of 3-D and 2-D objects was manipulated.

Of course, the influence of high-level cognitive factors on the results of the present experiments cannot be excluded. My claim, however, is that the results cannot be completely explained by high-level cognitive factors. The effect of visually perceived mass on the Launching Effect is, first of all, perceptual. Post-perceptual cognitive factors have probably only strengthened the results. Future research should

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[23] For instance, subjective interpretation of the instructions, causal reasoning, reference to past experience, etc.

try to confirm these results using sufficiently accurate indirect measures and possibly neurophysiological data.

3.5.3 The influence of perceived mass on visual perception of dynamic events: a new test bench for phenomenal causality models

The new experimental findings presented here may constitute a test bench for available models of visual perception of dynamic events. In the following, I’m going to discuss the implications of my findings for the two most popular models of that kind: Michotte’s model of ampliation of the movement, and White’s schema-matching model. The debate between the supporters of the one and the other model is still alive, and seems far from conclusion (e.g., Rips, 2011).

Michotte’s model of ampliation of the movement (see also Section 1.1.1) explains visual perception of dynamic events in terms of Gestalt principles. According it, the Launching Effect occurs because stimulus conditions are interpreted by the visual system as a unique motion initially carried by *A* and then transferred to *B*. This “conflict” would be resolved through the construction of a single dynamic event involving two distinct objects, one playing the role of “cause” (*A*) and the other playing the role of “effect” (*B*). According to the model, stimulus conditions have a prominent role in perception of causality, whereas the role of learning and past experience would be negligible. Phenomenal causality occurs whenever ampliation of the movement occurs, irrespectively of the similarity between the stimulus conditions and everyday experience. The phenomenon is thus very specific, and limited to the few stimulus conditions where ampliation of the movement occurs (see Section 1.1.1). Scholl and Tremoulet (2000) restated Michotte’s theoretical position in terms of the modular approach to visual perception: perceptual causality would be an automatic and encapsulated visual module, totally independent of learning, past experience, consciousness, and sensitive to specific stimulus conditions.

White’s schema-matching model takes a more cognitive perspective on phenomenal causality. The model predicts that the perceived scene is compared with several schemas of dynamic events stored in memory, and when a schema reasonably fits the perceived scene, the latter is interpreted according to that schema. Schemas are acquired through personal experiences of actions on objects haptically perceived, and fill out gaps in the stimulus information (White, 2006a). This recalls the idea of the philosopher Maine de Biran (1766 - 1824), who stated that the "sense of causality" originates from haptic experiences (Bozzi, 1969). According to the schema-matching model, stimulus conditions have an important role in visual perception of dynamic events, but the role of learning and past experience is not less important: new schemas can be continuously learned[24], and no limits are imposed on their number and complexity. Casual impressions would thus be less specific than suggested by Michotte's model.

The two models differ fundamentally in the role they attribute to learning and past experience, and in the supposed origins of causal perception, which are visual according to Michotte and haptic according to White. There are however two notable similarities: First, according to both models, phenomenal causality depends only on kinematic features of the stimuli, and not on the phenomenal aspect of the objects involved. Second, visual perception of dynamic events is fast, compelling, and automatic, and thus not influenced by high-level cognitive factors such as conscious reasoning.

3.5.4 The influence of perceived mass on visual perception of dynamic events and the "Ampliation of the movement" model

The findings presented here are at odds with Michotte's model of ampliation of the movement, and in general they are incompatible with the "modular approach" to phenomenal causality. The Launching Effect cannot be explained in terms of ampliation of the movement, because the phenomenon depends on visually perceived mass of the objects involved: even when the kinematic properties of objects *A* and *B* are optimal for the perception of the Launching Effect (i.e., the two objects have the same velocity), the Triggering impression occurs when the perceived mass of *A* is small and the perceived mass of *B* is large. Alternative models that maintain a "modular approach" to phenomenal causality would themselves have difficulties in explaining

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[24] Note that here learning refers to perceptual learning, not to explicit learning (intellectual, scholastic) of mechanical rules.

these results. For instance, it might be hypothesized a causal module which processes not only kinematic properties of the stimuli, but also their featural properties such as the material of which they are made of. In this case, the problem would be to explain how this visual module could have evolved: the advent of artificial materials like iron or polystyrene is evolutionarily too recent to have allowed the evolution of this hypothetical module. This does not exclude that humans and animals, at birth, are provided with a rudimental causal module, which processes only kinematic information and which directs successive learning of causal relations (see Mascalzoni et al., 2010); my claim is that this module cannot be the basis of adults' perception of causality, because the latter strongly depends on visually perceived mass of the objects involved.

I would like to point out that refuting the "modular approach" to phenomenal causality does not mean to deny that phenomenal causality is a genuine perceptual phenomenon. Consider this argument by Rips (2011): the recognition of cars is usually fast, automatic, and compelling, certainly a genuine perceptual process. However, nobody would seriously argue that there is a module for recognition of cars, because the development of modules requires much more time than that elapsed since the invention of cars. Visual processes which are independent of conscious reasoning do not necessarily need to be modular.

3.5.5 The influence of perceived mass on visual perception of dynamic events and the "Schema-matching" model

The influence of visually perceived mass on the Launching Effect is also partially at odds with White's schema-matching model. Remember that, according to this model, schema construction and matching are based only on kinematic properties of the stimuli. The results of the experiments presented here show that the model should at least be amended: both schema construction and matching are also based on featural properties of the objects involved in dynamic events. The latter idea is however compatible with the core structure of the schema-matching model: schemas are acquired through haptic perceptual learning, i.e., haptic experience with objects in everyday life. According to White, haptic experience is the preferential route for schema construction because "We receive particular kinaesthetic information relating directly to the muscular and skeletal involvement in the action, we receive skin pressure sensory information from the points of contact between the hand and the object, and there is continual co-ordination between the motor activity and the perceptual feedback" (White, 2006a, p. 172).

When interacting haptically with objects in our environment, we receive substantial information concerning their mass, the material of which they are made of, their mass distribution, etc. Some kind of knowledge of these properties is necessary for improving our interaction with objects since infancy: haptic experience exerts a prominent role in this learning process. Haptic experience is thus the preferential route both for acquisition of knowledge about dynamic properties of objects, and for causal schemas construction. In my opinion, this is a strong theoretical argument in favor of the interplay between causal schemas and dynamic properties: because these two sources of (perceptual) knowledge are acquired through the same system, the influence of dynamic properties on causal schemas should be expected. That is why the documented influence of visually perceived mass on visual perception of dynamic events ultimately supports the schema-matching model. People have learned through haptic experience that the amount of force required to make objects move depends on their mass, thus causal schemas contain both kinematic and dynamic information. For instance, suppose that observers are presented with a horizontal collision between two objects *A* and *B* (see Fig. 1), the first made of polystyrene and the second made of iron. When $v_A = v_B$ the stored schema for the recognition of the Launching Effect is not activated, because haptic experience suggests that a sphere made of polystyrene cannot make move a sphere made of iron with its same velocity. An important point is that, even though the three experiments presented here were focused on the Launching Effect, I expect dynamic properties to be influential in all kinds of dynamic events.

From the hypothesis that causal schemas are acquired through haptic experience with physical objects, one might deduce a strong degree of isomorphism between the rules of mechanics and causal schemas. Even though the results of the three experiments presented here support a fair degree of similarity between mechanical laws and perceptual rules, this similarity is only approximate. Causal schemas are built through haptic experiences with specific dynamic events and generalize to similar, but not identical events: a certain degree of discrepancy between physical rules and causal schemas is thus not surprising, especially when the stimuli are somewhat "idealized" like in laboratory experiments. That causal schemas are not perfect copies of physical dynamic events is also supported by the so-called "causal asymmetry" in visual perception of the Launching Effect (White, 2006b, see also Chapter 4).

3.5.6 The influence of perceived mass on visual perception of dynamic events and the origins of phenomenal causality

A long and fruitful debate has developed about the origins of phenomenal causality. Many studies have shown that infants as young as 6 months are sensitive to causal sequences involving simple and abstract objects (e.g., Leslie & Keeble, 1987). Infants start very early to use their haptic system in order to explore the environment: presumably, acquisition of causal schemas and of knowledge concerning dynamic properties of objects start in early stages of individual development. We may thus expect that phenomenal causality depends on dynamic properties of the objects involved since the first months of life. This hypothesis is confirmed by a study by Kotovski and Baillargeon (1998), who showed that infants as young as 5.5 months integrate information about size (perceived mass) into their representation of launching events. In an extensive review about infants' perception of causality, Saxe and Carey (2006) showed that infants integrate many cues when judging the plausibility of causal sequences. Infants' causal judgments are influenced not only by dynamic properties of the objects involved, but also by their dispositional status. For instance, infants consider a human hand, but not a toy train, a plausible agent of a throwing action (Saxe, Tenenbaum, & Carey, 2005; see also Kosugi & Fujita, 2002). The studies cited above support the idea that visual perception of dynamic events is strongly influenced by non-kinematic properties of the objects involved from infancy onwards.

3.5.7 Visual perception of dynamic events with abstract stimuli

To conclude, I would like to propose a tentative explanation of the fact that observers can perceive dynamic events even when they are presented with abstract stimuli which are totally different from everyday experience (like in my Experiment 3 or in Michotte's experiments). This fact seems at odds with the hypothesis that causal schemas are built through everyday haptic experiences. My hypothesis is that causal schemas are highly flexible, i.e., they can "adapt" to the information which is provided in the stimulus condition, and that this feature responds to an evolutionary necessity. As I proposed in Section 2.3.1, a fundamental role of causal schemas is probably that of allowing observers to discriminate mechanical from non-mechanical events. This prompts the individual to a proper interaction with the objects of the environment. Physical objects are subject to the laws of mechanics, and their motion is uniquely determined by the set of initial values of all the physical variables involved. However, it happens that these values are not perceptually available to the observer. For instance, when the observed event is far from sight, the material and the rotation of the objects involved might not be visible. Nonetheless, a quick decision about whether the event is mechanical or non-mechanical might be important from an evolutionary point of view, for instance for feeding purposes. The optimal way for the visual system to address the task, is to constrain the missing variables within plausible ranges. This can explain why we have no problems in judging dynamic events even in laboratory experiments where the stimulus conditions are abstract and highly degraded. A similar idea was proposed by White (2006a), who suggested that causal schemas fill out gaps in the stimulus information.

Chapter 4

Naïve Physics of Horizontal Collisions: an Empirical Study

While in Chapters 1-3 I focused on *visual perception* of horizontal collisions between objects differing in simulated material, size, and velocity, in this chapter I'm going to focus on how people *reason* about the same physical event. In other words, I'm going to investigate whether observers' intuitive predictions about horizontal collisions are similar to the laws of mechanics. The theoretical framework of this chapter is Naïve Physics, i.e., people's intuitive understanding of physical events. Naïve Physics is a blend of perception, cognition, and action. Even though perception and action are important parts of the subject, researchers are mainly focused on the cognitive side, i.e., how people reason about physical events. The two experiments that I'm going to present in this chapter have Information Integration Theory and Functional Measurement as their theoretical and methodological background, respectively. As I'm going to argue in the following, these are useful tools for the assessment of intuitive knowledge of physical events. In the first part of this chapter, I'm going to discuss the relation between Naïve Physics, Experimental Psychology, and Physics instruction in general.

4.1 Naïve Physics: an introduction

From when we are in the cradle onward, we make experience of the physical world around us. We continuously interact haptically with objects, we see them moving, falling, colliding, etc. A reasonable expectation is that, thanks to this extensive experience, our representations of physical events are reasonably accurate and consistent with the laws of Mechanics. For instance, because we continuously see objects falling to the ground, we should know that they fall with constant acceleration independently of their mass. On the contrary, many researchers in the field of Naïve Physics have shown that people without formal instruction in Physics hold striking misconceptions about elementary laws of classical mechanics. Physics teachers, educational psychologists, and experimental psychologists are particularly interested in, and concerned by, the fact that misconceptions are deeply rooted in people’s mind, and are very resistant to change. As a result, even students who underwent high school and college Physics courses, still exhibit important misconceptions at the end of the courses. The study of Naïve Physics is interesting for several reasons: on the one hand, perceptual and cognitive psychologists are faced with the problem of explaining whether misconceptions have a cognitive or perceptual origin (see Kaiser, Proffitt, & Anderson, 1985). On the other hand, educational psychologists and Physics teachers are faced with the problem of assessing students’ understanding of the subject, and of developing adequate educational programs aimed at the correction of misconceptions. Another question, which is interesting both for cognitive psychologists and for educational psychologists, is whether misconceptions are organized around a consistent naïve theory of the physical world which is alternative to the Newtonian one[25], or rather they are loosely organized and isolate. Needless to say, there is a strong connection between the perceptual-cognitive side of the problem and the educational one.

4.1.1 Naïve Physics and Physics instruction

A prominent predictor of students’ understanding of classical mechanics is their knowledge state at the beginning of the Physics course. It has been shown that high school and college students showing several misconceptions about basic Newtonian principles at the beginning of the course, tend to obtain poor marks at the end of the course itself (Halloun & Hestenes, 1985). Moreover, students’ good performance in ordinary tests may nevertheless hide poor qualitative understanding of Newtonian principles (Clement, 1982). These findings are important for three reasons. First, they show that everyday experience with physical objects does not imply adequate representations of physical laws. Second, they show that understanding the most basic principles of Mechanics is not as easy as teachers might believe. Third, they show that instruction is prone to fail its aim: in some cases, Newtonian principles which are presented by teachers through textbooks and classroom demonstrations, are distorted

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[25] McCloskey (1983) suggested that people’s representation of the physical world is similar to the medieval Impetus Theory.

and misinterpreted by students in light of their previous misconceptions. In other cases, new notions are memorized and coexist with previous misconceptions, with the result that as soon as students forget the taught material, or have to solve Physics problems which differ slightly from those presented in the classroom, old misconceptions reappear. In other words, while Physics courses should lead students to a gradual "change of paradigm" from erroneous beliefs to the Newtonian interpretation through textbooks and classroom demonstrations, actually the majority of students never achieve a stable "Newtonian outlook" of the physical world.

When students come into Physics courses, they are not "tabulae rasae": conversely, they usually hold several misconceptions about the rules governing the behavior of physical objects. If these misconceptions go undetected, then with high probability they will remain in students' mind, thus undermining correct understanding of new notions presented by teachers. This can be avoided by first assessing students' misconceptions of basic Newtonian principles, and then by allowing them to directly compare these misconceptions with Newtonian principles. In this way, students should realize that their predictions were wrong, and can move a step toward the rejection of their own beliefs in favor of the Newtonian system (see Halloun & Hestenes, 1985; McDermott, 1991). Communication of conceptual breakthroughs has always been difficult not only for teachers, but also for eminent scientists. As pointed out by Clement (1982, p. 70), Galileo's dialogs "…represent a marvellous attempt to deal directly with the common preconceptions and prevailing theories of his time at a qualitative level." The efficacy of Galileo's scientific communication lies in the idea of presenting his model in form of live dialogs where a "Galilean thinker" (Salviati) discusses and confutes the misconceptions of a "Ptolemaic thinker" (Simplicio). By analogy, it seems likely that students' understanding of the Newtonian system could be improved by a preliminary discussion and confutation of their own misconceptions.

4.2 Information Integration Theory and Functional Measurement as tools for the assessment of intuitive knowledge of physical events

As mentioned in the previous section, a fundamental part of Physics instruction is the assessment of students' knowledge of basic mechanical principles. This is the first necessary step for the correction of students' misconceptions. Several methods have been used by researchers in order to fulfill this aim. In this section I'm going to illustrate that Information Integration Theory (IIT) and Functional Measurement (FM) are particularly suitable theoretical and methodological frameworks to this end. In the Appendix to this chapter I present IIT model and FM method in more detail. According to IIT, people integrate stimulus information using simple algebraic rules. When required quantitative judgments about social or physical events, people typically integrate the cues available in the stimulus condition according to additive, multiplying, or averaging rules (Anderson, 1981). Many different quantitative judgments are thus supposed to be based on information integration and cognitive algebra. IIT and FM are powerful tools for investigating Naïve Physics because the behavior of physical objects in our environment is determined by multiple causality. For instance, suppose that an object travels along an inclined plane: its travelling time depends on the ratio between its starting position along the incline and the slope of the inclined plane. Survival in such an environment requires information integration. Even though it cannot be assumed that people integrate stimulus information according to the laws of Mechanics, it is reasonable to suppose that information integration is a general mode of perception and cognition (Anderson, 1983). Moreover, because several physical laws (e.g., Newton's laws of motion) are formalized as simple algebraic rules, IIT and FM are powerful tools for directly comparing cognitive and physical rules, thus unifying intuitive and symbolic knowledge.

In a typical Naïve Physics experiment with FM method, participants are presented with a real or virtual simulation of a physical event. The experimenter manipulates independent variables (e.g., physical variables such as velocity, force, mass, etc.) according to a factorial design. Participants are required a quantitative prediction of one or more variables of interest, given the combination of values of the independent variables. Participants are generally comfortable with this quantitative judgment task: they know that the magnitude of one variable generally depends on the magnitude of other variables, and thus they find the task quite natural. Function thinking (i.e., thinking in terms of functional dependencies between variables) seems to be a general mode of cognition (Karpp & Anderson, 1997, p. 360).

4.2.1 Assessment of students' knowledge state: A comparison between IIT, FM, and multiple-choice surveys

IIT and FM are especially suitable tools for the assessment of students' understanding of Physics, because they provide a picture-in-depth of each student's knowledge state. I'm going to discuss the advantages of the proposed method by comparing it with the most popular method used for the assessment of students' knowledge of Physics: multiple choice paper-and-pencil surveys. This latter tool is constituted by a verbal and/or graphical description of a physical event, and the student is asked to choose between alternative statements describing the event itself. Suppose that the researcher (or the teacher) wants to evaluate a student's understanding of Physics of inclined planes. When presented with the multiple choice survey, the student may be asked to indicate which one of two objects with different masses will arrive first at the end of a frictionless incline, provided that both objects have the same starting point. Suppose now that the student indicates that the heavier object will arrive first[26]. The researcher infers that the student holds a misconception about the proposed physical situation, because he/she incorrectly believe that mass influences the travelling time of an object falling down an incline (see Champagne, Klopfer, & Anderson, 1980; Halloun & Hestenes, 1985). By contrast, when the same student is tested on the same topic using FM and IIT, he/she is presented with a real or virtual simulation of an inclined plane, and he/she is asked to *predict* the travelling time of an object which falls down the incline. The experimenter manipulates the slope of the inclined plane, the starting point of the object, and the mass of the object. By this means, besides the qualitative observation that mass influences the predicted travelling time, the researcher (or the teacher) is provided with further *quantitative* information concerning the "magnitude" of this misconception: the influence of mass on predicted travelling time can be compared with the influence of the other two variables (starting point and slope). If the effect of mass turns out to be relatively slight, the student might significantly improve with a small amount of training. Vice versa, a deep revision of the fundamental concepts might be required. Moreover, data provide information concerning the cognitive algebraic rule used by the student to integrate the variables. Again, if the

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[26] Students usually show this misconception (see Halloun & Hestenes, 1985).

cognitive algebraic rule is identical to the physically correct integration rule, the student might need only small amounts of training in order to calibrate his/her answer. Otherwise, more drastic solutions would be required. As shown by Anderson (1983), allowing students to directly compare their own predictions with correct data may explicitly clarify their biases, helping them to calibrate their own answers.

It should now be clear that the main advantage of FM and IIT, as compared with multiple choice surveys, resides in the quantitative nature of the former method. As shown by Karpp and Anderson (1997), this advantage is maintained also with respect to more complex and refined versions of multiple choice surveys, which only provide qualitative information about students' knowledge state. To conclude, I would like to emphasize that IIT and FM can reveal important qualitative (not only quantitative) misconceptions of physical principles: Corneli and Vicovaro (2007) used IIT and FM to show that people incorrectly believe that the force required to move an object resting on a surface, and friction between the object and the surface, are different concepts.

4.3 Naïve Physics and realism of the stimulus conditions

One of the major determinants of the congruency between intuitive and formal knowledge of Physics appears to be familiarity with the task. Although people may fail in solving abstract problems, they may still be able to make accurate predictions of physical events in familiar concrete specifications of such problems (Kaiser, Jonides, & Alexander, 1986). Another major determinant of the aforesaid congruency is the realism of stimuli: when people make predictions concerning dynamic events, the use of dynamic animations as stimuli usually improves their performance (Kaiser et al., 1985; Kaiser, Proffitt, Whelean, & Hecht, 1992). The issue is important for Physics instruction: if participants' performance improves with realistic simulations of physical events, then teachers may refer to everyday life experiences to facilitate students' understanding of underlying mechanical principles. This should enhance the transfer of knowledge from concrete to abstract occurrences of the events in question. The topic is interesting also for experimental psychologists, because it is informative about the origin (perceptual vs. cognitive) of misconceptions. If observers' performance improves when realism of the physical simulation increases, this suggests that perception in ecological conditions actually helps correct interpretation of the event (Kaiser et al., 1985; Kaiser et al., 1992). Obviously, this runs counter the hypothesis that misconceptions stem from everyday perceptual experience. On the contrary, when misconceptions persist irrespectively of the realism of the simulated physical event, this may be viewed as a cue in favor of their perceptual origin. As shown by McCloskey, Washburn, and Felch (1983), the so-called “straight-down belief” is independent of the realism of the stimulus condition, thus suggesting that it stems from a visual illusion.

The topic is interesting also for another reason. As pointed out in Section 3.4, researchers in Naïve Physics often manipulate implied mass by manipulating area of abstract 2-D objects (e.g., Legrenzi & Sonino, 1984; Kozhevnikov & Hegarty, 2001; De Sá Teixeira et al., 2008). However, as emphasized in this section, the realism of the stimulus condition is one of the major determinants of the congruency between intuitive and formal knowledge. In the experiments that I’m going to present in this chapter, participants were asked to predict the outcome of horizontal collisions between virtual objects. As the stimuli in my experiments are more familiar and realistic compared with those used in previous experiments on the Naïve Physics of collisions, participants’ performance is expected to be closer to formal Physics than in previous experiments.

4.4 Physics and Naïve Physics of collisions: an introduction

Let us presume that a sphere (*A*) is moving horizontally towards another sphere (*B*) which is stationary, and that their centers of mass lie on a horizontal line (see Figure 1). If this system is isolated (i.e., not subject to external forces), if the spin of the two spheres is ignored, and if the collision is perfectly elastic, then:

$$v_A' = v_A\,(m_A - m_B) / (m_A + m_B) \qquad (5)$$

$$v_B' = 2\,v_A\,m_A / (m_A + m_B) \qquad (6)$$

where v_A' and v_B' are the post-collision velocities of *A* and *B*, v_A is the pre-collision velocity of *A* ($v_B = 0$ because *B* is stationary before the collision), and m_A and m_B are the masses of *A* and *B*. Equations (5) and (6) are derived from Newton’s Third Law of motion (Kittel et al., 1973). Note that according to Equation (5), if $m_A < m_B$, then v_A' is negative, which means that *A* bounces back.

An early study on the Naïve Physics of collisions with stationary 2D stimuli was conducted by Legrenzi & Sonino (1984), who found serious misconceptions about the proposed physical situation. More recently De Sá Teixeira et al. (2008) conducted a study using Functional Measurement and moving 2D stimuli. They showed that participants additively integrate the area and the velocity of a moving square to predict the distance travelled by a stationary square hit by the moving square, instead of the physically correct multiplicative rule[27]. White (2006b; 2009) showed that most observers are prone to ignoring the effect that a stationary object exerts on the post-collision behavior of a moving object colliding with it: this is the *causal asymmetry hypothesis.*

A common feature of the experiments mentioned above is the abstractness of the stimuli presented to participants: 2D objects varying only in velocity and area. The primary aim of my research was to determine whether these misconceptions are due (at least in part) to the abstractness of the stimuli employed. In ordinary life, we are immersed in a 3D environment where collisions usually take place between 3D moving objects differing in size, specific weight, and velocity. The 2D figures used as stimuli in the experiments mentioned above are highly simplified representations of people's everyday experience. Considering that familiarity with the task is one of the major determinants of the congruency between intuitive and formal physics (Kaiser et al., 1986), it is not surprising to find incongruity in experiments carried out with unfamiliar stimuli. Do these misconceptions still occur when people are presented with more naturalistic simulations of collisions? In my experiments, by means of computer graphics, I created a 3D scenario with moving spheres of different size, texture, and velocity. My prediction was that, in such situations, participants' intuitive knowledge would be more congruent with formal Physics than found in previous experiments. However, I did not predict that participants' performance would be perfectly isomorphic to physics: I intended to use FM and IIT as means to assess the degree of consistency between Equations (5) and (6) and cognitive algebraic integration rules.

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[27] The comparison between the additive integration rule of area and velocity and the physically correct multiplicative rule of mass and velocity makes sense only under the assumption that manipulations in area are conceived of as manipulations of implied mass. This assumption was made by De Sá Teixeira et al. (2008), and is common in naïve physics experiments.

4.5 Experiment 1: manipulating implied masses through manipulations of size

4.5.1 Experimental setup

Participants. The participants were 7 male and 13 female students of Psychology, aged between 20 and 26. They all had normal or corrected-to-normal visual abilities and were paid for participation.

Stimuli and Apparatus. The stimuli were presented on a personal computer equipped with a 37.5 cm × 30 cm screen, a mouse, and a keyboard. Figure 9 shows the scenario as it appeared to participants. Participants sat at a distance of about 50 cm from the screen, the background of which was white. A (35.5 cm × 22 cm) 3D animation was displayed in the upper part of the screen, leaving an 8-cm white space under the animation itself. This white space contained a horizontal graduated scale (*response scale*), composed of 30 red rectangular steps, separated by white edges. Numbers from 1 to 30 (from left to right) appeared below the steps of the response scale.

Animation. The animation was created by 3D Studio Max. It represented two 3D spheres on a 3D gray horizontal rectangular table. The background of the animation was black. The spheres were simulated as slightly raised above the table, so that they did not appear to touch its surface[28]. Participants had the impression of being in front of a table and viewing it in perspective. A horizontal graduated scale (*table scale*) composed of 30 red rectangular steps appeared in the middle of the table. Numbers from 1 to 30 (from left to right) appeared below the steps of the table scale. The table scale appeared to be so similar to the response scale that the correspondence between them was obvious. The response scale was intended to be a 2D representation of the table scale. The instructions given to participants also emphasized this correspondence. At the beginning of the animation, one sphere (*A*) appeared close to the left side of the table and the other sphere (*B*) in a central position. Then, 360 milliseconds after the

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[28] If the simulated spheres were resting on the surface of the virtual table, then those which differed in size would have collided off-center. This would have impeded to evaluate the effect of size of both spheres on participants' responses independently of other variables. This implies that the collisions presented here are somewhat idealized, as most of those presented in Physics courses.

appearance of the animation, *A* began to move horizontally from left to right towards *B*, and stopped about 2 mm (measured on the screen) from it. Sphere *A* moved at 8.9, 14.4, or 38.3 cm/s. At the end of the motion, *A* was located between steps 15 and 16 on the *table scale*, and *B* between steps 17 and 18, depending on the size of the two spheres.

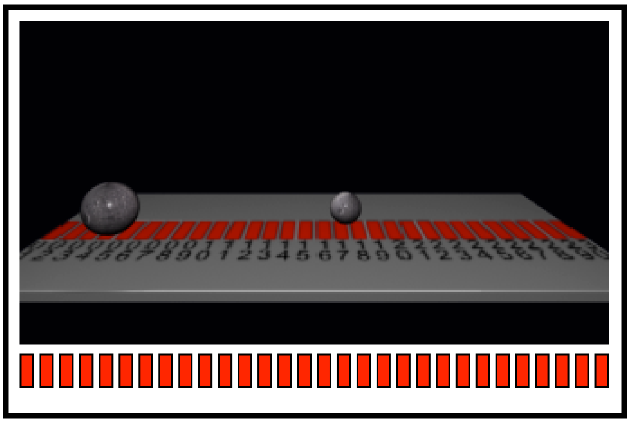

Figure 9: Drawing of one of the stimuli of Experiment 1.

A visual warning signal appeared 500 milliseconds after *A* had stopped moving. This signal was a yellow rectangular bar (23.5 cm × 0.7 cm measured on the screen) which appeared in the middle of the black background of the animation for 2 seconds. The simulated material (iron) of the two spheres was kept constant, so that variations in their implied mass (*IM*) were only obtained by manipulating their size. Their apparent volumes[29] were 4.2, 8.2, or 17.2 cm^3. The velocity of *A* was physically uniform throughout the motion. As shown by Runeson (1974), this kind of physical motion is perceived by observers as slightly decelerated. The two spheres moved without spin.

Procedure and Experimental Design. Participants were told that they would be presented with a video showing an iron sphere moving horizontally towards another iron sphere which was stationary, and that the video originally showed a collision between the two, but the video had been cut just before the collision took place. They were asked to pay attention to the yellow bar (visual warning signal) which appeared in the middle of the dark background after the moving sphere had stopped. Lastly, they should remember that the scale represented on the table (the table scale) corresponded

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[29] The volume of each sphere was calculated by measuring its diameter on the screen.

exactly with that below the video (the response scale). Two stimuli were randomly chosen and presented, in order to familiarize participants with them. Participants were then told that their task was to imagine that the collision between the spheres had really occurred, and to predict the positions they would have reached on the table scale (as if the video had not been cut) when the yellow bar (visual warning signal) appeared. They could watch the sequence as many times as they wanted by pressing SPACE on the keyboard. When they felt ready to answer, they could press ENTER, after which the cursor of the mouse appeared on the response scale below the animation. Participants had to rate the position (on the response scale) of *B* with a first click of the mouse, and the position of *A* with a second click. Four randomly chosen stimuli were then presented as examples. After these practice trials, all participants stated that they understood the task. The experiment followed a 3 (IM_A) × 3 (IM_B) × 3 (v_A)[30] factorial design. The stimuli were presented in random order twice.

4.5.2 Results

The rated positions of *A* (second click of the mouse) and *B* (first click) were analyzed separately.

Position of A. As a paired sample *t*-test showed that the effect of replication was not statistically significant ($t(539) = 0.897$, $p = 0.37$), the two responses were averaged across replications. An important preliminary consideration is that, according to Equation (5), sphere *A* can move after the collision in the same direction as its motion before the collision or, if $m_A < m_B$, it should bounce back. Surprisingly, eight participants (out of 20) did not take this possibility into account, never placing *A* any step backwards from step 15 of the response scale (i.e., the position of *A* when it stops moving). The top left panel of Figure 10 shows the mean rated position of *A*, averaged over its three velocities, as a function of the implied mass of *A* (horizontal axis) for each implied mass of *B* (different lines). The pattern of lines seems to be somewhat inconsistent, since they initially converge and then diverge. Although the position of *A* is proportional to the difference between IM_A and IM_B, no elementary integration rule can be deduced from this pattern of data.

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[30] IM_A = Implied Mass of Sphere *A*, IM_B = Implied Mass of Sphere *B*, v_A = Velocity of Sphere *A*.

The left panel of Figure 11 shows the mean rated position of *A* as a function of the implied masses of *A* and *B* (horizontal axis) for each velocity of *A* (different lines). A family of diverging curves fits the data, supporting a multiplicative rule for the integration of the combined effect of the implied masses and v_A (Anderson, 1981; see the Appendix to the present chapter). Since the implied masses of the two spheres were integrated according to an indefinite rule (top left panel of Figure 10), the left hand panel of Figure 11 supports this overall integration rule:

$$Position\ A = v_A \times f\,(IM_A, IM_B) \qquad (7)$$

where f is an unknown. Equation (3) may be called the *multiplicative-indefinite* integration rule.

According to the guidelines of IIT and FM methodology (see Anderson, 1981; 1982), I performed a three-way ANOVA on the mean rated position of sphere *A* in order to test Equation (7)[31]. Within-participants factors were the implied mass of sphere *A* (IM_A), the implied mass of sphere *B* (IM_B), and the velocity of sphere *A* (v_A). Two main effects of two factors were significant: IM_A ($F(2,38) = 14.36$, $p = 2.27 \times 10^{-5}$), and IM_B ($F(2,38) = 19.76$, $p = 1.31 \times 10^{-6}$). v_A was not significant ($F(2,38) = 2.4$, $p = 0.1$). The $IM_B \times v_A$ interaction was significant ($F(4,76) = 3.54$, $p = 0.01$), the linear-by-linear trend component of the interaction being the only significant one ($F(1,76) = 13.56$, $p = 0.0004$). The $IM_A \times v_A$ interaction was marginally significant ($F(4,76) = 2.43$, $p = 0.055$), the linear-by-linear trend component of the interaction being the only significant one ($F(1,76) = 8.96$, $p = 0.004$). No other interaction effects were significant. This pattern of statistical results supports Equation (7) (see Anderson, 1982, p. 117).

A basic assumption of IIT and FM methodology is that each individual integrates the available information using some kind of cognitive integration rule. In some cases, the cognitive integration rule subtended by group data may not reflect individual cognitive integration rules, but rather it may be due to averaging effects. For this reason, individual data were plotted in the same manner as group data, and visual

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[31] A basic assumption of IIT and FM is that the form of cognitive integration rules is revealed by the shape of factorial graphs (see the Appendix at the end of this chapter). Statistical analysis is conceived as a means to support what emerges from the observation of factorial graphs.

inspection of the graphs indicated that only three participants integrated the variables in accordance with Equation (7). Among the remaining participants, six used an *IM*-only integration rule, ignoring v_A, four used a v_A-only integration rule, ignoring the implied masses of the two spheres, four always placed *A* on the same step of the scale, and three seemed to respond at random.

Position of B. As a paired sample *t*-test showed that the effect of replication was not statistically significant, ($t(539) = -0.516$, $p = 0.57$), the two responses were averaged across replications. The top right panel of Figure 10 shows the mean rated position of *B*, averaged over the three velocities of *A*, as a function of the implied mass of *A* (horizontal axis) for each implied mass of *B* (different lines). The lines converge upwards-right. The unequal weights averaging model may account for this pattern of deviation from parallelism (Anderson, 1981, p. 67). The right hand panel of Figure 11 shows the mean rated position of *B* as a function of the implied masses of *A* and *B* (horizontal axis) for each velocity of *A* (different lines). A family of diverging curves fit the data, supporting a multiplicative integration rule between the implied masses of the spheres and the velocity of *A* (Anderson, 1981; see the Appendix to the present chapter). Since the implied masses of the two spheres were integrated according to an averaging rule (top right panel of Figure 10), the right panel of Figure 3 supports this overall *multiplicative-averaging* integration rule:

$$\mathit{Position\ B} = v_A \times (w_0 IM_0 + w_{A\mathrm{i}} IM_{A\mathrm{i}} + w_{B\mathrm{j}} IM_{B\mathrm{j}}) / (w_0 + w_{A\mathrm{i}} + w_{B\mathrm{j}}) \qquad (8)$$

where $IM_{A\mathrm{i}}$ is the implied mass of level *i* of *A*, $IM_{B\mathrm{j}}$ is the implied mass of level *j* of *B*, $w_{A\mathrm{i}}$ is the subjective weight associated with $IM_{A\mathrm{i}}$, $w_{B\mathrm{j}}$ is the subjective weight associated with $IM_{B\mathrm{j}}$, and w_0 and IM_0 are default values (see Anderson, 1981, p. 67).

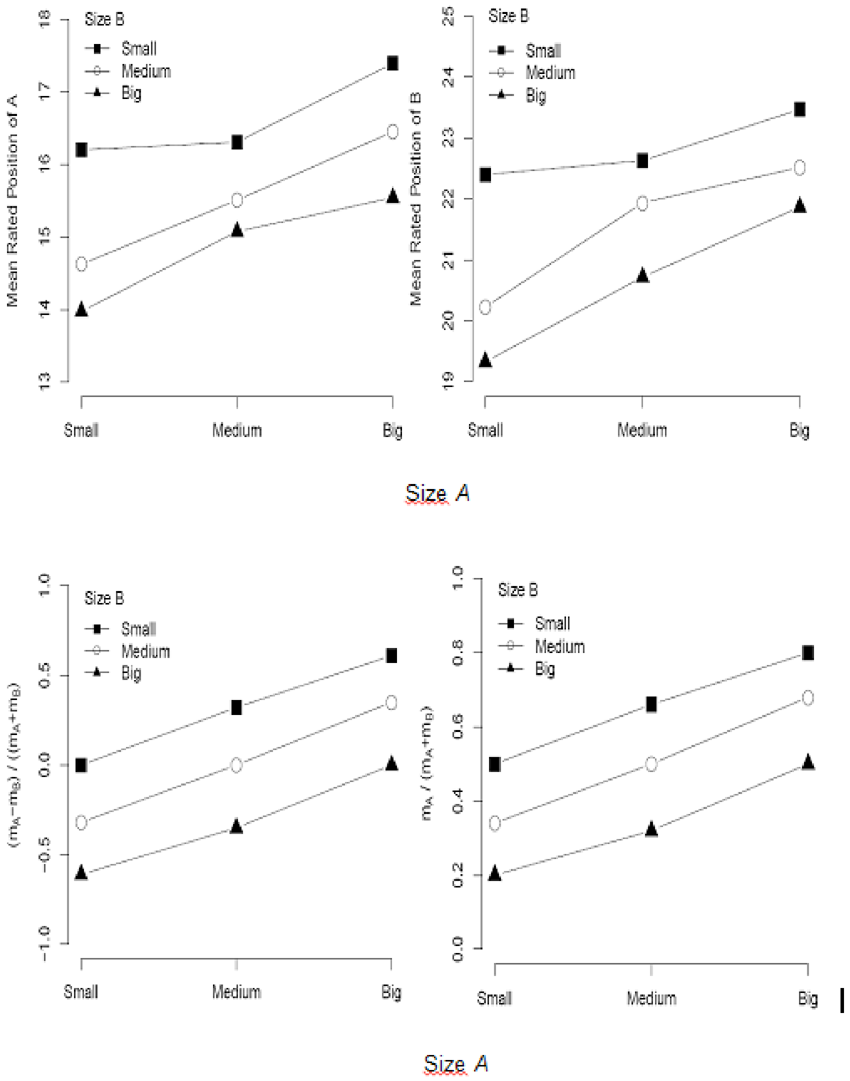

Figure 10: Top panels: Mean rated positions of *A* (top left) and *B* (top right) in Experiment 1, averaged over 3 velocities of *A*, as a function of size of *A* for each size of *B*. Bottom panels: Simulations of Equation (5) (bottom left) and Equation (6) (bottom right) as a function of m_A (horizontal axis) for each m_B (different lines) with v_A=1.

I performed a three-way ANOVA on the mean rated position of sphere *B* in order to test Equation (8). Within-participants factors were the implied mass of sphere *A* (IM_A), the implied mass of sphere *B* (IM_B), and the velocity of sphere *A* (v_A). All the main effects of all factors were statistically significant: IM_A ($F(2,38) = 34.7$, $p = 2.67 \times 10^{-9}$), IM_B ($F(2,38) = 57.58$, $p = 3.15 \times 10^{-12}$), and v_A ($F(2,38) = 75.38$, $p = 5.94 \times 10^{-14}$). All two-factor interactions were significant: $IM_A \times IM_B$ ($F(4,76) = 7.19$, $p = 5.71 \times 10^{-5}$), $IM_A \times v_A$ ($F(4,76) = 5.69$, $p = 0.0005$), and $IM_B \times v_A$ ($F(4,76) = 8.53$, $p = 9.75 \times 10^{-6}$). The three-factor interaction $IM_A \times IM_B \times v_A$ was also significant ($F(8,152) = 4.59$,

$p = 4.96 \times 10^{-5}$). This pattern of statistical results supports Equation (8) (see Anderson, 1982, p. 117).

Individual data were plotted in the same manner as group data, and visual inspection of the graphs indicated that only seven participants consistently integrated the variables according to Equation (8). Of the remaining participants, six used an *IM*-only integration rule, ignoring v_A, four used a v_A-only integration rule, ignoring the implied masses of the two spheres, and three seemed to respond at random.

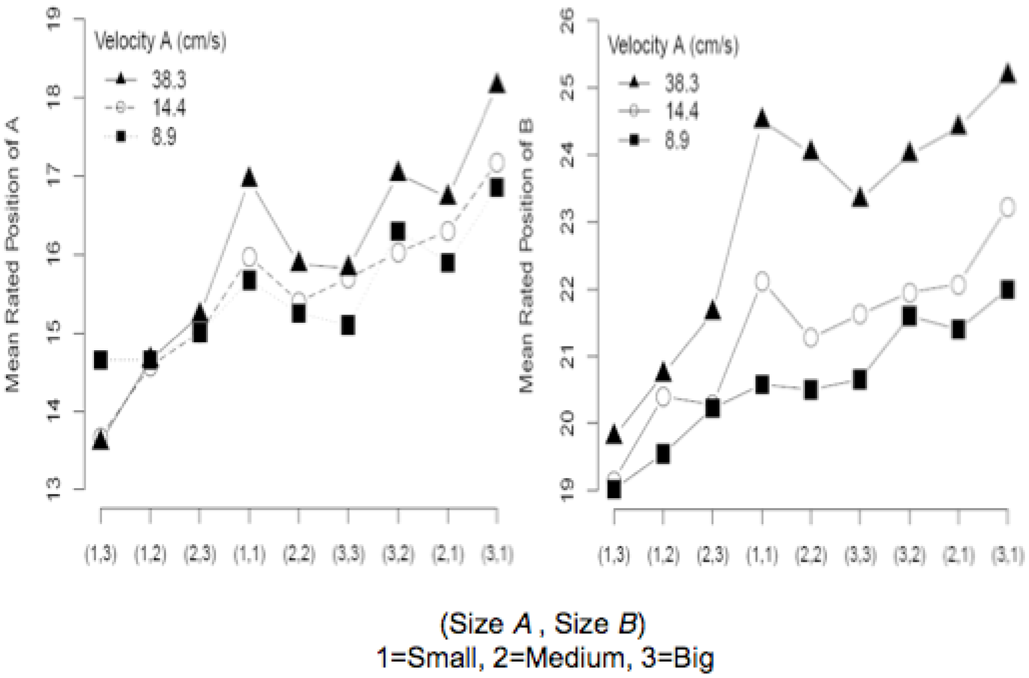

Figure 11. Mean rated positions of *A* (left) and *B* (right) in Experiment 1 as a function of sizes of *A* and *B* for each velocity of *A*. Since mean rated positions of *A* and *B* were both proportional to difference between Size *A* and Size *B*, I ordered pairs (Size *A* , Size *B*) on the abscissa trying to obtain approximately monotone trends.

4.5.3 Discussion

Participants were asked to rate the positions that both spheres would reach after a fixed time interval (500 ms) from the imagined collision (i.e., when the yellow bar appeared). This procedure is the easiest way of estimating the imagined post-collision velocities of the spheres. It was reasonably assumed that the rated positions were linear functions of imagined velocities: this would support the linearity of the response and facilitates comparisons between Equations (5) and (6) and cognitive integration rules.

This assumption rests on the hypothesis that the fixed time interval from the imagined collision to the appearance of the yellow bar was always perceived as being the same during the course of the experiment. There is no clear reason to believe that this hypothesis is not true[32].

The bottom left and right panels of Figure 10 show simulations of Equations (5) and (6), respectively as functions of m_A (horizontal axis) for each m_B (different lines) with $v_A = 1$, as if the two spheres were real material spheres with density 8 g/cm^3 (mean physical density of iron), with volumes of 4.2, 8.2, and 17.2 cm^3. Note that the two bottom panels are very similar to each other, both having a slightly slanted barrel pattern. This suggests that Equations (5) and (6) are substantially similar. The only notable difference between them is that Equation (5) accounts for negative values: if $m_A < m_B$, then the post-collision velocity of *A* is negative, i.e., *A* bounces back. When $v_A = 1$, Equations (5) and (6) may both be considered as instances of the general ratio integration rule (Anderson, 1981, p. 77).

Figure 10 allows us to compare the cognitive integration rules for the implied masses of *A* and *B* (top left and top right panels, respectively) with the physically correct ratio integration rules as formalized by Equations (5) and (6) (bottom left and bottom right panels respectively). The most striking differences appear between the cognitive and the physical integration rules for *A*. While Equation (5) predicts a slight upwards-right convergence of the lines according to a slanted barrel pattern (bottom left panel of Figure 10), the lines of the functional graph in the top left panel initially tend to converge and then to diverge. In addition to the notable differences concerning the integration rule, eight participants never considered the possibility that *A* could bounce back after the collision. Some differences also appear between the cognitive and physical integration rules for *B*. Equation (6) predicts a slight upwards-right convergence of the lines according to a slanted barrel pattern (bottom right panel of

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[32] This does not mean that the imagined post-collision velocity is a linear function of the theoretically correct physical velocity. If we presume that the participants imagined the spheres were subject to friction, the imagined velocity would be a non-linear negatively accelerated function of physical velocity. This is not essential for a discussion of the results.

Figure 10). This also appears in the top right panel, but the slanted barrel does not appear.

In sum, it seems that the greatest misconceptions about collision effects concern the post-collision behavior of *A*. Research on the perception of collision effects supports this tenet: O'Sullivan (2005) and Reitsma & O'Sullivan (2009) presented 3D collisions between simulated spheres to their participants, and reported that they are less sensitive to post-collision anomalies of the initially moving sphere with respect to those of the initially stationary sphere. White (2009) reported that perceived forces in collisions are asymmetrical: we perceive the force exerted by the moving object on the stationary one, but not vice versa. Despite these misconceptions, the intuitive physics of collisions as shown by the participants in Experiment 1 is definitely more consistent with normative physics than that of the participants in previous analogous experiments in the literature. For example, both cognitive integration rules concerning the predicted positions of *A* and *B* (as expressed by Equations (7) and (8)) show a multiplicative integration rule between the combined effect of the implied masses and v_A, whereas De Sá Teixeira et al. (2008) found that area and velocity were combined additively. Thus, 3D (realistic) stimuli rather than 2D (abstract) ones seem to improve participants' overall performances.

One explanation for the discrepancies found in Experiment 1 between cognitive and physical integration rules is the relatively small range of variation of the implied masses of the two spheres. In Experiment 1, the variations of the implied masses were only obtained by varying the sizes of the two spheres. To test this hypothesis, a second experiment used spheres differing in both size and simulated material (texture).

4.6 Experiment 2: manipulating implied mass through manipulations of simulated material and size

4.6.1 Experimental setup

Participants. Participants were 5 male and 15 female students of Psychology, aged between 20 and 26. They all had normal or corrected-to-normal visual abilities and were paid for participation. None had participated in Experiment 1.

Stimuli and Apparatus. The stimuli and apparatus were the same as those in Experiment 1, except that manipulation of the implied masses of the two spheres was carried out by varying both size and simulated material (texture) according to a 2 (*Texture*) × 2 (*Size*) factorial design. Two possible photographic textures were assigned to each sphere, one depicting iron (the same as in Experiment 1) and the other depicting polystyrene. In both cases, the reflectance of the spheres was manipulated to increase the realism of the photographic texture. When asked, all participants clearly identified the simulated material of the spheres. The apparent volumes of the spheres were either 4.2 or 17.2 cm^3. The pre-collision velocity of *A* was either 12.2 or 25.9 cm/s. In sum, there were four different implied masses of the spheres and two different pre-collision velocities of *A*.

Procedure and Experimental Design. The procedure was the same as that in Experiment 1, except that participants were told that the spheres in the video could be made of either iron or polystyrene. The experiment obeyed a 4 (IM_A) × 4 (IM_B) × 2 (v_A) factorial design. The stimuli were presented in random order twice.

4.6.2 Results

The rated positions of *A* (second click of the mouse) and *B* (first click) were analyzed separately.

Position of A. As a paired sample *t*-test showed that the effect of replication was not statistically significant ($t(639) = 0.4$, $p = 0.69$), the two responses were averaged across replications. As in Experiment 1, an important preliminary consideration was the number of participants – ten – who did not consider the possibility of *A* bouncing back. The top left panel of Figure 12 shows the mean rated position of *A*, averaged over the two velocities of *A*, as a function of the implied mass of *A* (horizontal axis) for each implied mass of *B* (different lines). The slanted barrel pattern supports a ratio integration rule for the implied masses of the two spheres (see Anderson, 1981, p. 77). The top panel of Figure 13 shows the mean rated position of *A* as a function of the implied masses of *A* and *B* (horizontal axis) for each velocity of *A* (different lines). Two diverging curves fit the data, supporting a multiplicative integration rule between implied masses and the velocity of A (Anderson, 1981; see the Appendix to the present chapter). Since the implied masses of the two spheres were integrated according to a ratio rule (top left panel of Figure 12), the top panel of Figure 13 supports this overall *multiplicative-ratio* integration rule:

$$Position\ A = v_A \times IM_A / (IM_A + IM_B) \quad (9)$$

I performed a three-way ANOVA on the mean rated position of sphere A in order to test Equation (7). Within-participants factors were the implied mass of sphere A (IM_A), the implied mass of sphere B (IM_B), and the velocity of sphere A (v_A). The main effects of all factors were statistically significant: IM_A ($F(3,57) = 24.0$, $p = 3.58 \times 10^{-10}$), IM_B ($F(3,57) = 26.8$, $p = 6.06 \times 10^{-11}$), and v_A ($F(1,19) = 16.14$, $p = 7.35 \times 10^{-4}$). All two factor interactions were significant: $IM_A \times IM_B$ ($F(9,171) = 4.02$, $p = 1.08 \times 10^{-4}$), $IM_A \times v_A$ ($F(3,57) = 3.32$, $p = 0.026$), and $IM_B \times v_A$ ($F(3,57) = 10.43$, $p = 1.44 \times 10^{-5}$). The three-factor interaction $IM_A \times IM_B \times v_A$ ($F(9,171) = 0.91$, $p = 0.52$) was not significant. According to Anderson (1982, p. 117) the three-factor interaction would be indispensable for statistical validation of Equation (9). This incongruence for the *multiplicative-ratio* model was probably due to the use of a wide range of variation of implied masses and a relatively narrow range of variations of velocity of A. Despite this statistical flaw, Equation (9) seems the best way to represent the data.

Individual data were plotted in the same manner as group data, and visual inspection of the graphs revealed that eight participants integrated the variables according to Equation (9). Among the remaining participants, seven used an implied masses-only integration rule, ignoring v_A, and five seemed to respond at random. Interestingly, the integration rule adopted by each participant was independent of considering possible bouncing back of sphere A. Some participants did consider it, but responded without applying a definite integration rule; others did not consider the possible bouncing back of A and nevertheless used the *multiplicative-ratio* rule of Equation (9).

Position of B. As a paired sample t-test showed that the effect of replication was not statistically significant, ($t(639) = -0.893$, $p = 0.37$), two responses were averaged across replications. The top right panel of Figure 12 shows the mean rated position of B, averaged over the two velocities of *A*, as a function of the implied mass of *A* (horizontal axis) for each implied mass of *B* (different lines). The slanted barrel pattern supports a ratio integration rule for the implied masses of the two spheres (see Anderson, 1981, p. 77). The bottom panel of Figure 13 shows the mean rated position of *B* as a function of the implied masses of *A* and *B* (horizontal axis) for each velocity of *A* (different lines). Two diverging curves fit the data, supporting a multiplicative integration rule between implied masses and the velocity of *A* (Anderson, 1981; see the Appendix to the present chapter). Since the implied masses of the two spheres were integrated according to the ratio rule (top right panel of Figure 12), the bottom panel of Figure 13 supports the following overall *multiplicative-ratio* integration rule:

$$Position\ B = v_A \times IM_A / (IM_A + IM_B) \tag{10}$$

I performed a three-way ANOVA on the mean rated position of sphere *B* in order to test Equation (10). Within-participants factors were the implied mass of sphere *A* (IM_A), the implied mass of sphere *B* (IM_B), and the velocity of sphere *A* (v_A). The main effects of all factors were statistically significant: IM_A ($F(3,57) = 79.9$, $p < 2.2 \times 10^{-16}$), IM_B ($F(3,57) = 94.6$, $p < 2.2 \times 10^{-16}$), and v_A ($F(1,19) = 32.07$, $p = 1.85 \times 10^{-5}$). All two factor interactions were significant: $IM_A \times IM_B$ ($F(9,171) = 7.73$, $p = 1.66 \times 10^{-9}$), $IM_A \times v_A$ ($F(3,57) = 3.14$, $p = 0.032$), and $IM_B \times v_A$ ($F(3,57) = 19.87$, $p = 6.12 \times 10^{-9}$). The three-factor interaction $IM_A \times IM_B \times v_A$ ($F(9,171) = 1.63$, $p = 0.11$) was not significant. Like the statistical validation of Equation (9), the lack of the three-factor interaction is probably due to the wide range of variation of implied masses and relatively narrow range of variations of velocity of *A*. Despite this flaw, this pattern of statistical results supports Equation (10) (see Anderson, 1982, p.117).

Individual data were plotted in the same manner as group data, and visual inspection of the graphs revealed that twelve participants integrated the variables according to Equation (10). Of these twelve, six had only a slight effect of variable v_A. Of the remaining participants, five used an implied-masses integration rule, ignoring the velocity of *A*, and three seemed to respond at random.

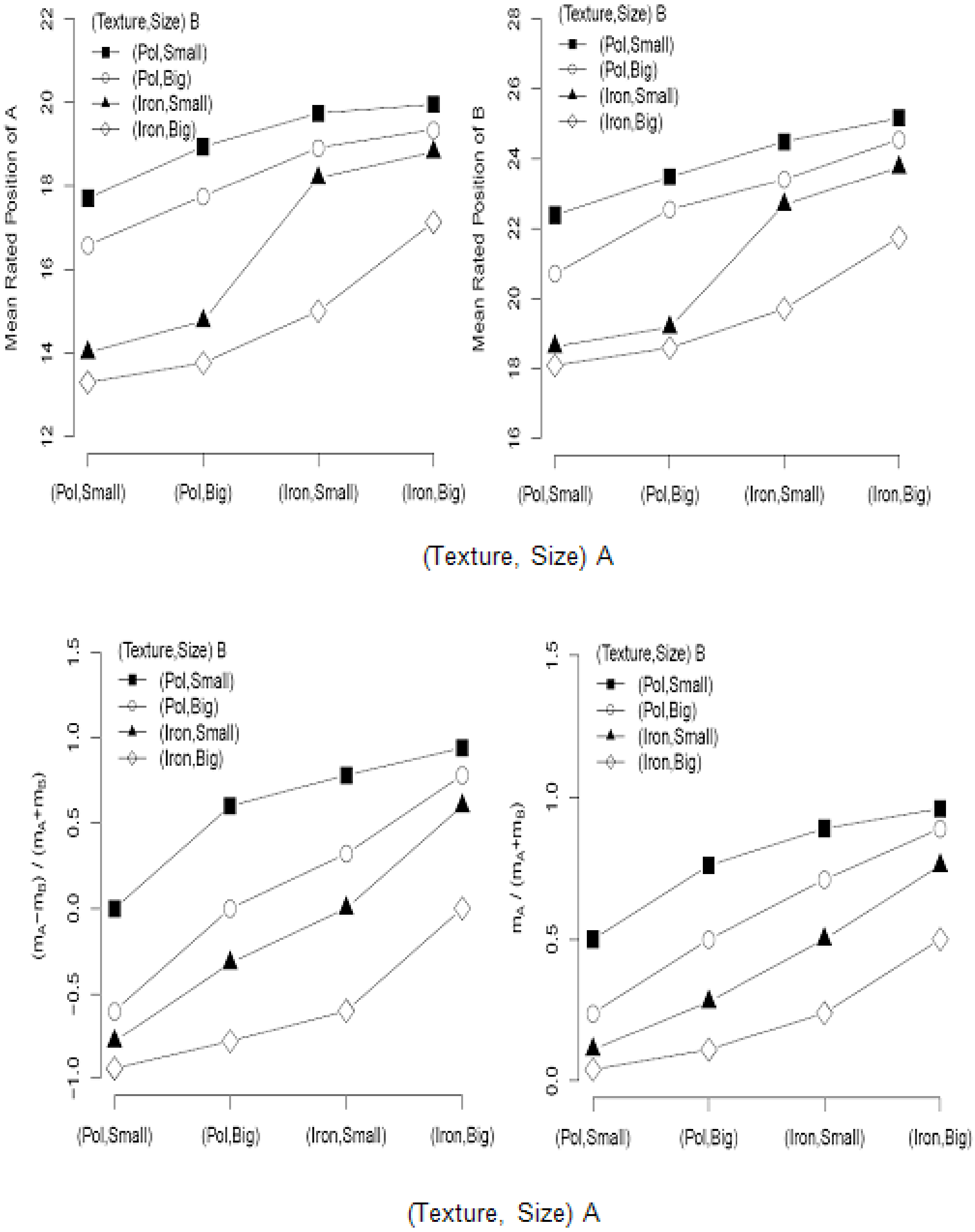

Figure 12: Top panels: Mean rated positions of *A* (top left) and *B* (top right) in Experiment 2, averaged over 2 velocities of *A*, as a function of implied mass of *A* for each implied mass of *B*. Bottom panels: Simulations of Equation (5) (bottom left) and Equation (6) (bottom right) as a function of m_A (horizontal axis) for each m_B (different lines) with $v_A = 1$.

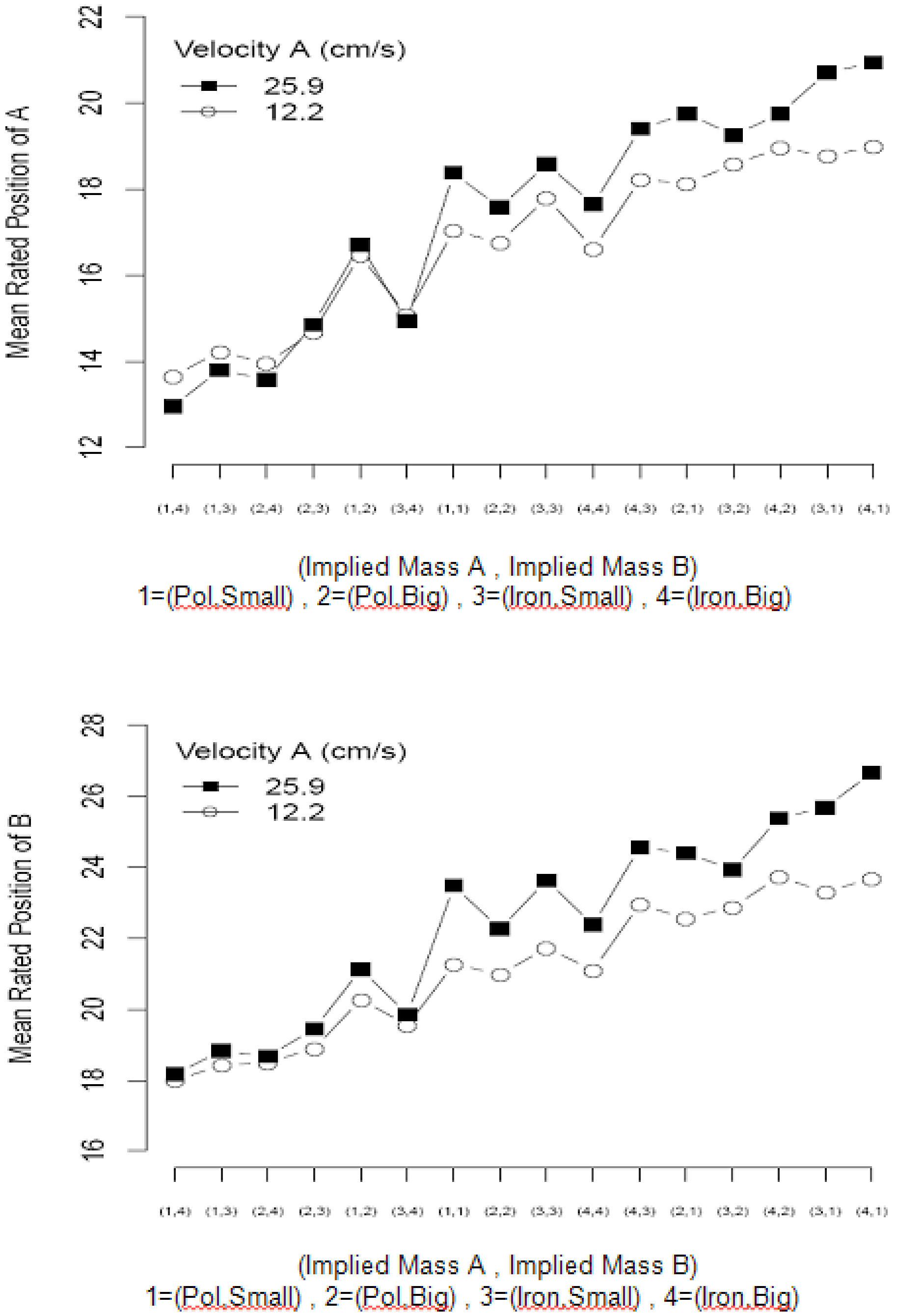

Figure 13. Mean rated positions of *A* (top) and *B* (bottom) in Experiment 2 as a function of implied masses of *A* and *B* for each velocity of *A*. Since mean rated positions of *A* and *B* were both proportional to difference between implied mass of *A* and implied mass of *B*, I ordered pairs (Implied Mass *A* ,Implied Mass *B*) on the abscissa trying to obtain approximately monotone trends.

4.6.3 Discussion

As in Experiment 1, in this second experiment I assumed that the rated positions of the two spheres is a linear function of their imagined post-collision velocity (see Section 4.5.3 and Note 32). The bottom left and right panels of Figure 12 show simulations of Equation (5) and (6), respectively as functions of m_A (horizontal axis) for each m_B (different lines) with v_A=1, as if the two spheres were real material spheres of density 8 g/cm^3 (the mean physical density of iron) or 1 g/cm^3 (the mean physical density of polystyrene), with volume of 4.2 or 17.2 cm^3. Figure 12 allows us to compare the cognitive integration rules for the implied

masses of *A* and *B* (top left and top right panels, respectively) with the physically correct ratio integration rules as formalized by Equations (5) and (6) (bottom left and bottom right panels, respectively). All four panels show a slanted barrel pattern, supporting the idea that participants used a physically correct ratio integration rule to integrate the implied masses of the spheres in order to predict the positions of *A* (top left panel) and *B* (top right panel) (see Anderson, 1981, p.77). However, some deviations do appear. The most conspicuous difference between the top and bottom panels is the non-parallelism of the second and third curves (from top) in the top panels. In particular, the rate of growth of these curves is not constant, as predicted by the ratio models shown in the bottom panels. The two curves are steeper when the implied mass of *A* (horizontal axis) is less than or equal to the implied mass of *B* (different lines), but are flatter when the implied mass of *A* is greater than that of *B*. Note that the physically correct ratio rules (Equations (5) and (6)) predict that the effect of a constant increase in the mass of *A* on the post-collision velocity of *B* decreases as the absolute difference between the masses of *A* and *B* increases. Thus participants have emphasized the physically correct ratio rule.

4.7 General discussion

The main findings of the above experiments may be summarized as follows:

(1) The data of these two experiments strongly indicate that, whether cognitive integration rules are isomorphic to physical rules or not, people are generally able to

integrate various stimulus cues (e.g., velocity and implied masses) to make predictions about physical situations (Anderson, 1983). Proffitt and Gilden (1989, p. 384) argued that "…people make judgments about natural object motions on the basis of only one parameter of information that is salient in the event...". By contrast, the results of the present experiments show that people are able to take into account different sources of information in making predictions about dynamic events.

2) The extent of the misconceptions found in previous experiments on intuitive physics of collision effects (Legrenzi & Sonino, 1984; De Sá Teixeira et al., 2008) is connected to abstract 2D stimuli. Although the participants in the present experiments showed some remarkable misconceptions, their overall performance (particularly in Experiment 2) was definitely more aligned with normative physics than that of participants in earlier experiments in the literature (note in particular the physically correct multiplicative integration rule between the velocity of *A* and the combined effect of the implied masses, which was found for both spheres in both experiments).

(3) The general cognitive integration rule for the post-collision position of *A* changed from the physically wrong multiplicative-indefinite rule of Experiment 1 to the physically correct multiplicative-ratio rule of Experiment 2. In addition, the number of participants who used the physically correct multiplicative-ratio rule to rate the post-collision positions of both spheres was larger in Experiment 2. This sounds like a warning to researchers on intuitive physics: functional knowledge varies as the nature of the stimuli varies. Some misconceptions about physical situations in which the masses of stimuli are important, may be due to the narrow range of variations in implied mass as induced by variations in the area of 2D stimuli.

(4) The results of both Experiments 1 and 2 showed that rating the position of *A* was the hardest task for participants. Previous research on the perception of collision effects is consistent with this finding (O'Sullivan, 2005; White, 2009).

(5) One striking misconception that cannot be avoided using realistic 3D stimuli is the failure to consider (by about half the participants) the possibility of *A* bouncing back. Surprisingly, some of the participants who ignored the possible bouncing back of *A* still used the physically correct *multiplicative-ratio* rule of Equation (9). This

suggests that the possibility of *A* bouncing back is independent of the cognitive integration rule.

(6) With few exceptions, in these experiments both participants who ignored the possibility of *A* bouncing back and those who did consider it used some algebraic rules involving the properties of both spheres to predict the post-collision position of *A*. One of the main tenets of White's "causal asymmetry hypothesis" (White, 2006; 2009) is that, in a collision event, we are generally prone to ignoring the effect that the stationary sphere (*B* here) exerts on the post-collision behavior of the moving sphere (*A* here). The results of the present experiments suggest that this was not the case.

4.7.1 Insights for teaching Physics of collisions

One of the main challenges in teaching elementary physics regards closing the gap between what is taught and what is learned (McDermott, 1991). An unavoidable requirement for this is to identify the actual status of students' knowledge. Differences between cognitive integration rules and normative physical rules should be the starting point to modify students' status of knowledge, until their functional knowledge becomes reasonably similar to the rules of physics.

FM and IIT provide a unique contribution in this regard, for they allow assessment of the functional knowledge of each single student (Karpp & Anderson, 1997). The data of the experiments presented here, indicate that the assessment of functional knowledge of the physical world is facilitated by using naturalistic stimuli. They also provide useful insights for teaching the physics of collisions. One of these is that physics teachers should focus on the post-collision behavior of the moving sphere (*A* here), and in particular on the possibility of its bouncing back. Participants who apply the correct *multiplicative-ratio* rule but ignore the possibility of *A* bouncing back probably only need to be informed about this fact, whereas participants applying a physically wrong integration rule probably need more practice in order to improve their functional knowledge.

Appendix: Information Integration Theory and Functional Measurement

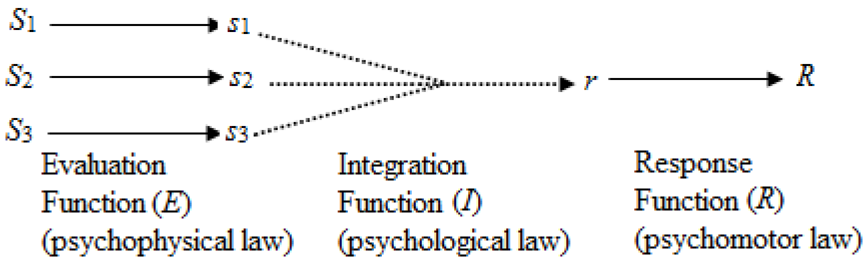

Figure 14: diagram representing the theoretical basis of Information Integration Theory.

The diagram depicted in Figure 14 outlines the core structure of Information Integration Theory (IIT) (Anderson, 1981). The first step is the *Evaluation Function*, which converts stimulus S_i into its corresponding psychological representation s_i. In Psychophysics, S_i is the physical stimulus, s_i is the sensation, and function E is the psychophysical law. However, here the concept of evaluation is more general because it can be applied also to symbolic or verbal stimuli, which do not have a physical metric. The second step is the *Integration Function*: psychological variables s_i are integrated into a unitary psychological (unobservable) response r. In the third step (*Response Function*), the implicit response r is converted into the explicit response R, which can be observed and registered by the experimenter. IIT is based on four fundamental and interrelated concepts: *stimulus evaluation*, *stimulus integration*, *cognitive algebra*, and *Functional Measurement*.

Evaluation. Evaluation refers to the process of extraction of information relevant for the task from the context. The main characteristic of the Evaluation Function is its constructive nature: people assign psychological values to the available stimuli through a constructive process, the results of which are difficult to predict a priori (ibid.). According to classical Psychophysics, the magnitude of sensation s depends on sensory processes converting the physical magnitude of stimulus S into the corresponding sensation. Conversely, the implicit assumption of IIT is that psychological values largely depend also on unobservable mental processes. More specifically, the relation between physical stimuli and their corresponding psychological representations depends on individuals' past experience and on the characteristics of the task. The magnitude of psychological variable s depends not only on physical magnitude of stimulus S, but also on the importance assigned by the subject to the stimulus in the specific task.

Because of the variety of subjective and contextual factors involved in the Evaluation Function, methodological difficulties emerge in dealing with this process. According to Anderson (ibid.), it is virtually impossible to investigate the *molecular* processes involved in the Evaluation Function. It is thus necessary to by-pass the problem: IIT meets this requirement because it deals with the Evaluation Function at a *molar* level. Molecular processes are all encapsulated in the magnitude of s, which can be measured using Functional Measurement. Information integration is independent of these values, and can thus be analyzed as a separate problem.

Integration. A number of perceptions, behaviors, and thoughts, depend on multiple stimulus information. Multiple causality can be considered under two different standpoints: *synthesis* and *analysis*. Synthesis is the process by which psychological variables s_i are integrated into a unitary response r. According to IIT, the Integration Function (I) is at the root of this process. Analysis is the reverse of synthesis, i.e., it refers to the decomposition of the unitary response r into its separate components s_i. IIT is primarily focused on synthesis, and thus seeks to determine the characteristics of I. At the same time, Functional Measurement contributes to analysis, because it allows researchers to decompose the observed response into its functional components (see *Functional Measurement* below). The efficacy of this method owes much to the fact that stimulus integration usually follows algebraic models.

Cognitive Algebra. As mentioned above, IIT is primarily focused on the Integration Function (I), i.e., how various psychological variables s_i are integrated into a unitary response r. From Aristotle onward, many students have hypothesized the existence of mental algebraic models, but the development of these models has always been hampered by the problem of psychological measurement. For instance, the hypothesis that two psychological variables s_1 and s_2 are integrated according to an additive rule ($r = s_1 + s_2$), seems impossible to verify without first measuring the three quantities involved (r, s_1, s_2) on real psychological scales (ibid.). Functional Measurement provides a solution to this problem.

Functional Measurement. The quantitative relation between magnitude of physical stimuli and magnitude of the corresponding sensations has always been the main concern of Psychophysics. FM reverses the traditional approach to psychological measurement: the Integration Function is fundamental, and provides the basis for measuring response r. The value of psychological variables s_i is obtained as a by-product of the analysis. Functional Measurement requires the simultaneous solution of three problems: measurement of psychological variables s_i, measurement of implicit response r, and determination of the algebraic form of the Integration Function I. All these entities are unobservable. The *parallelism theorem* and the *linear fan theorem* provide solutions for all these problems.

(i) *Parallelism Theorem*. Suppose that A and B are two independent variables. S_{Ai} is the stimulus corresponding to the i-th level of variable A (where $i = 1, 2,\ldots,n$), and S_{Bj} is the stimulus corresponding to the j-th level of variable B (where $j = 1, 2,\ldots,m$). s_{Ai} and s_{Bj} are their respective psychological counterparts. Suppose that the two independent variables are combined according a factorial design. Such an experimental design can be represented as a factorial matrix where stimuli S_{Ai} are placed in rows and stimuli S_{Bj} are placed in columns. Cell ij of the matrix represents the combination of stimuli (S_{Ai},S_{Bj}). The response to this combination of stimuli is denoted by r_{ij}. This implicit response should be linked to explicit response R_{ij}: it is conveniently assumed that overt response R_{ij} is a linear function of covert response r_{ij}. Thus, $R_{ij} = C_0 + C_1r_{ij}$, where C_0 and C_1 are the parameters of this linear function. Data should be represented on a *factorial graph,* which is a standard format in which each point represents a cell of the factorial matrix mentioned above: stimuli in columns are represented on the horizontal axis, stimuli in rows are represented as separate curves, and response R_{ij} is represented on the vertical axis. If the additive model is true, and if the overt response is a linear function of the covert response, then the factorial graph will exhibit a parallel pattern[33]. Moreover, marginal means of the rows of the factorial matrix will provide an interval scale of psychological variable s_A, whereas marginal means of the columns of the factorial matrix will provide an interval scale of psychological variable s_B. A test of parallelism, and thus a test of the additive model can be carried out by means of simple

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[33] Observed parallelism refers to parallelism between the curves in the factorial graph.

observation of the graph, and supported by some simple statistical tests (Anderson, 1981; 1982). The parallelism theorem allows the researcher to achieve three aims: first, to support the additive integration model, second, to support the linearity of the response function, and third, to obtain interval scales of the psychological variables.

(ii) *Linear Fan Theorem*. Physical laws are typically multiplicative rather than additive. In order to test whether cognitive algebraic rules in Naïve Physics tasks are similar to physical laws, a method for testing multiplicative cognitive integration rules seems required. The Linear Fan Theorem can be used for testing whether the multiplicative integration function ($r_{ij} = s_{Ai}\ s_{Bj}$) is a valid model for the task at hand. If the multiplicative integration rule is true, and overt response is a linear function of covert response, then the factorial graph will exhibit a linear fan pattern. Marginal means of the rows of the factorial matrix will provide an interval scale of psychological variable s_A, whereas marginal means of the columns of the factorial matrix will provide an interval scale of psychological variable s_B. There is a notable difference between the linear fan theorem and the parallelism theorem: a test of the former requires that psychological (functional) rather than physical values of the manipulated variables are represented on the factorial graph. This can easily be done, because according to the theorem itself, these values can be derived from marginal means of rows and columns of the factorial matrix. A test of the linear fan theorem can be carried out by means of observation of the graph, and supported by simple statistical tests (Anderson, 1981; 1982). Observed fan pattern[34] allows the researcher to achieve three aims: first, to support the multiplicative integration model, second, to support the linearity of the response function, and third, to obtain interval scales of the psychological variables.

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[34] Observes fan pattern refers to the layout of the curves in the factorial graph.

Chapter 5

Visual Perception of Virtual Throwing Animations: Applications to Computer Graphics

In this chapter I'm going to present a research on visual perception of virtual throwing animations. The chapter has two distinctive features: on the one hand, the focus is on a complex and rarely studied dynamic event which involves the interaction between a virtual human character and the motion of a virtual inanimate object (a ball). On the other hand, the results of the present research will be discussed in relation to possible applications to Computer Graphics (CG), whereas the general topic of visual perception of dynamic events (see Chapter 1) will be kept on the background[35]. In the introductive part of this chapter, I'm going to discuss the interconnections between visual perception of dynamic events and CG.

5.1 Visual perception of dynamic events in Computer Graphics

As discussed in Chapter 1, visual perception of dynamic events is common in everyday life, and its study has a long tradition in Experimental Psychology. In recent years, thanks to technological development, also virtual simulations of dynamic events have become important parts of our visual experience. Videogames and animated movies are increasingly more realistic and entertaining thanks to collisions, explosions, bounces, and other kinds of dynamic events occurring between virtual objects. A prominent effort of animators working for videogames and movies industry is the improvement of *perceptual realism* of such events. As a general rule, perceived realism increases with the similarity between physical and virtual dynamic events. Unfortunately, perfect isomorphism between physical and virtual dynamic events is difficult to achieve because of budget, computational, and time constraints during the development of movies and videogames. In other words, virtual simulations of dynamic

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[35] The research presented in this chapter originates from a collaboration with the Graphics, Vision, and Visualisation Group, Trinity College Dublin (Ireland). This group works in the field of Computer Graphics and its applications.

events usually deviate, to some extent, from the laws of Mechanics. Fortunately, this does not necessarily compromise their perceived realism: as shown by many researchers in the fields of visual perception and Naïve Physics (see Chapters 1-4), observers may perceive dynamic events as realistic and plausible even when they actually violate the laws of Mechanics. Indeed, as shown, for instance, by Bozzi (1959) and by Kaiser and Proffitt (1987), observers may fail to recognize large distortions in simulations of mechanical events. Of course, the probability that observers will recognize anomalies in virtual simulation of dynamic events increases with the discrepancy between the latter and the corresponding physical events. Importantly, if observers notice anomalies in virtual simulations of dynamic events, then the realism of the whole videogame or animated movie will be compromised. It should now be clear the reason why an important part of research in CG regards measurement of observers' sensitivity to physical distortions in virtual dynamic events. These measures should provide guidelines for the construction of perceptually plausible animations (Barzel, Hughes, & Wood, 1996).

In recent years, researchers in Computer Graphics have become interested in evaluating how much a physically correct animation can be *modified* and *still* look perceptually *plausible* (Barzel et al., 1996). Understanding whether observers are sensitive to physical distortions in mechanical events is important in order to develop plausible simulations while saving time on details that observers cannot perceive. For instance, the behavior of a single inanimate object (Kaiser et al., 1992; Nusseck, Lagarde, Bardy, Fleming, & Bülthoff, 2007), and sensitivity to errors in 3D rigid body collisions between simple objects (O'Sullivan, Dingliana, Giang, & Kaiser, 2003; Reitsma & O'Sullivan, 2009) have been investigated. Motion capture has also been used to evaluate observers' sensitivity to errors in the motion of virtual human characters (Chaminade, Hodgins, & Kawato, 2007), or in physical interactions between virtual characters (Hoyet et al., 2012). Reitsma, Andrews, and Pollard (2008) compared observers' ability to detect errors in the ballistic motion of a virtual human character and of a virtual ball, and found greater sensitivity to variations in the coefficient of gravity when the actor was a human character. Majkowska and Faloutsos (2007) also studied observers' sensitivity to errors in aerial human motions, and found that subjects were not sensitive to even significant changes in angular momentum during ballistic motion.

5.2 Visual perception of human motion with realistic virtual characters

As mentioned in the brief review presented above, human motion constitutes an important part of CG because videogames and animated movies are populated by virtual human (or humanoid) characters which interact with their environment. The study of visual perception of human motion has a long tradition in Experimental Psychology[36], originating with the seminal work of Gunnar Johansson (1973). As shown by many researchers, observers can finely recognize human figures and the actions they perform (e.g., walking, running, jumping, etc.) when presented with impoverished stimuli constituted of simple points of light moving on a uniform background (the so-called "point-light displays"). Visual perception of biological motion is extremely refined as observers can recognize intrinsic attributes of human figures (point-light displays) such as their gender, expectation, and deceptive intention (Runeson & Frykholm, 1983). It is important to note that, like experimental research on phenomenal causality (see Chapter 1), also experimental research on biological motion has been conducted using highly simplified stimuli.

Results of experiments on visual perception of biological motion are important sources of knowledge for animators. However, virtual human characters in videogames and animated movies are not constituted by simple points of light, but rather present highly realistic features which make them similar to real humans. Chaminade et al. (2007) showed that observers' *sensitivity* to physical distortions in human motion *increases* with realism of the geometric model used for the virtual human character. This suggests that results obtained in experiments conducted with point-light displays may not generalize to more realistic stimulus conditions. In other words, guidelines for the creation of realistic virtual human characters in CG should be provided by experiments which use realistic virtual human characters as stimuli. This could help animators to create virtual characters moving realistically, while saving time on details

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[36] This kind of study is generally defined, in the context of Experimental Psychology, as "visual perception of Biological Motion".

that observers cannot perceive. As discussed in the previous section, researchers in CG have recently started on this path (e.g., Majkowska & Faloutsos, 2007; Reitsma et al., 2008; Hoyet et al., 2012). This has been possible thanks to Motion Capture technique, which I'm going to discuss briefly in the following section.

5.2.1 Motion Capture technique: a brief introduction

Motion Capture is an important CG technique which is mainly used by animators for the construction of virtual human characters in videogames and animated movies. Recently, researchers have started using this technique in order to build realistic stimuli for experiments on visual perception of human motion. The technical equipment associated with Motion Capture is constituted, first, by a set of infrared cameras conveniently arranged in an empty room; second, by a black suit provided with a variable number of markers; third, by a software for the construction of virtual animations. In brief, the procedure for using this technique can be divided into the following steps: first, a real actor wearing the black suit provided with markers performs a series of actions which are recorded by the infrared cameras[37]. Then, by means of appropriate software, recorded actions are transformed into virtual animations. Figure 15 may help to illustrate the procedure. Virtual animations built using Motion Capture technique are called "captured motions".

5.3 Motion editing and the perceptual realism of virtual animations

Typically, virtual characters in modern videogames and animated movies perform a huge number of virtual actions. For instance, in American Football videogames (e.g., EA Sports Madden NFL^{TM}, Sony CE MLB 12: The Show^{TM}, 2K Sports NBA 2K12^{TM}), virtual players can throw the ball with various styles and in many different locations in the playing field. If these videogames were built using Motion Capture technique only (i.e., only using captured motions), an enormous number of real actions should be recorded and transformed into virtual animations. However, animation budget constraints during the development of videogames and

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[37] More precisely, infrared cameras record motions in 3D space of the markers attached on the suit of the actor.

movies often call for the use of a limited set of captured motions. Editing operations are thus generally required to animate virtual characters with a sufficient level of variety. Editing operations refer to the direct intervention of animators on captured motions: in brief, animators enlarge the set of available virtual animations by transforming captured motions into new virtual actions. For instance, suppose that a virtual character in an American Football videogame can throw the ball at a distance which varies from 1 to 30 meters. Because each throwing distance corresponds to a different throwing action (different force, different velocity of the arm, etc.), recording all the possible throwing actions would require endless Motion Capture sessions. The problem can be overcome with motion editing operations: only two or three real throwing actions will be recorded using Motion Capture (for instance, those corresponding to the throwing distances of 1, 15, and 30 meters). After that, animators will create all the remaining virtual throwing actions by modifying the three original captured motions. In other words, animators use editing operations to enlarge a small set of captured motions, thus covering the whole range of required virtual actions.

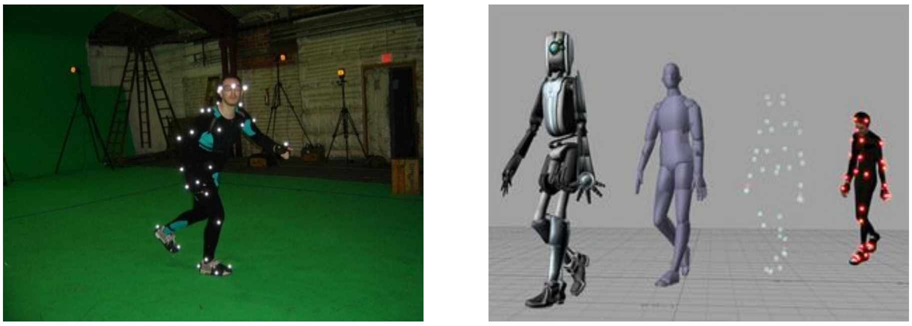

Figure 15. Left: an actor wearing a black suit provided with markers; motions of the markers are recorded by the infrared cameras on the background. Right: schema of the Motion Capture procedure: from right to left, motions of the markers are recorded, and then transferred to the virtual humanoid character . The final result is the humanoid character moving in the same way as the real actor.

The study of observers' sensitivity to physical distortions in virtual human motion comes into play at this point. Unlike animations created using Motion Capture technique, animations created through motion editing operations do not correspond to real actions performed by real actors. When animators apply motion editing operations, they physically distort original animations corresponding to real actions (captured motions). Even though it has been shown that observers tolerate, to some extent, distortions in dynamic events (see Section 5.1), we cannot generally take for granted that edited animations will be perceived as realistic by observers[38]. Because realism of the animation is fundamental in CG, it is then necessary to investigate whether virtual animation created through motion editing operations are perceived as natural by the observers.

5.4 Evaluating the perceptual plausibility of edited throwing animations

In this section I introduce a study (which is composed of two experiments separately described in the following sections) on observers' sensitivity to distortions in virtual throwing animations. The results of this study provide valuable insights for developers of games and virtual reality applications by specifying thresholds for the perceptual plausibility of two simple kinds of manipulations (editing operations) of throwing actions.

A small number of studies have been concerned with visual perception of mechanical interactions between human characters and inanimate objects. Throwing actions, as discussed here, are instances of these kinds of mechanical events. Most experiments on visual perception of throwing actions have been conducted using point-light displays as stimuli. Runeson and Frykholm (1983) displayed point-light characters throwing an unseen 2.5 kg sandbag at different distances, and found that estimates of the length of the throw were accurate. Munzert, Hohmann, and Hossner (2010) found that observers finely discriminated the traveled distances of a 600g ball when point-light displays of the arm of the thrower were shown. Knoblich and Flach (2001) showed video clips of people throwing light darts towards a target, and found that non-kinematic cues such as the direction of the thrower's gaze influence observers' ability to predict the final position of the dart. Hecht and Bertamini (2000) presented 2D stick characters and mannequin-like 3D characters performing throwing actions, and found that observers were relatively insensitive to added acceleration during the first phase of the ballistic motion of the projectile.

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[38] When animations are created using Motion Capture technique, their perceived realism can be taken for granted because they correspond to real actions performed by a real actor.

In the study presented here, I evaluate how observers perceive throwing animations which were manipulated using two simple editing methods: modifying the speed of the human and ball motions accordingly (Experiment 1), or creating a physical mismatch between them (Experiment 2). In the next section I present a brief introduction to the Physics of throwing actions.

5.4.1 Physics of throwing actions

The motion of a thrown object can be divided into two phases: the motion before it is released (*preparatory motion*) and the motion after the release (*ballistic motion*). When thrown in the air, an object that is subject only to the force of gravity and to air resistance is called *projectile*. If we neglect air resistance, a projectile always follows a parabolic trajectory, defined by its horizontal and vertical velocities at the time of release (v_{h0} and v_{v0} respectively). More precisely, the parabolic trajectory of a projectile is characterized by the following two equations:

$$v_h(t) = v_{h0} \tag{11}$$

$$v_v(t) = gt + v_{v0} \tag{12}$$

where $v_h(t)$ and $v_v(t)$ are horizontal and vertical velocities, g is the coefficient of gravity and t is time. While Equations (11) and (12) refer to the ballistic phase of the motion, the release velocities v_{h0} and v_{v0} are determined by the motion of the object during preparatory motion. In the case of a throw performed by a human, preparatory motion comprises all the movements of the human's body that influence the release velocities of the projectile, such as the motion of the throwing arm and the corresponding shoulder.

5.4.2 Creating virtual throwing animations using Motion Capture technique

Virtual throwing animations for the study described here were created recording the full body movements of a right-handed male actor (thrower hereafter). The thrower was nonprofessional and did not have any specific experience with sports involving throwing a ball. All throws were performed with the right arm using a standard tennis ball as projectile (diameter ≈ 7 cm, mass ≈ 60 g). Another person served as receiver, but was not recorded. The receiver stayed in front of the thrower at a distance of 5m. The thrower was instructed to look in front of him during the throw, and to avoid lateral movement of the ball. The trajectory of the ball was thus mainly displaced in two dimensions with respect to the thrower: forwards and upwards.

As I wished to determine if observers' sensitivity to errors in throwing animations depended on the way in which the throw is performed, the thrower was instructed to throw the ball to the receiver in two alternative ways: either with an *overarm* motion or with an *underarm* motion (Figure 16). I then registered three takes for each kind of throw. Other takes were discarded due to excessive lateral movement of the ball.

Motion capture was conducted using a 19 camera Vicon optical system, and 55 markers were placed on the body of the thrower (see Figure 15). In order to simultaneously capture the motion of the hand and of the fingers, six extra markers were placed on each hand: two markers on the thumb and one marker on the fingertip of each finger, as in Hoyet, Ryall, McDonell, and O'Sullivan (2012). Four markers were also placed on the tennis ball, so that they formed the vertices of a tetrahedron and did not have any appreciable influence on the trajectory of the ball. This allowed us to estimate the position of the center of the ball during the entire captured motion. The body and the ball motions were captured at 120Hz.

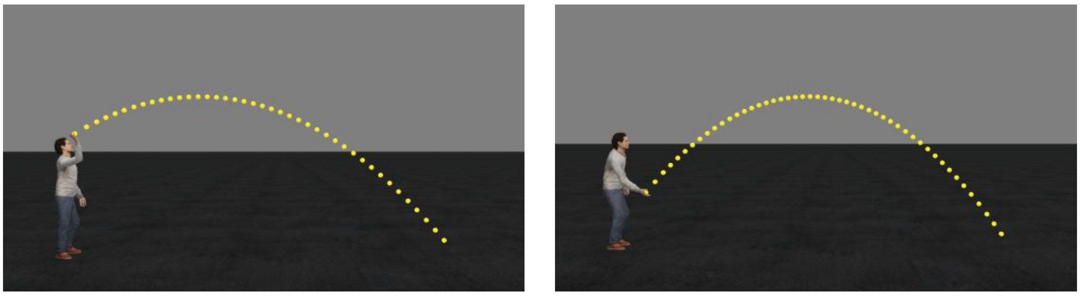

Figure 16: Examples of overarm (left) and underarm (right) throws.

In order to manipulate the velocity of the projectile, I first needed to determine the time of release t_0 to discriminate the preparatory from the ballistic phases. To automatically compute t_0, I selected the set of eight markers on the right hand of the thrower (T), and another set (P) consisting of the four markers on the projectile. I then computed the sum of the squared Euclidean distances (d) associated with every pairs of markers (t , p) with $t \in T$ and $p \in P$. Then, t_0 corresponded to the time when the derivative of d (as a function of time) exceeded a manually selected threshold, i.e. when the variation of the distance between the ball markers and the hand markers differed from capture noise.

I then used the captured trajectory of the projectile during the ballistic phase to automatically compute the release velocities that best fitted the whole ballistic motion. Table 1 shows the average release velocities of the ball over the three takes of overarm or underarm throws, together with the corresponding standard deviations. These parameters differed by no more than 5% between takes of the same kind of throw. Note that in overarm throws the horizontal component exceeds the vertical component, whereas the opposite is true for underarm throws.

	v_{h0} (m/s)	v_{v0} (m/s)
Overarm	5.58 ± 0.16	3.32 ± 0.08
Underarm	4.41 ± 0.03	5.50 ± 0.11

Table 1: Average and standard deviation of the horizontal (v_{h0}) and vertical (v_{v0}) release velocities for the two types of captured human throws.

5.5 Experiment 1: Full Throw Editing Experiment

In this experiment, I studied observers' sensitivity to simultaneous manipulations of preparatory and ballistic motions in biological human throwing animations. As the release velocity of the projectile depends on the preparatory motion, Dynamic Time Warping (see the next section) was used to modify the speed of the biological throwing motion, and the release velocity of the projectile was manipulated accordingly. I was interested in studying to what extent biological throws can be slowed down or speeded up while still being perceived to be natural. I was also interested in testing whether the tolerance to these manipulations depends on the type of throw (overarm or underarm).

5.5.1 Dynamic Time Warping (DTW)

Modifying the speed of a motion to speed it up or slow it down is called Time Warping. Similarly, Dynamic Time Warping (DTW) handles non-uniform compressions or dilatations of parts of a motion by varying the speed modification over time. This is commonly used in computer animation to synchronize motion sequences which in their original form have different durations (Bruderlin & Williams, 1995).

In the case of throwing motions, the release velocity of the projectile depends on the preparatory motion of the human character. In the experiment described below, I used DTW to modify the speed of the biological throwing motion, and manipulated the release velocities of the projectile accordingly. According to physics, this corresponds to modifying the horizontal and vertical components of release velocity by the same percentage as the speed modification of the preparatory motion. This modifies the magnitude of the release velocity without changing the angle of release of the projectile. As the release velocity is influenced only by the throwing gesture, I modified the speed of the motion of the human character only during the throwing action. This action was defined by the period of time including the moment of release, with a local minimum release velocity of the arm at the boundaries of the throw phases (i.e., preparatory, release and follow-through). In order to manipulate the release velocity of the throw, I modified the duration of the throwing action by the corresponding amount and recomputed the new time of release. The modified parabolic trajectory of the projectile was then recomputed according to Equations (11) and (12) using the modified release velocities. Such editings are reasonably straightforward to perform and would therefore be typical in real-time applications such as videogames.

5.5.2 Experimental setup

Participants. Eleven volunteers took part in this experiment (aged from 20 to 50, 5 females). They were all naïve to the purpose of the experiment, came from various educational backgrounds, and received a book voucher for their participation.

Stimuli and apparatus. To display the biological human motions, I selected a virtual character who roughly matched the morphology of the actor (see Section 5.4.2). The captured body motion was then mapped onto a skeleton, where joint angles were computed and used to drive the virtual character. I selected a camera viewpoint to the right of the thrower (Figure 16), where the fixed position of the camera was chosen to maximize the amount of preparatory and ballistic motion information available to participants. The ball was displayed with a bright-yellow photographic tennis ball texture (similar to the real captured tennis ball), and the ground was displayed with a dark grey asphalt-like textured plane. The background was light-gray, and shadows were not rendered. These settings were chosen to enhance the contrast between the ball and the rest of the virtual environment, thus making the visual tracking of the ball easier. Because I wanted the participants to focus on the trajectory of the ball during its flight phase, and not on the reaction with the environment once the ball landed, the ball disappeared before making contact with the ground. For some modified throws, the ball went outside of the border of the screen. I did not simulate air resistance because this would have a negligible perceptual effect on the trajectory of the ball. All the stimuli were displayed at 1600 × 1200 pixels and at 85Hz on a 21-inch CRT screen.

Procedure. In each trial, participants had to indicate whether the presented animation appeared natural (left click of the mouse) or modified (right click of the mouse). They were given some information on how motion capture data are created. Participants were told that some of the animations had been modified, and explicitly told that the throwing motion of the virtual character could appear excessively fast or slow. To facilitate the task, the participants were allowed to feel the weight of a real tennis ball before and during the experiment, and they were told that the tennis ball displayed in the animation had the same weight as the real one.

Experimental design. To accurately determine the perceptual threshold for the modification of the throwing speed, I used a randomly interleaved staircase design (Levitt, 1971), with fixed up and down steps. The staircase (or up-down) method is an effective psychophysical technique for identifying thresholds, since it ensures that most of the trials are presented near the threshold for each particular observer (see also Section 3.2.1). The ascending staircase starts with the unmodified throw and increases the magnitude of speed modification until the observer perceives the stimulus as "modified". The magnitude of speed modification is then decreased (in smaller steps) until the observer perceives the stimulus as "natural", then increased until it results in another “modified” response. This “up-down” process is repeated, until a pre-specified number of reversals is obtained. As suggested by Garcia-Perez (2001), I used a down/up step ratio of 0.871, and set the stopping condition to 8 reversals. This ascending staircase is complemented by a descending staircase, which starts at a clearly superthreshold level (i.e., the stimulus appears glaringly “modified”) and decreases until a “natural” response is given. It then reverses course, and follows the same reversal process as previously described. To avoid observers anticipating the next stimulus (and hence biasing their response), trials from several staircases are interleaved; the trials then appear random to the observer. This psychophysical method gives a sufficient number of binary responses around the absolute threshold level to fit a psychometric curve to the data. The psychometric curve is a mathematical model representing how the observers’ response to the stimuli varies depending on the variation of these stimuli. This procedure allows us to calculate the Point of Subjective Equality (PSE), i.e., the magnitude of speed modification of the original throw at which the throw is perceived as “natural” 50% of time, and the Just Noticeable Difference (JND), i.e., the magnitude of speed modification of the PSE necessary to improve the detectability of the modifications by 25%. Note that the same psychophysical method was used in the experiments presented in Chapter 3. There are however two notable differences in the details of the two experimental procedures. First, here the down/up ratio of the staircase was 0.871, whereas in the experiments of Chapter 3 it was 1. Second, here individual thresholds were computed using psychometric functions, whereas in the experiments of Chapter 3 they were computed by averaging the midpoints of the last four runs of both staircases. These differences depend on the diversity of the two experimental apparatuses, but both methods are valid for the computation of individual thresholds.

Based on a pilot study, the *Magnitude* of modifications of the original motion speed varied between 0% and 90%[39]. The *Sign* of the manipulation of the speed was either a decrease (slowing down) or an increase (speeding up). I used two *Throws* (overarm or underarm), and in order to obtain reasonably short experimental sessions, I

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[39] To clarify the meaning of this sentence, 0% modification means that the original motion speed was kept unchanged, whereas 90% modification means that it was almost doubled or halved.

selected only one take of each captured throw. I chose the take with the release velocity closest to the average velocity of the three captured takes. Therefore, I had eight staircases: 2 Throw (overarm, underarm) × 2 Sign (slowing down, speeding up) × 2 Direction of the staircase (ascending, descending). In order to avoid any anticipatory effect, I randomly interleaved the presented experimental conditions.

5.5.3 Results and discussion

For each experimental condition, I used the Matlab psignifit toolbox (Fründ, Haenel, & Wichmann, 2011) to fit a logistic psychometric curve to the data, both to each participant and to the overall merged results. The overall psychometric curve for each condition is presented in Figure 2. The overall PSEs and JNDs are reported in Table 3.

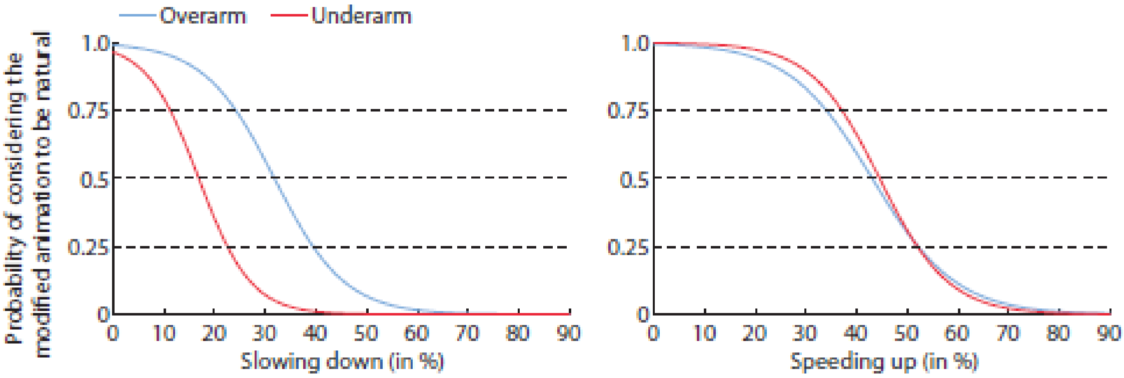

Figure 17: Overall psychometric curves representing the probability of 'natural' responses for each magnitude of slowing down and speeding up of the original motion, for overarm and underarm throws.

To evaluate how speed modifications and throw influence the PSE, I performed a two-way Repeated Measures ANOVA on individual estimated PSEs with within subjects factors: 2 Sign × 2 Throw. I used Newman-Keuls post-hoc tests to further explore interaction effects. Table 2 summarizes the main results, which show that participants are significantly less sensitive to speeding up throws than to slowing them down, especially for underarm. The same analysis was performed on JNDs and showed no main or interaction effects, showing that the response strategy was consistent over the four experimental conditions.

Experiment 1 - Full Throw Editing Experiment – 2 *Throw* × 2 *Sign*

Effect	**F-Test**	**Post-hoc**
THROW	$F(1,10) = 5.368$, $p < 0.05$	Greater sensitivity on average for underarm throws
SIGN	$F(1,10) = 5.666$, $p < 0.05$	Greater sensitivity on average for slowing-down
THROW × SIGN	$F(1,10) = 11.085$, $p < 0.01$	Greater sensitivity on average for slowing-down, in particular for underarm throw

Table 2: Significant results for Experiment 1

The results suggest that observers are relatively tolerant to speeding up throwing motions, independently of the kind of throw (≈44% speeding up of the original motion was tolerated 50% of the time). Tolerance for slowing down is generally lower (with -31.8% of the original speed accepted 50% of the time for the overarm throw), and particularly low for the underarm throw (-16.9%). These findings show that observers' sensitivity to speed modifications does not only depend on the general action being performed (a throw), but also on finer features of the action (overarm vs. underarm).

		Slowing down	Speeding up
Overarm	PSE	31.8% ± 5.8%	43.1% ± 7.3%
	JND	6.9% ± 2.0%	8.2% ± 1.6%
Underarm	PSE	16.9% ± 4.1%	44.5% ± 5.2%
	JND	5.1% ± 0.5%	6.8% ± 1.4%

Table 3: Mean PSEs and JNDs with standard errors for the Full Throw Editing Experiment

To sum up, DTW can be used to achieve big increases in the throwing distance, i.e., the horizontal distance between the thrower and the landing position of the ball, while still keeping the phenomenal "naturalness" of the virtual throwing action. In this experiment, a 43.1% speeding up resulted in a 75% increase in the overarm throwing distance, and a 44.5% speeding up resulted in a 99% increase in the underarm throwing distance. However, observers are more sensitive to slowed down motions, resulting in a 52% decrease in the original throwing distance for the 31.8% slowed down overarm throw, and a 28% decrease in the original throwing distance for the 16.9% slowed down underarm throw. The latter result suggests that DTW can be used to decrease the throwing distance of an underarm throw only by a small amount.

5.6 Experiment 2: Ballistic Motion Editing Experiment

The results of the first experiment demonstrated that DTW can be used to modify the throwing distance of the ball by a large amount. However, DTW requires the modification of the motion of the virtual character and of the ball. In the second experiment, I was interested in evaluating if throwing animations can be modified using a simpler editing operation. I evaluated the perceptual effect of manipulating only one component of the release velocity of the projectile, while leaving the other component of velocity and the motion of the virtual character unchanged. This editing operation introduced a physical mismatch between preparatory and ballistic motions, because the latter was modified while the former remained unchanged. As in the first experiment, I also tested whether the sensitivity to manipulations depends on the way in which the throw is performed.

5.6.1 Experimental setup

Participants. Fifteen volunteers took part in this experiment (aged between 20 and 55, 5 females). They were all naïve to the purpose of the experiment, came from various educational backgrounds, and received a book voucher for their participation.

Stimuli and apparatus. I used the same environment and camera viewpoint as those used in the first experiment (see Section 5.5.2). Similarly, all the stimuli were displayed at 1600 × 1200 pixels and at 85Hz on a 21-inch CRT screen.

Procedure. In each trial, participants had to indicate whether the trajectory of the ball was “correct” (left click of the mouse) or “incorrect” (right click of the mouse). They were instructed that an incorrect trajectory could be too high, too shallow, too long, or too short compared with the force exerted by the virtual character. As in the first experiment, the participants were allowed to feel the weight of a real tennis ball before and during the experiment.

Experimental design. Because of the relatively large number of experimental stimuli for this experiment, I chose a 2-Alternative Forced Choice paradigm (2AFC), where participants had to indicate whether the trajectory of the ball was correct or incorrect. The ballistic motion was modified by manipulating the original release velocity of the ball, while the preparatory motion remained unchanged. Based on a pilot study, I selected a set of *Magnitude* modifications of the original release velocity: 15%, 30%, 45% (see Note 39). The *Sign* of the manipulation could be either a decrease or an increase in velocity. Also, the *Components* of the original release velocity were modified independently (horizontal or vertical component) by modifying one of the two components and keeping the other one unchanged: I thus modified the ratio between horizontal and vertical components of release velocity, which implied a change of the angle of release of the ball. The modified parabolic trajectory of the projectile was then recomputed according to Equations (11) and (12) using the manipulated release velocities.

I presented the animations corresponding to the three takes of each captured throw (overarm and underarm, see Section 5.4.2). The small differences between takes (See Table 1) did not affect the fundamental mechanics of the throwing action, as suggested by the similarity of the release velocities of the projectile between the three takes of each kind (difference of no more than 5%).

A total of 168 stimuli were shown in random order to participants. There were 144 modified animations: 2 Throw (overarm, underarm) × 2 Component (horizontal, vertical) × 2 Sign (decrease, increase) × 3 Magnitude (15%, 30%, 45%) × 3 takes × 2 repetitions. In addition, the six unmodified takes were presented four times each, for a total 24 unmodified animations.

5.6.2 Results and discussion

As a preliminary analysis showed no main effect or interaction effects of takes, participants' responses were averaged over takes and repetitions. I then performed a four-way repeated measures ANOVA on the observed percentage of "incorrect" responses (i.e., throws judged as "incorrect" by participants) with within subject factors: 2 Throw × 2 Component × 2 Sign × 3 Magnitude. I used Newman-Keuls post-hoc tests to further explore main and interaction effects. Table 4 summarizes the significant results. Figure 18 shows the mean percentage of "incorrect" responses for the overarm and the underarm throws for each modified component. While appropriate to study a large number of experimental factors, the psychophysical method we used in this second experiment (2AFC) does not allow a precise calculation of the individual PSEs. However, Table 5 reports the overall estimated mean 50% PSEs for each experimental condition. These values were computed by intersecting the curves represented in Figure 18 (representing participants' responses) with the 50% value on the vertical axis.

Experiment 2 – Ballistic Motion Editing Experiment – 2 *Throw* × 2 *Component* (COMP) × 2 *Sign* × 2 *Magnitude* (MAGN)

Effect	**F-Test**	**Post-hoc**
MAGN	$F(2,28) = 176.038$, $p \approx 0$	Sensitivity is proportional to magnitude
SIGN	$F(1,14) = 8.251$, $p < 0.05$	Greater sensitivity on average for decreases
THROW × SIGN	$F(1,14) = 8.253$, $p < 0.05$	→ but only for underarm throw
THROW × COMP	$F(1,14) = 65.377$, $p \approx 0$	Greater sensitivity for the main component of velocity
THROW × COMP × MAGN	$F(2,28) = 6.037$, $p < 0.01$	→ but only for 30% and 45% levels of magnitude
COMP × SIGN × MAGN	$F(2,28) = 5.725$, $p < 0.01$	Small random effect independent of throw

Table 4: Significant results for Experiment 1.

The results suggest that manipulations of the greater component of velocity (horizontal for overarm throws and vertical for underarm throws, see Table 1) were easier to detect than manipulations of the smaller component. This result may be due to the fact that manipulations of the greater component of velocity produce larger absolute modifications of the original trajectory of the ball compared to manipulations of the smaller component. Similarly to the Full Throw Editing Experiment (see Section 5.5), decreases in the ball velocity for the underarm throw were the less accepted manipulations (see Table 5).

In order to allow a comparison between these results and those of the Full Throw Editing Experiment, I estimated the overall mean PSEs by intersecting each curve in Figure 18 with the 50% value on the vertical axis (Table 5) and evaluated the corresponding modification of the throwing distance. Note that in the case of manipulations of the horizontal component of velocity, the magnitude of such manipulations equals the modification of the throwing distance. This results in modifications of around ±25% of the original throwing distance for all the conditions, except for the underarm throw where the throwing distance can be increased up to 40%. In the case of manipulations of the vertical component of velocity, the PSEs corresponded to modifications of around ±15% of the throwing distance, except for the increase in the vertical component of the underarm throw (24% increase of the original throwing distance).

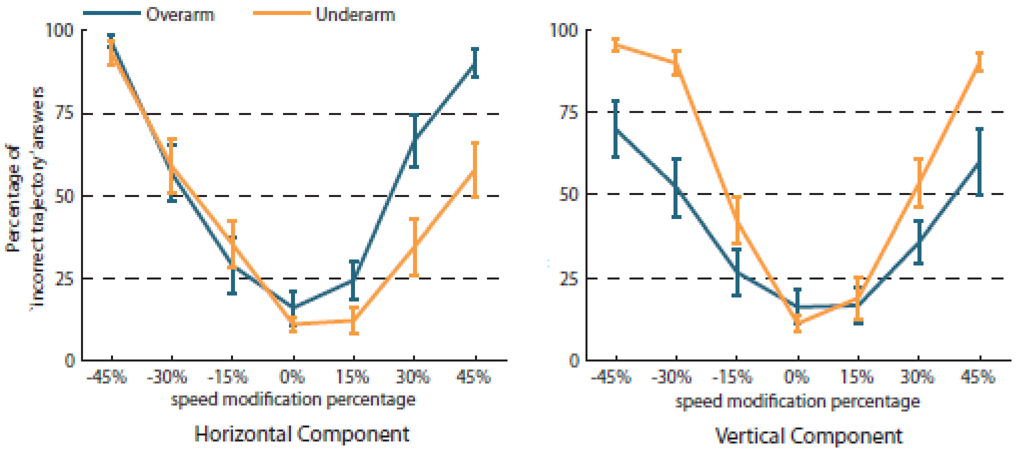

Figure 18: Mean percentages of ‘incorrect’ responses in the Ballistic Motion Editing Experiment for each Magnitude of manipulation, for the different Throws and manipulated Components of release velocity.

	Horizontal		Vertical	
	Decrease	Increase	Decrease	Increase
Overarm PSE	-26.4%	24.1%	-28.7%	38.8%
Underarm PSE	-24.3%	40.0%	-17.5%	28.5%

Table 5: Mean PSEs for the different conditions of the Ballistic Motion Editing Experiment.

To sum up, the pattern of sensitivity to manipulations of horizontal and vertical components of velocity depends on the type of throw. The PSEs for the studied manipulations hardly exceed ±30% with respect to the original velocity. Considering the results obtained in the Full Throw Editing Experiment, this demonstrates that observers are quite sensitive to physical mismatches between the preparatory motion and the ballistic motion. As the preparatory motion seems to provide observers with enough information to predict the ballistic motion accurately, observers detect physical mismatches between these two phases quite easily (see also Reitsma et al., 2008). The maximum amount of modification of throwing distance considered to be perceptually plausible by observers is an increase by 40% in the underarm throw. This means that the simple editing operation studied in this experiment can be used only for small manipulations of the throwing distance.

5.7 General discussion

In this chapter I presented two experiments addressing the perceptual effect of two kinds of editing operations in throwing animations: modifying the velocity of both the character and the projectile, or manipulating the release velocities of the projectile alone. In the first experiment, I have shown that DTW can be used by animators to achieve big increases in the throwing distance (99% increase in throwing distance for the underarm throw considered to be correct 50% of the time). However, the sensitivity to timewarped biological throws depends also on the interaction between the kind of throw being performed by the virtual character (overarm vs. underarm) and the sign of the manipulation (speeding up vs. slowing down). In the second experiment, I have shown that the sensitivity to manipulations of the two components of release velocity of the projectile depends on the way in which the throw is performed. Relatively small increases in the throwing distance are achievable using this simple editing operation (40% increase in throwing distance for the overarm throw considered to be "correct" 50% of the time). Interestingly, I found in both experiments that observers are most disturbed by short-distance underarm throws. This may be due to the fact that we have a general preference for overarm throws over underarm throws when aiming at short distances, which gives us better control of the direction of the projectile.

These results are important for motion editing purposes. Throwing animations that require small changes of the throwing distance may be modified by manipulating only the horizontal and/or vertical components of the release velocity of the projectile, leaving the motion of the thrower unchanged. However, DTW has to be used to achieve bigger manipulations without compromising the realism of the animation. These manipulations allow animators to cover a wide range of throwing distances without extensive motion capture sessions. Of course, the results of my experiments also suggest that animators need take into account the type of throw when editing animations. These guidelines can be used in throwing games where a set of throwing motions can be edited to reach new throwing distances.

5.7.1 Future work

In the experiments presented here all the captured motions were characterized by a throwing distance of 5m. To test the effect of manipulations on a wider range of throwing distances would have required an impractically large number of stimuli. For the same reason, I tested only the two most common throwing motions (overarm and underarm) from the vast set of possible throwing actions. The camera viewpoint was fixed, and set to maximize the visual information available to the participants: tolerance to modified animations might be larger with other arbitrary camera viewpoints. In order to study the interaction between the manipulated component and the type of throw, in the Ballistic Motion Editing Experiment I manipulated only one component of release velocity while keeping the other one unchanged. This procedure was used in previous works on ballistic motion editing (Reitsma et al., 2008), and it is especially suitable if the animator needs to modify, for instance, only the length of the throw while keeping its height constant. However, it would be interesting to study the perceptual effect of combining manipulations of both components while leaving the preparatory motion unchanged. Horizontal and vertical release velocities can also be manipulated by changing the time of release of the ball.

While the above mentioned choices were well-justified for a first-stage experiment, future research on the perception of throwing animations may involve a wider range of throwing distances and actions, evaluate the effect of the camera viewpoint on the perception of physical distortions, and evaluate the perceptual effect of simultaneous manipulation of both components and of the time of release while leaving the preparatory motion unchanged.

Epilogue

In this dissertation I presented various experiments on visual perception and cognition of dynamic events. A prominent element of novelty of my experiments is the use Computer Graphics techniques as a means for the creation of elaborate and realistic experimental stimuli. Nonetheless, as discussed in Chapter 1, investigation on the stated topic started well before the invention of these techniques. Albert Michotte (1881 - 1965) was a pioneer in demonstrating that psychological properties which had traditionally been considered exclusive domain of cognition, such as the notion of causality, are actually embedded in our visual system. To recap Michotte’s argument, when observers are presented with abstract objects moving on a uniform background, they are aware that no real causal relations can exist between these objects; nonetheless, they perceive dynamic events connected by causal relations. This proves that visual perception of dynamic events is (to some extent) independent of conscious thinking. This argument has become one of the “pièce de résistance” of Gestalt theory (also in domains different from phenomenal causality), and still sounds very convincing. That visual perception of dynamic events is a purely perceptual phenomenon (at least partially) independent of conscious thinking has been confirmed by several researchers (as documented in Section 3.5.1).

In my opinion, the overwhelming importance of Michotte’s work had a side effect: researchers seem to have focused more on the debate about theoretical models of phenomenal causality (and the philosophical problems they raise), rather than on improving and extending experimental research on the topic. Experiments on phenomenal causality are still characterized by highly abstract and simplified experimental stimuli, which are similar in many respects to those used by the Belgian researcher about seventy years ago. It is however undeniable that which experimental variables are believed to influence a psychological phenomenon closely depends on what kind of experimental stimuli are used in the research on the phenomenon itself. For instance, in the case of visual perception of dynamic events, when experimental stimuli are constituted by abstract 2D objects moving on a uniform background, researchers are probably prone to ignore the influence of featural properties of objects involved in dynamic events (such as their simulated mass).

Michotte’s revolutionary findings were made possible by the use of an ingenious experimental apparatus called “rotating disks”. However, this device allowed him to create only experimental stimuli involving simple 2D shapes moving on a uniform background. Seventy years later, thanks to advances in Computer Graphics, we are able to build simulations of dynamic events characterized by realistic scenarios involving many virtual objects as well as virtual human characters. Besides reducing the gap between experimental stimuli and everyday experience, this opens the possibility of manipulating a wide range of experimental variables which for practical reasons were ignored in previous research. Unfortunately, experimental psychologists do not have fully exploited this possibility yet. In contrast, researchers in the field of Computer Graphics have recently started on this path (see Section 5.1). However, I would like to emphasize that research in Computer Graphics cannot replace research in Experimental Psychology on this topic: the former kind of research is almost exclusively concerned with the applications of experimental findings to videogames and movies industry, but generally fails to consider theoretical implications and connections with the psychological literature. This dissertation can be conceived as an attempt to create a bridge between these two fields of research.

Collaboration between experimental psychologists and computer scientists may bring strong advantages to both sides. Computer scientists, who possess the technical skills for the creation of realistic simulations of dynamic events, may help experimental psychologists in the construction of experimental stimuli. For instance, the research on virtual throwing animations presented in Chapter 5, has been made possible to me thanks to the collaboration with specialized computer scientists. Another important advantage that psychologists may draw from this collaboration, is that the results of their research on visual perception of dynamic events may of use for practical applications in videogames and movies industry. This suggests that this kind of collaboration is beneficial also when considered the other way round: experimental psychologists may provide computer scientists helpful insights for the improvement of simulations of dynamic events, also offering adequate psychophysical methods for this kind of research.

As shown in Chapter 4 of this dissertation, experimental psychologists may exploit computer graphics techniques not only for studying visual perception of dynamic events, but also for studying Naïve Physics. This is an interesting and perhaps neglected topic, which is very useful for Physics instruction. Research in Naïve Physics has been mostly conducted using simple experimental stimuli, which are only approximate representations of the proposed physical events. Computer Graphics may help researchers to investigate how people understand physical events in more realistic and ecologically valid conditions. As discussed in Chapter 4, this may allow researchers to distinguish misconceptions which are deeply rooted in people’s mind, from those which are due to the abstractness of the representations of the proposed physical events.

To conclude, I would like to emphasize that this dissertation is characterized by some notable elements of novelty, but it is also deeply connected with traditional research in Experimental Psychology. Besides the obvious connections with Michotte’s seminal work on phenomenal causality, a prominent source of inspiration for my dissertation was the work of Paolo Bozzi (1930 - 2003). Even though his fame has been limited by the prevailing use of the Italian language in his scientific publications, with his research on inclined planes and pendulum motion, he can be considered in all respects an authoritative and creative pioneer of the study of Naïve Physics. Notably, his work is characterized by the close connection between Naïve Physics and visual perception of dynamic events, which is also the leading thread of my dissertation.

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Riassunto (Lingua Italiana)

Il tema centrale di questa tesi è la percezione visiva degli eventi dinamici. L'argomento è degno d'interesse, come testimoniato dalla sua lunga tradizione nella storia della Psicologia Sperimentale, iniziata con il lavoro fondamentale di Albert Michotte (1881 - 1965) sulla causalità fenomenica. L'argomento che ho scelto non è dunque originale in sé. Tuttavia, un elemento di novità nella mia tesi è l'utilizzo di tecniche di Computer Grafica per creare stimoli sperimentali realistici in esperimenti psicologici. Oltre al vantaggio di ridurre il gap tra gli esperimenti di laboratorio e l'esperienza quotidiana, questo può rivelare l'importanza di variabili sperimentali che sono state tradizionalmente ignorate nella ricerca sulla percezione visiva degli eventi dinamici.

Il lettore deve essere informato che questa tesi è caratterizzata da diverse linee di ricerca, che sono intrinsecamente connesse con il tema centrale della percezione visiva degli eventi dinamici. In alcuni esperimenti, indago la percezione visiva degli eventi dinamici, mentre in altri indago la cognizione degli stessi eventi. Vengono studiati due diversi eventi dinamici: collisioni orizzontali e lanci. Inoltre, i risultati degli esperimenti vengono discussi non solo in relazione alle loro implicazione teoriche per i modelli psicologici, ma anche in relazione alle loro potenziali implicazioni nel campo dell'insegnamento della Fisica e nel campo della Computer Grafica. Di conseguenza, il contenuto di questa tesi è abbastanza eterogeneo, ma spero di fornire al lettore una prospettiva ampia e multidisciplinare sull'argomento in questione.

Questa tesi è composta di cinque capitoli, che possono essere divisi in tre gruppi. (i) Nei capitoli 1-3, dopo una presentazione del background teorico sulla percezione visiva di eventi dinamici, indago l'influenza delle proprietà dinamiche degli oggetti virtuali sulla percezione visiva delle collisioni orizzontali. I risultati di questa ricerca sono importanti per l'antico e ancora vivo dibattito sulla causalità fenomenica. (ii) Nel Capitolo 4 presento una ricerca sulla Fisica Ingenua delle collisioni orizzontali tra sfere virtuali di cui verranno manipolate massa simulata e velocità. In questo capitolo assumo una prospettiva più cognitiva che percettiva, indagando come le persone ragionano sull'evento fisico proposto. (iii) Nel Capitolo 5, presento una ricerca sulla percezione

visiva delle animazioni virtuali di lancio, che sono eventi dinamici complessi e poco studiati. Questo capitolo spicca per la sua natura multidisciplinare, poiché in esso discuto come i risultati possano essere applicati alla Computer Grafica. La ricerca presentata in quest'ultimo capitolo è stata condotta come parte dei miei studi di dottorato quando sono stato ospite del Graphics, Vision, and Visualisation Group al Trinity College Dublin, dove ho collaborato con la Professoressa Carol O'Sullivan ed il Dottor Ludovic Hoyet, che sono ingegneri informatici che lavorano alle applicazioni della percezione visiva alla Computer Grafica.

Più nel dettaglio, nel Capitolo 1 discuto il background teorico della percezione visiva degli eventi dinamici e della causalità fenomenica. In primo luogo, mi focalizzo sul classico lavoro di Michotte. In secondo luogo, discuto alcuni importanti problemi che sono stati dibattuti per lungo tempo in questo campo di ricerca. Infine, presento lo "*schema-matching model*" di White sulla percezione degli eventi dinamici, discutendo le sue differenze e somiglianze con il modello di Michotte. Questo capitolo è concepito per servire da punto di riferimento teorico per l'intera tesi.

Nel Capitolo 2 discuto l'ipotesi che le proprietà dinamiche (percepite visivamente) degli oggetti coinvolti in eventi dinamici influenzano la percezione visiva degli eventi dinamici stessi. In primo luogo, provo a confutare due popolari argomentazioni contro questa ipotesi. Poi, evidenzio il vantaggio evolutivo della percezione visiva delle proprietà dinamiche, discutendo la loro possibile influenza sulla percezione visiva degli eventi dinamici. Infine, discuto il modello *KSD* di Runeson in relazione all'ipotesi presentata.

Nel Capitolo 3 presento tre esperimenti, i quali confermano l'ipotesi discussa nel Capitolo 2. In particolare, mostro che il materiale simulato (Esperimento 1) e la dimensione (Esperimenti 2 e 3) degli oggetti virtuali coinvolti nelle collisioni orizzontali influenzano fortemente come le persone percepiscono l'evento. Discuto anche le implicazioni teoriche di questi risultati, facendo riferimento ai modelli di White e di Michotte.

Nel Capitolo 4 presento una ricerca sulla Fisica Ingenua delle collisioni orizzontali. In primo luogo, discuto l'importanza generale dello studio della Fisica Ingenua per migliorare l'insegnamento della Fisica elementare. In secondo luogo, presento la Teoria dell'Integrazione delle Informazioni e la metodologia della Misurazione Funzionale come strumenti adeguati per la valutazione della conoscenza ingenua degli eventi fisici da parte degli studenti, evidenziando i loro vantaggi rispetto ai questionari a scelta multipla. Infine, presento due esperimenti (condotti utilizzando la Teoria dell'Integrazione delle Informazioni e la Misurazione Funzionale) sulla Fisica Ingenua delle collisioni orizzontali tra sfere simulate che differiscono per dimensione, velocità, e materiale. Verrà anche discussa l'importanza dei risultati per l'insegnamento della Fisica.

Infine, nel Capitolo 5 presento una ricerca sulla percezione visiva di animazioni virtuali di lancio modificate. Prima discuto le relazioni tra percezione visiva degli eventi dinamici (del movimento umano in particolare) e la Computer Grafica. Poi presento due esperimenti sulla sensibilità degli osservatori alle anomalie in animazioni virtuali di lancio realistiche, discutendo l'importanza dei risultati per l'industria dei videogiochi e dei film.