Temporal Integration in the Perception of Biological Motion

Bruno Armando Aragão Henriques

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Universidade do Minho
Escola de Psicologia

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Temporal Integration in the Perception of Biological Motion

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Professor Doutor Jorge Almeida Santos
e do
Professor Doutor Miguel Castelo-Branco

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We cannot define *anything* precisely! If we attempt to, we get into that paralysis of thought that comes to philosophers, who sit opposite each other, one saying to the other, "You don't know what you are talking about!". The second one says, "What do you mean by *know*? What do you mean by *talking*? What do you mean by *you*?" (...).

The Feynman Lectures on Physics (1963, vol. I, p.8-2)

Agradecimentos

Tenho mais a retribuir do que a agradecer, ou pelo menos assim prefiro. Pelo sim pelo não, aqui ficam, mais ou menos públicos, mas sem dúvida insuficientes, os meus agradecimentos. Insuficientes como as desculpas pela ausência de tanto tempo e por um certo isolamento a que me votei, nem sempre justo, quase sempre egoísta, mas acreditei que necessário.

Nada se faz sozinho, muito menos em ciência. Tentei como Newton ver pelos ombros de gigantes. Aqui e ali consegui vislumbrar qualquer coisa. Nunca tive pretensão de mais. Bastou-me uma equipa de investigação e de trabalho que ultrapassou, faz muito tempo, a fronteira da amizade e da cumplicidade. Seria incapaz de distinguir essa linha, mas nunca o contributo sério e apoio incondicional que me devotaram. O Rogério e o João, os engenheiros que me ensinaram o que não pude aprender na tropa: a desenrascar. Sempre me fizeram sentir um deles e soube tão bem acreditar que o era. O Carlos, o mais novo dos camaradas, forte concorrente à maior biblioteca pessoal do mundo, a quem espero ganhar, mas de quem espero nunca me perder. O Paulo Noriega, um dos meus-melhores-amigos-para-sempre, com quem partilhei ciência, livros, música, e *filosofices* sobre o mundo. Das angústias desses tempos de convívio já pouco me lembro, mas do prazer daquelas deambulações ao final do dia nunca me quero esquecer. A Sandra, que nos tornou uma família, e deu aos dias um sabor tão mais *trendy*. Nela, a toda a família Mouta-Soares, que me abriu a porta e foi deixando entrar. Às vezes sou espaçoso, com eles nunca o senti. E por fim, propositadamente a Lili, a quem agradecer por tudo seria ainda muito pouco. Duvido que algum dia consiga retribuir na mesma medida, mas nunca deixarei de o tentar.

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Também aos investigadores do IBILI. Receberam-me como se me conhecessem desde sempre e levaram-me nas palminhas. O apoio do Gregor Philipiak e do Sérgio Tafula, o entusiasmo do Carlos Ferreira e a paciência do Gil Cunha tornaram possível o que eu próprio achei não ser. Sem eles, o capítulo 6 teria sido uma bonita miragem de um longínquo plano de doutoramento.

Aos meus orientadores que simpaticamente ignoraram alguns insucessos e generosamente valorizaram alguma da minha normalidade. Ao Prof. Jorge Santos, que me recebeu e me foi aturando, sem desistir. Ao Prof. Miguel Castelo-Branco que, quase num acto de fé, me acolheu e incentivou.

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Ao meu pai, para quem tudo é poesia, que incentiva a partir sem pensar se há regresso. À minha mãe, que nunca me deixa esquecer o regresso, qualquer que seja a partida. Aos dois, incondicionalmente, por me fazerem crer em Kipling e, segundo por segundo, que é todo meu o mundo *e - o que ainda é muito mais - que és Homem, meu filho!*

A mim próprio, porque não? Apesar de nem sempre optar pelos caminhos mais óbvios ou fazer as escolhas mais seguras, continuo espantado de existir!

Temporal integration in the perception of biological motion

Abstract

The visual perception of motion is crucial to human survival. The information provided by *objects* in motion and by our own movements allows for an effective adaptation to the environment, especially in the interaction with others. The perception of humans in motion is so critical that our capacity to perceive it appears to be innate (Fox & McDaniel, 1982; Pavlova et al., 2003).

The studies on biological motion met a great development in the last forty years, enhanced by the work of Johansson (1973), who developed a paradigm characterized by the use of impoverished visual stimuli - *point-light walkers*. The research with point-light walkers showed that we can extract relevant information from human motion, allowing for instance the distinction between different kinds of actions (Dittrich, 1993; Mather & Murdoch, 1994). Several authors have shown that we can not only differentiate actions, but also perceive social information, such as gender (Barclay, Cutting, & Kozlowski, 1978), identity (Cutting & Kozlowski, 1977), emotions (Dittrich et al. 1996), or deception and vulnerability (Runeson & Frykholm, 1983).

Although many of the spatial characteristics of biological motion perception are sufficiently studied, their temporal characteristics are not (Giese & Poggio, 2000; Thornton, Pinto, & Shiffrar, 1998), even in the neuroimaging field. Nevertheless, numerous studies have shown that the perception of biological motion takes longer than the perception of motion of rigid objects (Giese & Lappe, 2002). The evidence shows that an object in motion can be perceived 2000 ms faster than biological motion (Neri, Morrone & Burr, 1998). These results seem to be in contradiction with the biological motion's survival value. In spite of this, the larger temporal summation found in the perception of biological motion stimuli remains unexplained.

Our main goal was to investigate why large temporal summation is required in the perception of biological motion. We hypothesized that the kinematic properties of biological motion carry out relevant information and that this information is provided by the motion signal's spatiotemporal characteristics. To demonstrate our hypothesis, we developed a set of experiments that investigated the perception of temporal properties of biological stimuli.

Firstly, we needed to ensure that the biological motion stimuli contained the real properties of human motion. For that, we captured subjects' free gait and constructed biological stimuli that preserved their kinematic properties. We developed a new methodology that describes the procedures to capture the natural human motion and the techniques to transpose those properties into biological stimuli, without neglecting its kinematics. The result was an acquisition protocol of human motion and the correct procedures to construct and manipulate the biological motion stimuli.

In a second moment we investigated if the large temporal summation in the perception of biological motion could be better explained by the insufficient temporal sampling used in visual perception experiments. In a first experiment participants were asked to identify the motion stimuli's direction, and in the second experiment they were asked to choose the most natural of two stimuli. In both experiments the same stimuli were displayed at different frame rates. The results showed that the stimuli's temporal sampling does not explain the large temporal summation, but provided some evidence that the temporal properties of motion signals could be involved in visual perception.

Thus, we investigated the temporal characteristics of biological motion in two experiments where we manipulated the velocity and acceleration patterns of biological motion, maintaining the spatial component intact. In both experiments participants were asked to choose the most natural of two stimuli, representing either both feet or only one foot of a walker. The results showed that the visual system is highly sensitive to small variations in velocity and acceleration patterns, demonstrating that the temporal characteristics of the motion signal had affected the subjects' performance. Using the same kind of stimuli and the same methodology, the neuroimaging experiment corroborated the psychophysical results. The results showed the brain areas involved in biological motion perception, but also the areas involved in the processing of motion signal properties.

In a last experiment we studied our hypothesis in a perception-action paradigm, trying to extend the evidence collected in the psychophysical experiments. We captured participants' arm movements, manipulating their temporal but not their spatial properties, as we proposed in the previous experiments. Participants were asked to perform a specific arm movement while simultaneously visually tracking the stimuli previously captured and manipulated. The results showed that temporal properties of biological motion affect not only perception but also action. The interference on the motor response reflected the congruency of the movements of the stimuli and the movements executed by the participants, demonstrating that temporal properties can have a different impact on the participants' action.

Our findings indicate that the visual system is highly sensitive to small changes in physical motion properties, demonstrating that temporal characteristics affect human perception and action. We discuss the importance of signal properties to visual perception and suggest new experiments to support our data, proposing in the end a new approach about signal processing in the perception of biological motion.

Integração temporal na percepção do movimento biológico

Resumo

A percepção visual do movimento é crucial para a nossa sobrevivência. A informação fornecida por *objectos* em movimento e pelos nossos próprios movimentos permite uma adaptação eficaz ao meio ambiente, especialmente na interacção com outras pessoas. A percepção de seres humanos em movimento é tão importante que a nossa capacidade de percebê-lo parece ser inata (Fox & McDaniel, 1982; Pavlova et al, 2003).

Os estudos sobre movimento biológico tiveram um grande desenvolvimento nos últimos quarenta anos, depois de Johansson (1973) ter desenvolvido uma metodologia de estudo que se baseava na utilização de estímulos visuais empobrecidos – *point-light walkers*. A investigação com *point-light walkers* mostrou que podemos apreender informações relevantes do movimento humano, permitindo por exemplo a distinção entre diferentes tipos de acções (Dittrich, 1993; Mather & Murdoch, 1994). Vários autores têm mostrado que não só podemos diferenciar acções, mas igualmente perceber informações sociais, como género (Barclay, corte, & Kozlowski, 1978), identidade (Cutting & Kozlowski, 1977), emoções (Dittrich et al. De 1996), ou farsa e vulnerabilidade (Runeson & Frykholm, 1983).

Embora muitas das características espaciais da percepção do movimento biológico estejam suficientemente estudadas, as suas características temporais não estão (Giese & Poggio, 2000; Thornton, Pinto & Shiffrar, 1998), mesmo no campo de neuroimagem. Efectivamente, numerosos estudos têm mostrado que o tempo necessário para a percepção de movimento biológico é maior do que o tempo necessário para a percepção do movimento de objectos rígidos (Giese e Lappe, 2002). As evidências mostram que um objecto em movimento pode ser percebido 2000 ms mais rápido do que o movimento biológico (Neri, Morrone & Burr, 1998). Estes resultados parecem estar em contradição com o valor de sobrevivência da percepção do movimento biológico. Apesar disso, o maior tempo necessário para perceber movimento biológico permanece por explicar.

O principal objectivo deste trabalho foi perceber porque são mais longos os tempos de percepção para o movimento biológico. A nossa hipótese é que as propriedades cinemáticas do movimento biológico transportam informação relevante e que essa informação é transmitida pelas características espácio-temporais do movimento. Para demonstrar esta hipótese, foi desenvolvido um conjunto de experiências que procuraram estudar a percepção de propriedades temporais dos estímulos biológicos.

Em primeiro lugar, foi necessário assegurar que os estímulos de movimento biológico respeitavam as propriedades reais do movimento humano. Para isso, capturámos o movimento de pessoas em marcha livre e construímos estímulos biológicos que preservassem as suas propriedades cinemáticas. Desenvolvemos uma nova metodologia que descreve os procedimentos para capturar o movimento natural do ser humano e as técnicas para transpor essas propriedades para estímulos

biológicos, sem descurar a sua cinemática. O resultado foi um protocolo de aquisição do movimento humano e os procedimentos correctos para construir e manipular os estímulos de movimento biológico.

Num segundo momento investigámos se o maior tempo de percepção do movimento biológico poderia ser melhor explicado pela insuficiente amostragem temporal dos estímulos utilizados nas experiências de percepção visual. Numa primeira experiência solicitámos aos participantes que identificassem a direcção do movimento dos estímulos, pedindo numa segunda experiência que eles escolhessem o mais natural de dois estímulos. Em ambas as experiências foram apresentados os mesmos estímulos, a diferentes taxas de amostragem. Os resultados mostraram que a amostragem temporal não explica os maiores tempos de percepção encontrados para o movimento biológico, mas forneceram algumas evidências de como as propriedades temporais do sinal de movimento poderiam estar implicadas na percepção visual.

Assim, investigámos as características temporais do movimento biológico em duas experiências onde manipulámos os padrões de velocidade e aceleração do movimento, preservando intacta a sua componente espacial. Em ambas as experiências foi pedido aos participantes para escolherem o mais natural de dois estímulos, representando os pés ou o pé de uma pessoa a caminhar. Os resultados mostraram que o sistema visual é bastante sensível a pequenas variações dos padrões de velocidade e aceleração, demonstrando que as características temporais do sinal de movimento afectaram o desempenho dos sujeitos. Utilizando o mesmo tipo de estímulos e a mesma metodologia, a experiência de neuroimagem corroborou os resultados psicofísicos. Os resultados mostraram as áreas cerebrais envolvidas na percepção do movimento biológico, mas também as áreas envolvidas no processamento das propriedades do sinal de movimento.

Numa última experiência analisámos a nossa hipótese num paradigma de percepção-acção, tentando acrescentar evidências às encontradas nas experiências psicofísicas. Capturámos movimentos de braço dos participantes e manipulámos as suas propriedades temporais, mas não as espaciais, como tínhamos proposto para as experiências anteriores. Aos participantes foi pedido que executassem um movimento específico com o braço, enquanto faziam simultaneamente o seguimento visual dos estímulos capturados e manipulados previamente. Os resultados mostraram que as propriedades temporais do movimento biológico influenciam não só a percepção, mas também a acção. A interferência na resposta motora reflectiu a coerência entre o movimento dos estímulos e o movimento executado pelos participantes, demonstrando que as propriedades temporais podem ter um impacto diferente sobre a sua acção.

Os resultados indicam que o sistema visual é altamente sensível a pequenas alterações nas propriedades físicas do movimento, demonstrando que as características temporais afectam a percepção e acção humanas. Discutimos a importância das propriedades do sinal na percepção visual e sugerimos novas experiências que reforcem os nossos dados, propondo no final uma nova abordagem sobre o processamento de sinal na percepção de movimento biológico.

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3. Inside *Point-Light Walkers*: from human motion capture to visual stimuli construction

4. Temporal Sampling in the Perception of Biological Motion

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ABBREVIATIONS, SYMBOLS AND UNITS

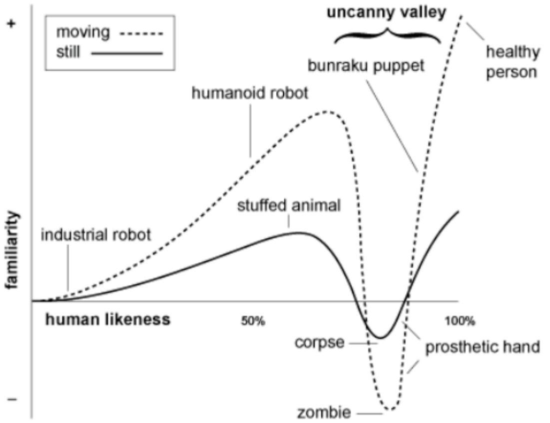
°	Degrees
2D	Two dimensions
3D	Three dimensions
ANOVA	Analysis of Variance
fMRI	Functional magnetic resonance imaging
Hz	Hertz (1/s)
ISI	Interstimuli interval
ITI	Intertrial interval
m	Metres
m^2	Squared metres
m^3	Cubic metres
mm	Millimetres
ms	Milliseconds
M	Mean
m/s	Metres per second
m/s^2	Metres per squared second
m/s^3	Metres per cubic second
MT	Middle temporal area
ns	not significant
PLW	Point-light walker
PM	Premotor area
s	Seconds
s^2	Squared seconds
s^3	Cubic seconds
SFM	Structure-from-motion
SD	Standard deviation
VT	Ventral temporal area

1. General Introduction

In 1906 the German psychiatrist Ernst Jentsch wrote about *the uncanny*: a psychological state characterized by an intellectual uncertainty. In his work "*On the psychology of the uncanny"* the author defined the *uncanny* as a sensation of unfamiliarity that a person feels towards a familiar object or event. It is as if something that we know and recognize as part of our everyday life causes a strange feeling of unknown or nonsense. Jentsch illustrated that feeling by describing the story of Olympia, a humanoid doll created by the German writer Hoffman in his short story "The Sadman". Olympia, according to Jentchs, introduces in that story the uncanny effect, a mixture of unfamiliarity and familiarity feelings. Why does a charming object, like a doll, awake a repulsive sensation when it assumes human actions, such as motion?

The theoretical explanation was given nearly seventy years later by the Japanese roboticist Masohiro Mori (1970). Retrieving Jentsch's concept of *uncanny*, Mori hypothesized that when robots look and act like human beings, observers present an avoidance and repulsive behaviour, as if something was wrong despite the robot's coherence and familiarity. Mori states that when the appearance of a machine is more human, the sense of familiarity experienced by a human observer increases until an abrupt moment characterized by a repulsive response caused by a strong feeling of unfamiliarity. But this unexpected depression in the curve of familiarity decreases again when the machine's appearance becomes less distinguishable from a human being. That abrupt decrease in the sense of familiarity followed by an immediate increase was called by Mori the *uncanny valley* and is shown in figure 1.1. The graph plots the sense of familiarity as a function of the robot's appearance, presenting this unexpected response to animate (moving) and inanimate (still) conditions.

Figure 1.1 The Uncanny Valley by Mori (1970).



Credits: Simplified version of the figure shown in the English translation of Mori's original article by MacDorman and Minato (available at www.androidscience.com).

According to Mori (1970), the problem of the uncanny valley could be resolved not by increasing the similarity between humans and machines, but by investing in a non-humanlike design, giving as an example the option for using glasses instead of prosthetic eyes. However, this option responds to a practical issue, saying nothing about the fundamental problem: why do we have a strong sense of unfamiliarity in the presence of robots acting as humans? Why does this feeling happen only when the similarity is closer to that of a healthy person?

The explanation that probably provided the most forceful arguments explains that it is an issue of congruency between structure and motion features (Saygin et al., 2011; Seyama and Nagayama, 2007). The reasoning is that if a robot acts like a human and looks like a human, no perceptual problem is elicited by the observers. If a robot acts like a robot and looks like a robot, again no perceptual problem is elicited. On the contrary, the perpetual problems arise when appearance and action are in divergence, explaining why familiarity feelings fall down to the uncanny valley. So, the contradiction between appearance or structure and functionality can justify this uncanny effect, and the difference between the curve representing the moving robots and still robots appears to be an empirical evidence of that.

In fact, we can see in the graph that the curve depression for moving machines is more pronounced than that of static machines, as the information carried out by motion not only does not bring more information but also hinders the human-robot interaction. However, the increase in familiarity from the dip of the valley is steeper for animate machines. If, on the one hand, feelings of familiarity increase with moving machines, on the other hand, it is also true that movement is one of the things that can elicit strong feelings of unfamiliarity. Why does this happen? Why does motion have a strong contribution to the uncanny valley? Why is this effect so pronounced in the motion condition? And why does it permit the faster recovery after its decrease along the valley?

The explanation for these questions can be found in some motion properties that are likely to have a critical role on perception. Considering the argument, it appears to be defensible that only by investigating the biological motion properties could we understand their importance for perception and action. Actually, the arguments presented above do not explain, at all, why the depression on the curve occurs so closer to a healthy person's condition or why motion contributes for a strong recovery.

More than an applied issue about robotics or, in general, about human-machine interaction, the uncanny valley demonstrates that many questions about biological motion and their properties remain unanswered thirty years after the relevant work of Gunnar Johansson (1973). Systematizing a methodology that made it possible to isolate biological motion as a variable, the point-light figures of Johansson persist in being a powerful tool for research on biological motion. In the present work we will return to Johansson's research, specifically to the point-light stimuli as proposed by the author. We will go inside point-light walkers, from which we will start effectively investigating motion properties.

Basically, and stating it clearly, we will try to demonstrate that biological motion carries with it some crucial motion properties that, more than biological, are spatiotemporally defined and, in this sense, temporally processed and integrated. In other words, any motion pattern could be defined in terms of its displacement in respect to time, which, consequently, presupposes specific velocity and acceleration patterns. These patterns, on the other hand, cannot be dissociated from their temporal component. Thus, by changing the temporal component we are changing the motion properties and the question remains central: how do we perceive this kind of information? Considering the common *dictum* of classical physics that states that *in nature everything is continuous*, how do we process the temporal motion component? What is the specific spatiotemporal information carried out by biological motion and how do we use it? Or, specifically, how do we integrate the *continuous* temporal component in biological motion perception?

1.1 Background: Biological motion and its study

Broadly speaking, biological motion refers to any characteristic movement of an animate entity. Actually, it could refer to natural or biological entities, thereby meaning that biological motion applies to all natural kind of movements, from the obvious human motion to the movement of a tree crashing on the ground. In this sense, a flower opening in the morning or closing in the afternoon, a person running to the bus, the movement of tides or the wind moving the trees of a forest are examples of biological motion (Thornton, 2006, p.262). However, for scientific purposes, the perception of biological motion concerns the perception of people or animals in motion (Dekeyser, Verfaillie, & Vanrie, 2002; Giese, 2006; Johansson, 1973).

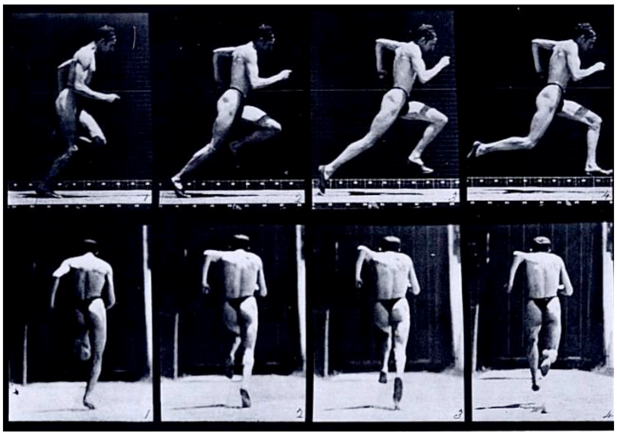
The majority of the studies on the visual perception of biological motion have been concerned with the perception of animal's motion patterns, but mainly with visual perception of human movements, perhaps, as Thornton (2006) pointed out, explained by its social relevance. Typically, human observers judge the actions of other humans, such as walking, jumping, running or throwing (Ahlstrom, Blake, & Ahlstrom, 1997), but there are studies about the human perception of animal motion patterns (Mather & West, 1993). Nevertheless, we can find numerous studies that investigate the perception of biological motion in animals. Among mammals, the study of Siegal and Andersen (1988) found the ability to discriminate structure-from-motion in monkeys and the ability to recognize the biological motion of their species (Oram & Perrett, 1994). Blake (1993) found the same results with cats as well. There are also strong evidence with birds, such as Emmerton (1986) demonstrating the capacity of pigeons to discriminate complex motion patterns and Omori and Watanabe (1996) finding that pigeons could distinguish biological motion using conditioning procedures. Equivalent ability was found in dolphins (Herman et al.,1990), in quails (Yamaguchi & Fujita, 1999) or even in chickens (Regolin, Tommasi, & Vallortigara, 2000). All of these findings, supported by the evidence of children's early ability to distinguish biological motion, demonstrate the survival importance of biological motion perception. As shown by Simion, Regolin and Bulf (2008), 2-day-old babies were able to discriminate biological from non-biological movements, preferring upright biological motion patterns. Citing the authors, "these data support the hypothesis that detection of biological motion is an intrinsic capacity of the visual system, which is presumably part of an evolutionarily ancient and non species-specific system predisposing animals to preferentially attend to other animals"(p.809).

In the history of science it is easy to find old references to the study of biological motion. Probably the oldest of them refers to Aristotle's work *De Motu Animalium* - On the Movement of Animals. The Greek philosopher had considered that animal locomotion was more than a mechanical system of movements, allowing for the difference that could exist between imagining and performing an action (Martins, 1999). Other prominent scientists dove into the study of biological motion, trying to describe the mechanics of standing, walking up and down hill, rising from a sitting position, and jumping, such as those made by Leonardo da Vinci or Galileo's efforts to mathematically analyse the physiologic function of motion. Among others, the work of Borelli, that studied the forces implied in equilibrium in various joints of the body, also stands out, as does Newton's, which postulated the laws of motion. (see Roetenberg (2006) and Martins (1999), for a review).

Nevertheless, Muybridge (1887/1979) was the first to dissect human motion, by taking a set of high-speed photographs of human and animals in action and trying to capture the patterns of human motion, as showed in figure 1.2. However, the credits for using photographic techniques to scientific purposes were due to Étienne-Jules Marey (1884). The French physiologist developed the "chronophotography," a high-speed photographic technique inspired by Muybridge's work that can acquire consecutive images on a single photographic plate. To capture human movements, Marey filmed an actor walking while wearing a black suit with small markers attached to the joints. Then, he added lines connecting the markers, to make a stick-like figure. Figure 1.3 shows one of Marey's chronographs, a sequence of images of a person walking, taken at 12 frames per second. This method was the starting point for the modern techniques of capturing and studying biological motion. Without much exaggeration, we can say that the idea of capturing the movements of an actor wearing a black suit with small markers attached to the joints remains perfectly contemporary.

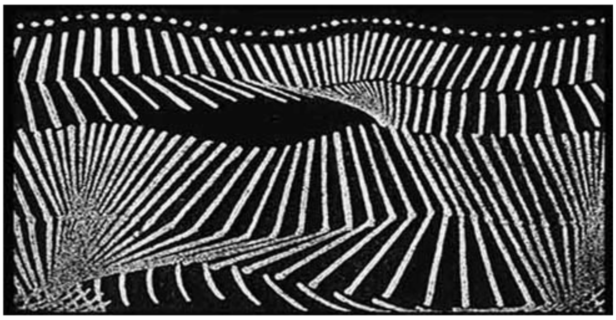
Presently, the majority of studies on biological motion perception use point-light displays to study biological motion, a technique developed by the Swedish psychologist Gunnar Johansson (1973) that uses the same principle of Marey's technique: dots attached to the main joints of a person. Initially, Johansson attached small light bulbs to the main joints, a procedure later replaced by retro-reflective markers that subjects secured over a black suit, and then he filmed the patterns of a person moving. The result was a set of twelve dots – shoulders, elbows, wrists, hips, knees and ankles – against a black background. Later, a marker was attached to the head, resulting in a stimulus with thirteen dots, as showed in figure 1.4.

Figure 1.2 Man running at full speed by Muybridge (1887).



Credits: Muybridge, E. (1887/1979). Complete Human and Animal Locomotion, vol.5. New York: Dover Publications, p.646.

Figure 1.3 "Analyse cinématique de la marche" by Marey (1884).

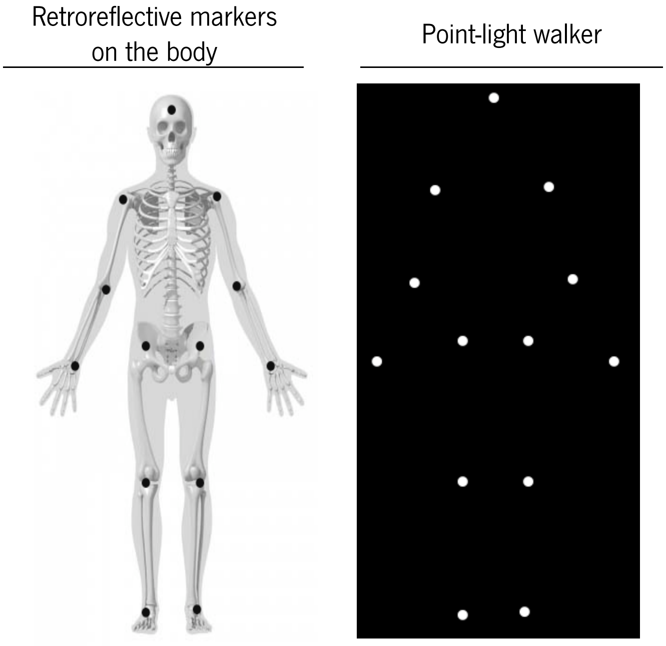


Credits: Marey, E. J. (1884). Analyse cinématique de la marche. Comptes rendus des séances de l'Académie des sciences, p.2.

With point-light walkers all form features associated to the human body, such as body shape, familiarity and volume are absent. Only the motion properties are being represented. Because of that, in a static condition where the figure has no motion, observers cannot recognize a human being or, at least, the recognition is awfully poor. Nevertheless, when the stimulus is animated, the perception of a human being in motion is so vivid and powerful that all subjects recognize it. The impressive recognition of a person in motion and the possibility to isolate motion patterns as independent variables made this technique popular in the field of biological motion perception.

Effectively, after Johansson's work (1973), the stimuli used to investigate motion patterns were based almost always in the point-light walkers. Even tough the procedures to create them changed with technological advances, the central idea remains valid: dots representing the joints of a person or animal. One of these advances consisted in an artificial synthesis of the motion patterns, i.e., a computer-based algorithm that simulates human motion. One of the most used, since Johansson's work, was developed by Cutting (1978). The author artificially generated a human figure walking in a sagittal perspective during one step cycle. The facility in generating movement patterns without capturing real movements made this procedure one of the most used in biological motion research. In fact, in numerous studies cited previously the stimuli were produced with Cutting's algorithm or a variant of it. For instance, to simulate more perspectives than the sagittal view developed by Cutting, Verfaillie, De Troy, and van Rensbergen (1994) modified the Cutting' algorithm. Nowadays the point-light stimuli are mostly produced with motion capture systems working with near infrared retro-reflexive markers or electromagnetic markers. Like Johansson, markers are attached to the body of a subject and his movements are captured in a 3D coordinates system, something not possible with Johansson's 2D-films. These capture systems, as we will discuss in detail in chapter 2, make it possible to accurately reconstruct motion coordinates and is less time consuming when capturing different kinds of movements.

Figure 1.4 Point-light walker as proposed by Johansson (1973).



Retroreflective markers on the body

Point-light walker

Independently of the procedure adopted to create the stimuli, relevant information can be portrayed via point-light walkers, such as sex of the walker, the motion pattern of a friend, emotions or intentions. It is possible to find different names for the stimuli, such as point-light figures, point-light displays or point-light stimuli. Usually it is considered that point-light walkers refers to the classic proposal of Johansson, a walker with dots attached to his body, not necessarily twelve or thirteen. Point-light displays or point-light figures can allude to other kinds of movements or stimuli to which the same technique is applied. In the present work we will use all of them indistinctively, except when there is a need to distinguish them, which will be noted.

1.2 The study of biological motion and our main goals

The intrinsic capacity to perceive biological motion explains one of the main issues on biological motion research: the determination of the information that can be extracted from biological motion. The common idea is simple and hypothesizes that if we have a higher and earlier capacity to perceive biological motion, it probably means that we can extract useful information from biological motion, such as the age of the person for instance (Montpare & Zebrowitz-McArthur, 1988).

This information could help us in numerous tasks in our everyday life by mediating our actions. In fact, research has demonstrated that social relevant features can be provided by biological motion patterns. Kozlowsky and Cutting (1977) showed that observers could perceive the sex of a walker from dynamic features provided by the ankle of male and female walkers. The same result was found by Braclay, Cutting and Kozlowsky (1978) – the possibility to recognize the sex of a walker from motion cues –, an ability that Mather and Murdoch (1994) argued could be due to the differences in velocity of shoulders and hip. These studies also showed that it is possible to distinguish the identity of a friend just from his/her motion patterns (Cutting & Kolowski, 1977) and recognize oneself's motion patterns (Beardsworth & Buckner 1981, Jokisch, Daum, & Troje, 2006). Moreover, the observers can distinguish easily different kinds of actions just from motion. Dittrich (1993) demonstrated that subjects could recognize locomotory actions better and faster than social and instrumental actions.

But not only features directly related with dynamics and structure could be extracted from biological patterns. Numerous researches have demonstrated that observers can infer psychological states and intentions from the movements of others. Dittrich and collaborators (1996) showed that subjects could discriminate different kinds of emotional states from biological motion. The authors presented observers with video clips of two trained dancers, who were asked to convey the following emotions: fear, anger, grief, joy, surprise, and disgust. The results demonstrated that subjects correctly judge and describe the emotional state of the dancers, but only if they were moving. In a static position or in a non-conventional position, such as upside down, the observers were unable to judge or describe the same emotional state. If we understand that motion patterns carry out relevant information, we can suppose that it is possible to extract that information, as suggested by Maruta and Ishii (2007). They proposed a set of equations that extract the vectorial features of motion, making it possible to distinguish the five kinds of emotions proposed by Dittric and colleagues (1996). According to the authors, a computer program could easily identity the emotion of a person just by his/her own movement patterns. Moreover, Pollick and colleagues (2001) showed that arm movements influence the perceived affect. The researchers presented subjects with the arm movements of two actors performing drinking and knocking movements, concluding that the perceived affect is related to the kinematics of motion and that the pleasantness of the movement appears to be extracted from the relation between the different limb segments.

These examples provide good evidence that biological motion carries features that not only allow the recognition of other humans, but also allow for the processing of crucial social information. Effectively, biological motion properties appear to be sufficiently powerful to provide information of pure psychological states, such as intention. As Darwin (1872/1890) had already pointed out in his work about the expression of emotions in men and animals, actions speak louder than static appearance or structure when it comes to understanding what others are feeling. Citing the author, "most of our emotions are so closely connected with their expression, that they hardly exist if the body remains passive – the nature of the expression depending in chief part on the nature of the actions which have been habitually performed under this particular state of the mind" (1872/1890, pp.237-238). Effectively, as shown by Manera and her colleagues (2010), information available through motion patterns is sufficient to recognize the intention of an action and, more specifically, the communicative gesture performed by an observed person.

In spite of the range of information provided by biological motion patterns, from the perception of sex differences to the perception of intentions, the motion properties that support the perception of biological motion have remained poorly understood comparatively to the information that could be extracted from it. In fact, the information provided by biological movements does not explain, or explains little, which motion properties are involved in the perception of biological motion. This is curious if we think that the majority of studies are supported by Johansson's methodology of point-light walkers, a stimulus that reduces movements to a set of dots attached to the major joints of a person or animal. In contrast to the studies described above, in his original work Johansson (1973) was concerned with the properties and mechanisms of movements that allow for the perception of biological motion itself and that enables the availability of other information as described above. However, the majority of the studies that tried to understand the properties and mechanisms were developed later. Currently, perhaps this is the main theme on biological motion perception. The main assumption is that the efficiency with which we can perceive biological patterns can be due, as Johansson (1973) noted, to an automatic process that extracts the mathematically lawful spatio- temporal relations from visual motion patterns. How can we integrate a range of spatial and temporal motion features in a congruent and vivid percept of biological movements?

Research has found numerous evidence that support the common idea that biological motion is an integrated percept of structure features and dynamic cues, i.e., form and motion characteristics. Although the authors' opinions diverge about the importance of each one, it is clear that dynamic information represents the most powerful source of information (Di Luca, Domini, & Caudek, 2004; Garcia & Grossman, 2008; Johansson, 1977; Troje, 2002). In fact, biological motion can be defined by its kinematic properties. More than global translational patterns or local characteristic movements, its complexity contains unique and distinctive features that allow an efficient perception. As a time-varying function, a biological signal is a sequence of spatial moments occurring in a natural temporal order with respect to biomechanical and physical laws. This entails the integration of spatiotemporal characteristics available through biological kinematic properties, such as velocity and acceleration. As pointed out by Winter (2009), "*all of the biomechanical variables are time-varying, and it doesn't matter whether the measure is kinematic, kinetic or EMG; it must be processed like any other signal. Some of these variables are directly measured: acceleration and force signals from transducers or EMG from bioamplifiers. Others are a product of our analyses* (...). *All can benefit from further signal processing to extract cleaner or average waveforms, correlated to find similarities or differences or even transformed into the frequency domain*" (p.14).

With this assumption, we can assume that if kinematic features were not present, or if they were neglected, the signal processing would be affected and, consequently, so would the visual perception of biological motion. In other words, the kinematic properties of biological motion, expressed in terms of velocity and acceleration patterns, are central to the perception of biological motion, and visual perception depends largely on the temporal integration of those properties. Effectively, the high capacity to recognize biological motion (Johansson, 1973) is not reflected in a high capacity to integrate the signal – biological motion is a more time-consuming type of perception, despite being easily recognizable (Burr & Santoro, 2001; Neri, Morrone & Burr, 1998; Watamaniuk & Sekuler, 1992). Here, the results of Neri and colleagues are probably the most intriguing. According to the authors, an observer needs around 2000 ms to perceive a biological stimulus, whereas for a simple translation pattern 600 ms are usually more than enough. If we can recognize biological motion patterns so easily, why do we need more time to perceive them? This is our central question. Why do we find long time summation for biological motion? Is it due to intrinsic characteristics of biological motion or can we expect that the larger temporal summation might be just a consequence of an insufficient temporal sampling of the stimuli?

Commonly, the studies about biological motion perception use low temporal samplings (i.e., frame rates), between 30Hz and 60 Hz (e.g.., Bruggeman & Warren, 2010; Schlack, Krekelberg, & Albright, 2008; Thurman et al., 2010). Considering that biological motion is characterized by complex translational and rotational patterns, it can be expected that the lower the frame rate is, the less information is available in the stimuli and, consequently, the more time it takes to integrate the biological motion signal. Clearly, we are hypothesizing that temporal sampling can explain the higher temporal summation found in studies about visual perception of biological motion.

Nevertheless, if we demonstrate that our hypothesis is true, we are still not explaining what is happening. Which biological motion features can explain that? Which specific motion signal features are being processed over time? Considering that the biological motion signal is defined by its kinematic properties, and considering that higher temporal summation is more than an issue of temporal sampling, can the way in which they are being processed explain why we need more time to perceive biological motion patterns? Our hypothesis is clear: the acceleration and velocity patterns associated with biological motion are specific features that are being processed over time. This means that we are able to process the characteristic velocity and acceleration patterns of biological motion but, simultaneously, that it is the specificity of kinematic properties that could explain the higher temporal summation and, consequently, the temporal integration process in biological motion perception.

The argument appears to be more relevant if we think that, during an action, our performance could be affected by the perception of velocity and acceleration patterns. In other words, the correct processing of these properties over time developed a central role not only in perception itself but also in our motor actions (e.g. Jacobs and Shiffrar, 2005; Kilner, Hamilton and Blakmore, 2007). According to these authors, our motor performance is influenced by velocity and acceleration patterns of stimuli in motion. So, considering our hypothesis, we can also hypothesize that kinematic properties of biological motion can explain differences in motor responses when we change the stimuli’s temporal component. Furthermore, the argument is strengthened by the existence of different brain areas involved in processing biological motion that together constitute a specialized network that plays a central role in biological motion perception and action understanding (see Grossman, 2006, for a review). The main issue is the same: if kinematic properties, expressed in terms of velocity and acceleration patterns, are critical in perception and action, and explain the higher temporal summation for biological motion, we can expect that brain activity too reflects this phenomenon.

Overall we are hypothesizing that the higher temporal summation found for biological motion is a consequence of its kinematic properties. Therefore, we can expect evidence of that in terms of perception, action and brain activity. This is precisely what we will try to do in the present work.

1.3 Thesis overview

Before describing our experimental work, we will describe in chapter 2 some concepts associated with biological motion study, such as human gait concepts and motion equation. After that we will present the construction of motion biological stimuli. It is crucial that we know in detail all of the kinematic properties of our stimuli. Chapter 3 details this process, from the motion capture to the stimuli construction. The technical problems and their consequences in the stimuli quality will be presented, explaining all methodological options.

Then, in chapter 4, we will discuss a technical issue that can explain some known evidence about biological motion. Before trying to demonstrate that the visual perception of biological motion is better explained by its kinematic properties, we will discard technical explanations. As we are defending a temporal integration in the perception of biological motion, we need to ensure that the lower temporal sampling commonly used in these experiments does not justify the large temporal summation of biological motion. Our results pointed to the rejection of the technical hypothesis and provided evidence that the temporal integration of kinematic properties can explain the perception of biological motion.

After discussing the nature of biological motion and the stimuli's characteristics, and after discarding some methodological issues, we will present a set of experiments where we manipulated the kinematic properties of biological motion. We will try to demonstrate that temporal characteristics, expressed in velocity and acceleration patterns, improve the perception of biological motion. This will be chapter 5.

Considering the psychophysical arguments discussed in previous chapters, we will able to analyse, in chapter 6, the brain processing of biological motion. The correlation between brain areas involved and the psychophysical results brings a new perspective about biological motion's visual perception. The results not only respond to the temporal integration argument, but also allow for new hypotheses.

Knowing the psychophysical results and the brain areas implied in the visual processing we then need to understand what happens in behavioural terms. In chapter 7 we will propose an action-perception experiment where we explore the influence of biological kinematic properties on the person's motor activity.

Finally, we will propose a general discussion, returning to the uncanny valley and suggesting future works. In this sense, chapter 8 presents a summary of the main conclusions and their implications for biological motion research.

2. Transversal concepts and assumptions

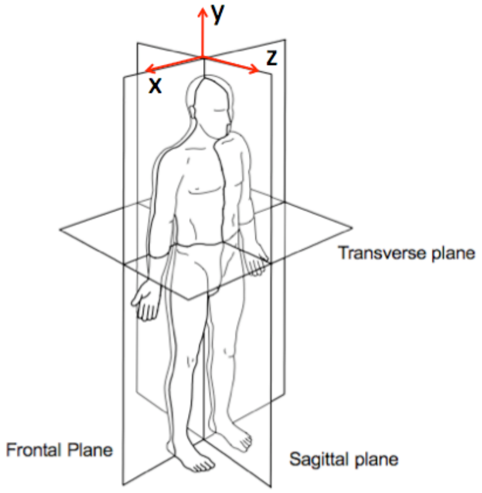
In the present chapter we will describe some concepts associated with biological motion, such as human gait concepts and motion equations. As we will make reference to these topics frequently, we opted to explain them in an independent section, before starting the discussion of methodological questions concerned to biological stimuli construction, and before presenting our experiments about perception of velocity and acceleration patterns in biological motion.

2.1 Human gait concepts

Studying human motion patterns presupposes the definition of the three primary planes of the human body and the definition of the different phases and events of human gait. Thus, we present a brief description of human gait concepts, suggesting for an exhaustive review the works of Inman, Ralston, and Todd (1981), Vaughan, Davis, and O'Connor (1999) or Winter (2009).

Three main planes define human gait: coronal, sagittal and transverse (figure 2.1). Coronal plane corresponds to a frontal or back view of the human body. For instance, we say that coronal plane is parallel to an observer when he/she is face-to-face with another human body. In terms of locomotion, coronal plane corresponds to the elevation movements (y-axis in the figure). A plane corresponding to a side view is called sagittal plane. It is also called translational plane because the typical translational movements take place in it (z-axis in the figure). The third is the transverse or axial plane and it corresponds to the lateral body movements (x-axis in the figure). When a person is moving in a perfect straight line, the transverse plane measures the trajectory's deviation. In human gait this is probably the most neglected plane while the sagittal plane is the most considered. Working with 3D systems, such as the motion capture systems to create point-light stimuli and 3D display systems, the definition of these three dependent planes becomes even more relevant.

Figure 2.1 Reference planes in standard anatomical position.

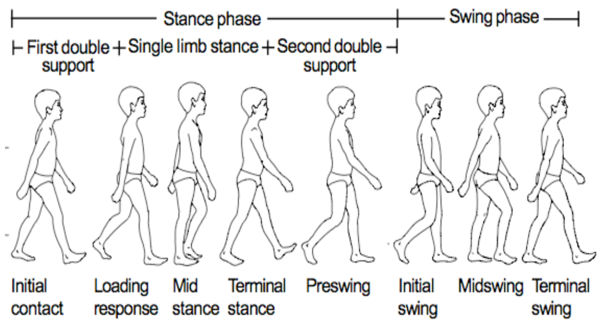


Credits: Vaughan, C. L., Davis, B. L. & O'Connor, J. C. (1999). Dynamics of Human Gait. Cape Town: Kiboho Publishers, p.7.

The human gait cycle comprises two phases (figure 2.2) involving eight events (figure

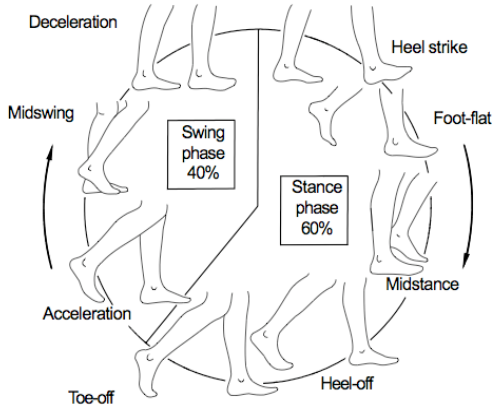
2.3), considering one foot only. The stance phase corresponds to the moment when the foot is on the ground and the swing phase corresponds to the moment when the foot is not in contact with the ground and is moving forward. Thus, if one foot is in swing phase the other is in stance phase, although both can be in stance phase, a condition called double support. Effectively, this is the distinctiveness of human gait, compared with other actions such as running or jumping. Walking presupposes, at least, one-foot support, a foot in stance phase when the other is in swing phase, or two feet support, when both feet are in stance phase.

Figure 2.2 Human gait phases.



Credits: Vaughan, C. L., Davis, B. L. & O'Connor, J. C. (1999). Dynamics of Human Gait. Cape Town: Kiboho Publishers, p.9.

Figure 2.3 Human gait events.



Credits: Vaughan, C. L., Davis, B. L. & O'Connor, J. C. (1999). Dynamics of Human Gait. Cape Town: Kiboho Publishers, p.11.

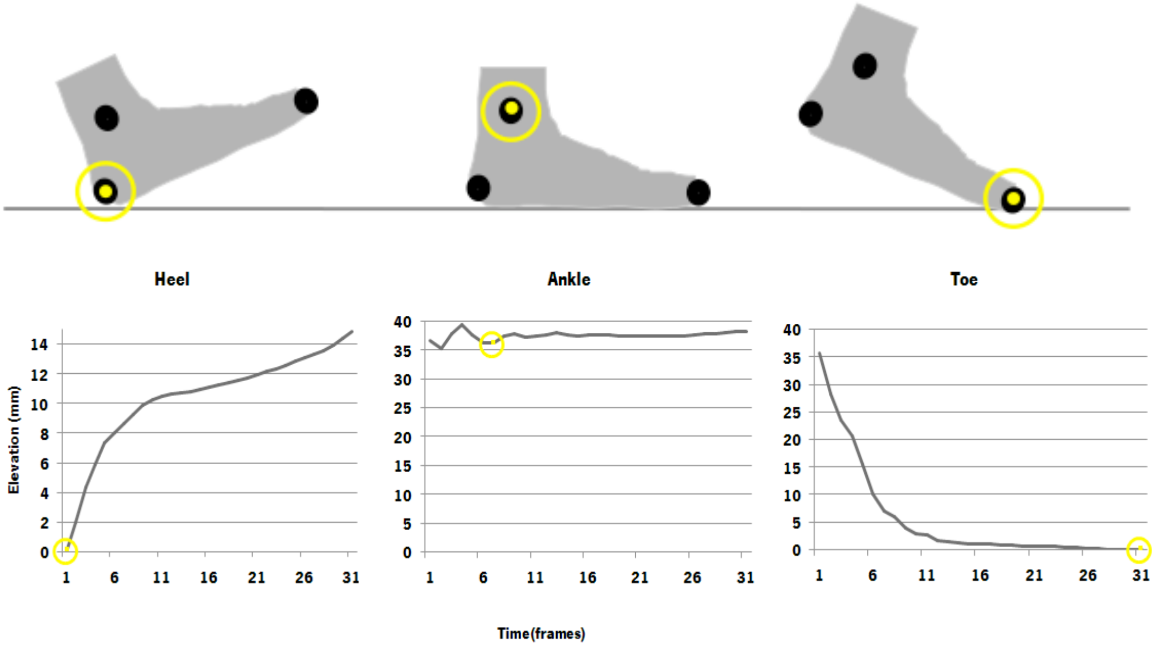
The stance phase can be divided in three distinct moments. As showed in figure 2.2, this phase starts with the moment corresponding to the first double contact, when the foot is on the ground and immediately before the other foot stars its swing phase. Then follows the single limb stance when only one foot is on the ground and then the last moment, the second double support, with both feet again on the ground.

The swing phase is shorter than the stance phase corresponding, on average, to 40% of the total duration of the cycle. It can be divided in three distinct moments corresponding to the first moment of no ground contact, followed by the moment when the foot is in the middle of the translation movement and finishing with the last moment before the first ground contact.

Both phases can be defined in terms of events, considering the full gait cycle. Starting with the first moment of the stance phase we have the first ground contact (heel-strike), followed by the full foot support (foot-flat and midstance) and finishing with the last ground contact (toe-off). Once in swing phase, the foot starts accelerating at the midswing, after which it decelerates. Along the present work we will refer frequently to these events to explain the stimuli construction and to discuss the results of our experiments.

Note that the gait cycle is described considering two foot parts, the heel and toe. However, in point-light walkers a marker attached to the ankle corresponds to the foot, as proposed by Johansson (1973). So, in point-light walkers, the ankle represents the different stance phase moments, as illustrated in figure 2.4. The graphs represent the movements of the heel, ankle and toe in stance phase, with the yellow circle highlighting the three events that help to define that phase: heel-strike, foot-flat and the instant before toe-off. The stance phase in point-light walkers starts in the instant that corresponds to the heel-strike in human gait and finishes in the instant before toe-off. In other words, we consider the spatial coordinates of the ankle but the temporal coordinates of the heel and toe, respectively.

Figure 2.4 Stance phase – correspondence between real human gait and point-light walker's.



2.2 Motion equations: physical assumptions

Any body in motion presupposes a space-time relation, and biological motion is not an exception. Global body motion or its local movements can be defined always as a space translation as a function of time. The spatiotemporal condition implies a set of related and dependent functions generally designed as motion equations. In a strict sense, motion equations refer to the behaviour of a physical system in terms of its motion during a specific period of time. Commonly, the first equation describes a simple translational pattern in a period of time from which we can compute the differential equations associated, such as velocity and acceleration for example. This spatiotemporal explanation of motion is called kinematics, i.e., the description of motion without considering its causes, the reason why it is also referred as the geometry of motion. The kinematics also describes the motion of a system composed by different joint components, as in the case of a human body.

It is frequent to indiscriminately use kinematics and dynamics concepts as referring to the same phenomenon. This is not necessarily an error, but an operationalization can be useful. Dynamics deals with the relation between motion and its causes. In this sense, kinematics could be a branch of dynamics. For instance, in the study of the role of gravity forces on biological motion we are studying the dynamics involved in it. However, if we just describe the velocity or acceleration patterns of a human body we can talk just on kinematic terms.

The study of biological motion perception involves the description of the biological stimuli but also the manipulations made on the natural stimuli. These manipulations imply frequent changes in position as well as in velocity and acceleration patterns. In the present work we will do it frequently, not only to construct the stimuli, but also mainly to discuss the importance of perceived velocity and acceleration patterns to process biological movements.

Human motion can be defined as the body's displacement over space as a function of time. This is called global motion and can be measure in meters. The full body translation generates a position vector defined as the common translational component. It is common because it affects all body parts equally. When we analyse a specific body part, such as the wrists for instance, we are analyzing the local motion that defines that specific part. Taking the wrist as an example, when a person is walking the wrist movements are characterized by the translational motion from one place to another and, simultaneously, the pendulum's distinctive movements, backwards and forwards. A good example is provided when a person is walking on a treadmill, where the common translational component is absent but the local movements backwards and forwards are not. The displacement (Δp), global or local, is easily computed considering the difference between the position in an initial instant (p_i) and the position in a final instant (p_f), such that

$$\Delta p = p_i - p_f \Leftrightarrow p_f = \Delta p + p_i \text{ (SI Units in meters).}$$

Both local and global movements can be defined in terms of average velocity and acceleration. The average velocity is found by dividing the difference between initial and final positions by the length of the time interval, such that

$$v = \frac{p_f - p_i}{t_f - t_i} = \frac{\Delta p}{\Delta t} \text{ (SI Units in meters per second).}$$

The average acceleration is the difference between the initial and final velocity for a given period of time and can be calculated as

$$a = \frac{v_f - v_i}{t_f - t_i} = \frac{\Delta v}{\Delta t} \text{ (SI Units in meters per second squared).}$$

This means that displacement, velocity and acceleration are related concepts. The relation is clearer when assuming that motion is a continuous function so that its position is a function of time, such as p =p(t), where *p* is the position and *t* the instant. The velocity, v(t), is the limit of the average velocity when t → 0, i.e., it is the rate of change of position with respect to time and can be calculated deriving the position's function, such that

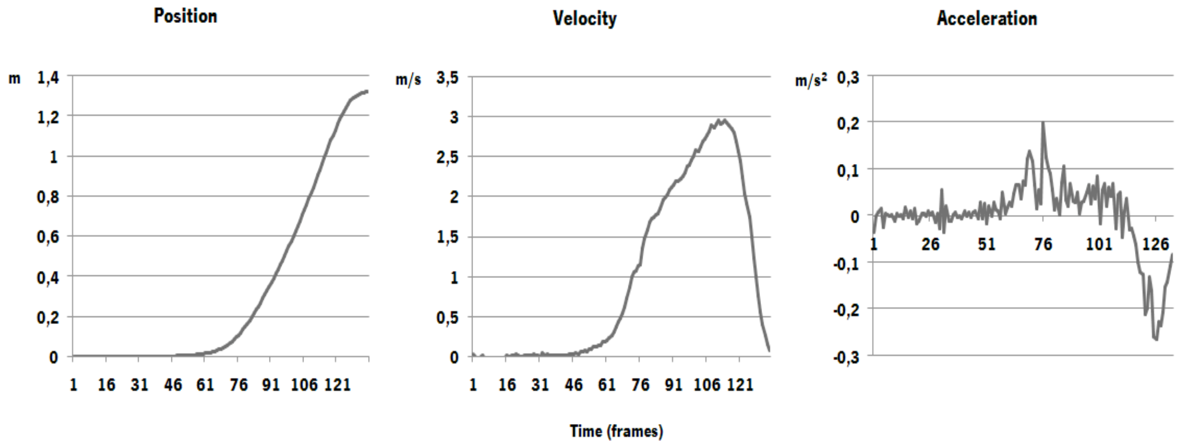
$$v(t) = \frac{dp}{dt} = p'(t)$$

Also, the rate of change of the velocity with respect to time is the acceleration, its derivative or the second derivative of the position, so that

$$a(t) = \frac{dv}{dt} = v'(t) = \frac{d^2 p}{dt^2}$$

This relation will be useful to understand the stimuli of our experiments, as will be explained in chapters 4, 5 and 6. In fact, the kinematic properties of motion are always expressed in terms of displacement, velocity and acceleration. By a derivation or integration process we can obtain the three components. Figure 2.5 illustrates the kinematic properties of an ankle movement, starting in the stance phase (heel-strike) and finishing in the swing phase (previous to the next heel-strike).

Figure 2.5 Motion equations.



3. Inside *Point-Light Walkers*: from human motion capture to visual stimuli construction

3.1 Introduction

Nearly forty years after Gunnar Johansson's work (1973), his paradigm remains the most widely used in the study of biological motion. Despite all the technical developments, the power of *Point-light walker* (PLW) stimuli is explained by their specificity. In spite of the difference between classical studies (Johansson 1973, 1976; Cutting & Kozlowski, 1977) and more recent approaches (Chang & Troje, 2009; Thirkettle, Benton, & Scott-Samuel, 2009; Thurman, Giese & Grossman, 2010), the PLW paradigm remains unquestionable. Therefore, most experimental studies on visual perception of biological motion assume that this kind of stimuli is perfectly known and explained – when we have markers attached to the main joints of a person we presume that we have a PLW and can therefore study everything about biological motion. This confidence can be explained by Johansson's results in his experiment in 1973.

Actually, point-light walkers stimuli have become a common tool on biological motion research. Despite their simplicity, these figures provide relevant and ecological information about a complex phenomenon – the human motion patterns. A pattern of a few dots allows research about temporal, spatial, local and spatiotemporal components of biological motion. Furthermore, as Johansson pointed out, subjects need no more than 200 ms to perceive biological motion with moving stimuli (Johansson 1976). Effectively, the ease with which these stimuli are manipulated makes them useful in this research area (see details in Thornton, 2006). Nevertheless, the most relevant characteristic is the possibility to understand the dynamic of human motion. The impoverishment of the stimulus makes it unique because it enables the isolation of one variable: motion.

In fact, we can say that PLW provide two sources of information: dynamic and structural (Troje, 2002). Dynamic information refers to motion *per se*. For instance: translation, velocity and acceleration patterns are dynamic components of motion, which means that this kind of information is only available with moving stimuli. However, this does not mean that structural information refers to the static figure. Normally, in the literature, structural cues refer to the information given by the relationship between dots – more specifically, the articulation of the body. This holistic nature of the stimulus is presented as evidence of structural clues (Bertenthal & Pinto, 1994). The dichotomy dynamic-structure, also called motion-form, has generated a lot of research and is often discussed, for instance, in gender issues (Barkley, Cutting, & Kozlowski, 1978; Mather & Murdoch, 1994, Troje, 2002). Given that even structural information refers to the relation between dots, we can say that this information is available during the stimuli's motion. Therefore, structural and dynamic information are motion dependent and, consequently, their study depends on the stimuli's motion patterns. Although this assumption is controversial, here we assume that this dichotomy is irrelevant, precisely because we are always talking about motion.

In their work, Beintema and Lappe (2002) clarify this question by suggesting that the emphasis on the analysis of motion signals in most studies makes no sense, and they show that it is possible to perceive biological motion only from sequential position cues. As the authors pointed out, the perception of motion is explained from form instead of from motion. They presented a PLW walking on a treadmill, but they reallocated the dots after each frame. The reasoning behind this procedure is that when we change the dots' position we reduce the motion signals because the motion's vectors become impaired. The perception of biological motion is possible because the stimuli maintain posture. The results are defensible, but not the arguments proposed. If the concepts change perhaps we can understand the question differently.

The main issue is always motion, which can be express dynamically or structurally. Regarding temporal or spatial components we need to know if our stimuli effectively represent what they should. Thus, when we manipulate any attribute of biological motion we are manipulating temporal or spatial components, or both. In others words, we have to ensure that when we present a point-light figure we are presenting biological motion with its spatio-temporal components intact. Basically, it means that point-light walkers are real human motion figures, more than prototypical figures of a human being. It is not a question of "looks like" but "being", and we would expect that all researchers explain how they construct their stimuli. Instead, we find a generic and brief description: dots located on the main joints of a subject. Two main reasons can explain this fact.

On the one hand, visual systems organize the moving dots into a vivid perception of a human being in motion (Dekeyser, Verfaillie, & Vanrie, 2002). Such as Johansson (1973) showed (see details in chapter 1), despite the degradation of the stimulus, subjects can easily recognize a human being. His results are so clear and simple that we have no room for doubt. If the perception is so strong, why would we need more than a few dots attached to the joints of a moving subject? Because the research topics now are more than the simple recognition tasks used in the '70s. Nowadays researchers are concerned with topics such as local cues of motion, small variations inside the gait cycle, and synchronization patterns, just to name a few (e.g. Chang & Troje, 2009; Thurman, Giese, & Grossman, 2010).

On the other hand, the PLW construction requires time, resources and knowledge. Maybe this is the main reason. Assuming this is true, it is understandable why Cutting's algorithm (1978) has become the most used technique for PLW construction (Dekeyser et al., 2002; Runeson, 1994). This algorithm artificially synthesizes one human step cycle in a sagittal view. Later, Verfaillie, De Troy, and Van Rensberg (1994) made some enhancements that enable different angle views, but the artificiality is equal. Thirkettle and colleagues (2009) draw attention to this. Citing these authors' conclusion in their work, "because the complex nature of the stimulus, studies of biological motion using the PLW are *particularly vulnerable to the presence of artifacts* in the method which can skew the results. Careful *consideration of possible artifacts is essential* when interpreting data from biological motion experiments" (pp.8-9, emphasis added). Most of these artifacts are related, precisely, with the PLW construction.

3.1.1 Distal and Proximal Approach

An old question in the research on biological motion, the distal and proximal approach distinction might be central in the construction of PWL. Despite his most cited work (Johansson, 1973), Johansson (1950) began the study of motion using a proximal approach. In his previous research the author presented observers with events manipulated on the screen, which is to say, synthesized movements. Later he opted for a different method that preserved the real characteristics of the movements presented. In his work on biological motion (1973, 1975, 1976), he presented observers with motion patterns previously captured, on which the researcher didn't interfere. Consequently, the movements maintain their complexity and real kinematic properties. Because the possibility of manipulation is away from the "visualization moment" it is called distal approach. In contrast, the proximal approach allows the synthesis of motion patterns "at the moment", in which the researcher can choose the features of patterns, and the movements lose their real kinematic properties. Cutting's algorithm (1978) provides a good example of this.

More recently, a third approach can be identified – a mix between the proximal and distal approaches. According to the definition above, this would be classified as a distal approach because the data are captured before the screen ("the visualization moment"). However, effectively, there are a number of numerical processes that can change the real kinematic motion properties applied between the motion capture process and the visualization. In this sense it is a proximal perspective. We are not even talking of an algorithm of motion or a pure motion capture. Instead, we refer here to the motion capture manipulated by powerful mathematical models. Most likely, the majority of authors have included it in the distal approach.

However, if we concede that manipulations on the original data change, even slightly, the naturalness of motion, we are changing the kinematic properties and we have chosen the features that we consider relevant. If this is not a pure manipulation, then it is at least a smoothing of movement patterns.

After capturing a specific action, programmers use an amount of "cleanup data models". The analysis of the motion data captured is simpler and faster using specific mathematical models and, as pointed out by Cutting (1978), they were "chosen simply because they yielded the most natural-looking movements". For instance, nonlinear models, such as B-Splines, are common techniques for parameterizing movement features (Ramsay & Silverman, 1997). In periodic functions, Fourier's techniques are very useful in the analysis of translational components and local sinusoidal patterns (Unuma, Anjyo, & Takeuchi, 1995; Kay & Warren, 2001). The Principal Components Analysis (PCA) supports the manipulations in the dimensionality of the spaces, for example, by reducing the degrees of freedom (Troje, 2002). We can easily find linear models too, since problems related to gait patterns, redirection and actions' recognition are best resolved by them (Aragão, Santos, & Castelo-Branco, 2010; Giese & Poggio, 2000). These kinds of models are applied to the motion capture data, but only after using techniques that remove "noise" from the signal. Motion capture systems use specific filters that eliminate unwanted features. The Woltring filter (Woltring, 1995) and the Butterworth filter (Butterworth, 1930; Yu et al., 1999) are the most common. The first is applied to amplitude and frequency signals and their components, and the second is applied to temporal components, for example, to remove the phase lag and ensure accurate measures.

3.1.2 *Kinematic Specification of Dynamics*

The degree of naturalness of human motion is one of those artifacts, probably the most central of them. Nevertheless, as referred above, the artificial synthesis of motion patterns is the most commonly used technique, and where a lot of naturalness is lost (Dekeyser et al., 2002; Ren, Patrick, Efros, Hodgins, Rehg, 2005). In fact, it's not enough to ensure that stimuli preserve more than the relevant features, it is crucial that they preserve them all.

Towards an answer, Runeson (1994) transposed to biological motion a concept firstly developed to study collisions between inanimate objects (Runeson 1977/1983). He argued that "properties pertaining to a person that have a dynamic ("causal") role in the generation of his or her movements are specified by the resulting kinematic patterns" (1994, p.386). Specifically, the *Kinematic Specification of Dynamics Principle* advocates the uniqueness of movement patterns and the particular information they carry. The artificial models synthesize animated objects that only mimed the motion properties. So, the best way to ensure the stimulus' quality, in respect to kinematic properties of movements, is to use the human motion without manipulation.

We find in the literature efforts to develop measures to quantify the naturalness of motion. Ren and colleagues (2005) proposed a mixed model that relates Gaussians, Markov, and linear dynamic models. According to the authors, their measures can verify if synthetic models or the manipulation of motion capture don't destroy the original data, and how much different the final result is. Despite the fact that researchers can choose stimuli that do not respect kinematic dynamic properties of human motion, they know how different they are. The solution recognizes the problem and, at least, fits the results and the conclusion, but does not ensure the naturalness of the stimulus.

3.1.3 Translational Patterns

In relation to the last topic, translational patterns are a central question in this discussion. The majority of studies with PLW don't have translational patterns, which results in the perception of the PLW as if walking on a treadmill. Stimuli created artificially include parameter settings that allow the researcher to opt for the translational component. This option doesn't affect the naturalness of the stimuli, because the parameters that support the algorithm are the same for both settings. In contrast, stimuli based on motion capture data are generated differently, either with movements captured on a treadmill or with the translational component subtracted later. In the first, the treadmill changes the kinematic properties of human gait, particularly in the relation between stance and swing phase (see chapter 2). During the stance, the foot is on the ground in the fixed position, something that does not occur on a treadmill. We can observe a translation in the opposite direction to the movement, because the treadmill drags the foot. In the second case, the translational component is subtracted using mathematical processes. The most frequent method is the Principal Components Analysis that subtracts the common translational component. Other methods use non-linear models such as B-Splines.

Even in the case where subjects really are on the treadmill, we can say that although real, it is not natural human motion, since the differences introduced on the gait patterns are sufficient to influence the perception of biological motion (Fujimoto, 2003; Kourtzi & Shifrar, 1999; Verfaillie, 2000). One of the most interesting researches about the influence of a treadmill on the observer's response was developed by Paccalin and Jeannerod (2000). When a seated observer was viewing a person running on a treadmill, his or her own respiration rate changed with the treadmill's speed. The observers perceive small differences in the motion patterns, which translates into a greater capacity to recognize biological motion, but not necessarily on a conscious level. This question is strongly discussed by bottom-up and top-down theories, and each author defends his or her position (see Blake & Shiffrar, 2007; Runeson 1994; Thornton & Vuong, 2004).

In summary, we need to know all details of PLW stimuli, particularly when they are the basis of our work. More than knowing their specification, we have to be able to ensure "the richness and complexity of real-life human kinematics" (Runeson, 1994, p.384). "*Inside Point-light walkers"* denotes control of the motion capture, of the post-processes applied to the data, and of the biological motion visualization methods. From human motion capture to biological motion visualization (Mouta et al., 2011) is a new approach to the construction of PLW. Firstly we will describe the human motion capture method, highlighting the subjects' selection, the technical options for capture, the subjects' task, and finally the results obtained. Afterwards, we will present the stimuli construction based on the data captured before, explaining the procedures that guarantee the minimum amount of noise between capture and visualization. Finally, some of the major questions are discussed.

3.2 Human Motion Capture

Motion capture is the first step in the construction of biological motion stimuli. We support the argument that the naturalness of motion patterns depends on the quality of stimuli, and this quality is more related to the motion capture procedures than with the mathematical models applied later. The reasoning behind this approach is that the more questions we anticipate in this stage, the less data manipulation will be needed. Consequently, the preservation of kinematic motion properties depends strongly on motion capture models, in a pure distal approach.

3.2.1 Participants

Twenty-one subjects, thirteen female and eight male, were used as models. In five of them small gait patterns irregularities were detected caused mainly by structural body problems, and they were removed from the final sample. They were all students and swimmers, and their ages ranged from 13 to 21 years old, with an average of 16 years old (see details in table 3.1). Swimming is a sport that guarantees a

Table 3.1 Participants' age details.

	Mean	SD	Range
Males	17	2	14 - 21
Females	16	2	13 - 18
All Participants	16	2	13 - 21

symmetrical body development and anatomically correct posture. At this level, swimming practice has the advantage of improving the athlete's temporal accuracy, without the negative consequences of a professional sports practice. For each participant the main anthropometric measures were taken – heights, perimeters and widths – as listed in table 3.2. Appendix I presents the procedures used to take the correct anthropometric measures.

3.2.2 Motion Capture System

Data were captured using a motion capture system (VICON; Oxford Metrics, Oxford, UK), with six near-infrared cameras (VICON MX F20 of 2 megapixels with a frame rate of up to 500 Hz). After calibration, the system tracks the three-dimensional position of the retro-reflective markers with a temporal resolution of 240Hz and spatial accuracy of 2 millimetres. The calibration options are not negligible and we will make some comments about that. It’s important to note that we worked with the minimum number of cameras, which means more restricted procedures.

One of these options is related with the minimum number of cameras needed for reconstruction of the three-dimensional trajectories. As is known, the number and position of the cameras can have a negative impact on the reconstruction of motion data (Bottino & Laurentini, 2001), which is especially true when trying to capture translational motion patterns with only six cameras, as is the case. Three-dimensional trajectories are computed from at least two cameras.

Table 3.3 Motion capture system calibration settings.

Settings	Values
Spatial Accuracy	2 mm
Temporal resolution	240Hz
Minimum number of cameras for 3D	2

More cameras means more accuracy, but simultaneously more occlusions. Fewer cameras imply more virtual markers (markers that really do not exist), less accuracy, but fewer occlusions. What kind of compromise should we adopt? The answer is simple: the compromise that ensures natural motion patterns. Let's look at the options.

The occlusion problem is the most cited problem in motion capture. It means that some markers temporarily disappear, due to biomechanical constrictions. The ideal solution is to increase the number of cameras and locate them at different heights around the space (Chen & Davis, 2000). However, the number of cameras set to compute three-dimensional trajectories affects the occurrence of occlusions – the more cameras are set, the more likely it is that, at some point, one of them will not

Table 3.2 Anthropometric measures.
(weight in kilograms; BMI in kilograms per meter^2; heights, perimeters and widths in millimetres)

	Mean	SD	Range
Body mass	62.3	12.5	46.0 – 89.8
Stature	1674	110	1455 - 1855
BMI	22.1	2.8	17.1 – 26.8
Knuckle height	607	47	507 - 684
Hip height	946	77	757 -1051
Elbow height	1040	87	907 -1155
Shoulder height	1381	97	1179 -1555
Eye height	1548	106	1338 - 1717
Knee height	452	50	342 -549
Knee width	101	7	91 -113
Ankle width	65	5	56 - 72
Shoulder offset	384	30	334 - 450
Elbow width	67	8	59 - 80
Wrist width	52	3	48 - 57
Hip breadth	280	19	255 - 320
Waist width	235	27	192 - 294
Transverse thoracic width	289	19	265 - 330
Antero-posterior thoracic width	211	17	191 - 246
Hip width	81	7	70 - 96
Neck perimeter	338	31	290 - 392
Thoracic perimeter	875	75	760 - 1010
Arm perimeter	261	32	201 - 330
Forearm perimeter	212	24	172 - 250
Wrist perimeter	158	12	140 - 182
Waist perimeter	709	70	585 - 851
Thigh perimeter	489	46	410 - 565
Leg perimeter	336	37	270 - 435
Ankle perimeter	249	31	205 - 315
Hand Thickness	27	5	20 - 36

be able to capture the marker. Thus, with only six cameras the best solution is to use the minimum number of cameras to compute three-dimensional trajectories – two cameras. In reality, the probability of markers reflecting the near infrared of two cameras is greater than three cameras, which means that we have fewer occlusions. The argument against this is that computing three-dimensional trajectories with two cameras reduces the spatial accuracy, and the best option should be to choose at least three cameras. We can easily destroy the argument: on the one hand, we operate with a spatial accuracy of 2 millimetres, so we can neglect small loss of accuracy. One the other hand, the real problem with the use of three cameras is the number of occlusions and the proposed solution. To clarify, if one chooses to have a minimum of three cameras to compute a marker's trajectory, there is a likelihood that one of them will, eventually, loose sight of the marker. However, if the minimum number of cameras changes to two, it is less likely that an occlusion may occur, which is why the option was made of having only two cameras needed to compute three-dimensional trajectories.

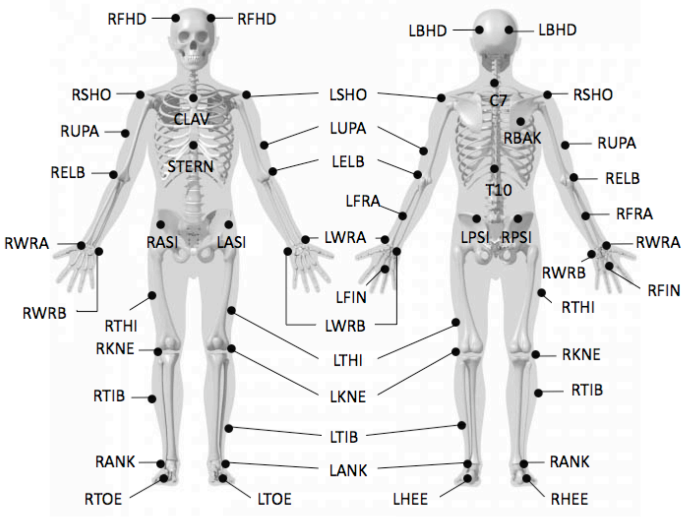
An occlusion means no motion data and loss of naturalness. To compute these missings, researchers use interpolation or extrapolation methods. Interpolation calculates a missing marker between two points and is less accurate than extrapolation, which calculates missings around a set of points, including future events. Both methods imply synthesizing artificial motion data, which affects the kinematic motion properties. Precisely, extrapolation is used in the study of exaggerated movements (Pollick, Fidopiastis, & Braden, 2001), demonstrating that observers perceive the extrapolations as caricatured figures that are recognized better than the original movements. Interpolation methods are more common and their accuracy depends on the method and the complexity of the data. We will discuss this method in the next paragraph, due to another calibration option: the frame rate. For now, we stress that the crucial point is to preserve the real motion, avoiding any sort of manipulation or synthesis – opting for two cameras represents the best solution.

Another calibration option is the frame-rate. Despite the fact that the VICON System can capture with a frame rate of up to 500 Hz, the majority of visualization systems operate in a range of 30 to 120 Hz. Strictly speaking, higher frame rates don't mean more visual accuracy, so why not capture only the maximum frame rate allowed by visualization systems? Because we often need to manipulate the motion data: 1) we have occlusions and we need to compute the missing data; 2) we need a different frame rate according to the experiments' method; 3) or we have different visualization systems with specific frame rates. If we have a lot of data, interpolation between two points is easier. Effectively, the smaller the distance between two points of a function is, the greater the data fitting and the lower the error. Of course critics can say that, even if the distance is short, if we calculate a new point between two known points, we are creating new and artificial motion patterns. Although this is true, the error decreases with the increasing frame rate. For example, Safonava and Hodgins (2005), suggested a new interpolation technique that "in some circumstances will produce significantly more natural looking motion" (p.171).

3.2.3 Capture Method

Thirty-nine retro-reflective markers were attached to the participants' body, directly onto the skin, since they were wearing swimsuits. Only the markers on the head were attached to a specific cloth helmet. This increases accuracy, as it avoids movement caused by the elasticity of clothes. The markers were attached according to the Plug-in-gait Marker Placement protocol, based on the Helen-Hayes Protocol (Davis, Ounpuu, Tyburski, Gage, 1991; Tabakin & Vaughan, 2000). Figure 3.1 shows the marker placement protocol that we adopted and Appendix II describes all markers.

Figure 3.1 Plug-in-gait Marker Placement Protocol.

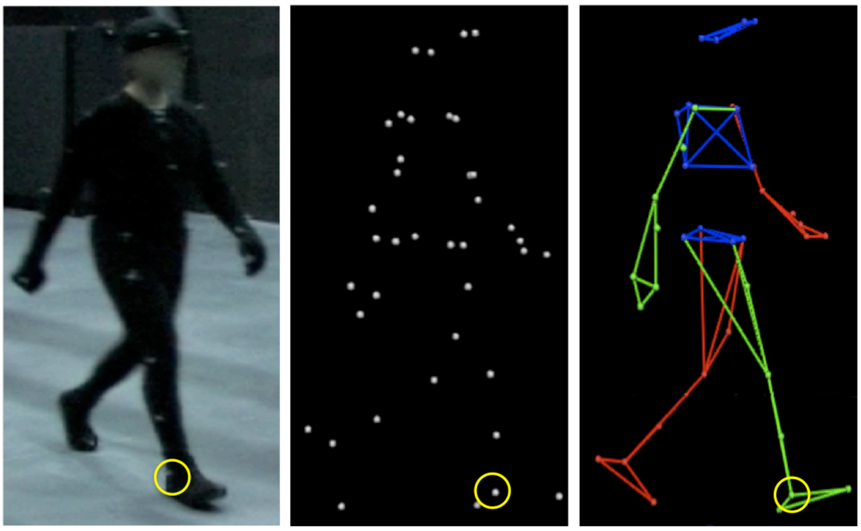


Participants were requested to walk comfortably across a carpet 14 meters long and 0.5 meters wide. The carpet limits the course, without harming the free gait. The 14 meters make it possible for participants to start walking 3 meters before the "capture area" and finish walking 2 meters beyond the end of the "capture area", thereby ensuring that gait initiation and termination were not processed in data collection. The instruction was simple: "Imagine that you are walking on the street. When I say 'Go!', please start." This first instruction gives information on the participant's average velocity, a kind of "baseline instruction". We measured the average velocity in real-time with a speedometer attached to the participant's waist. The aim was to capture a set of natural average velocities ranging from 0.5 m/s to 1.9m/s, at intervals of 0.2m/s. The standard deviation admitted was 0.02 m/s. At the end of each trial, we asked participants to move faster or slower, depending on the average velocity wanted. The biofeedback provided was useful to adjust the average velocity of the next trial (Lünenburger, Colombo, Riener & Dietz, 2004). Two trials were performed for each velocity. The failed trials or trials with standard deviations greater than 0.02 m/s were discarded.

3.2.4 Capture Output

Figure 3.2 shows the sequential stages of capture: a) the subject with markers attached to his or her body; b) the raw data captured; and c) the label data without virtual markers or occlusions. To ensure the same velocity twice in the range described above, we captured an average of 43 trials for each participant (SD=9; ranging from 30 to 60). Failed trials, where the motion capture system or speedometer didn't work, were not considered. If occlusions were detected, despite the velocity being correct, the trial was repeated. Figure 3.3 illustrates the output of the speedometer. Both images illustrate trials for an average velocity of 0.9m/s, the first representing a failed trial and the second a selected trial. The first part of the graph represents the gait initiation, and the second half represents the velocity corresponding to the capture motion. The speedometer output was automatically saved as an image, and no editing was permitted. For each trial the motion capture data was saved and matched with the speedometer graph. These files were saved per subject and it is possible to correspond them with his or her anthropometric measures. The motion data was saved in c3d (VICON native files).

Figure 3.2 Sequence stages of motion capture.



a) Subject b) Raw Data c) Labelled data

We can access the discrete values of position, velocity, acceleration, angles between markers and distance from origin, frame by frame, for each marker. For instance, the ankle's motion for one gait cycle is illustrated in figure 3.4, one graph for each 3D coordinate. The first graph represents the translational pattern, beginning with the stance phase and finishing with the end of swing phase; the second represents the elevation pattern and the third the lateral movements. The yellow circle in figures 3.2 and 3.4 signals the same frame.

Figure 3.3 Speedometer output.

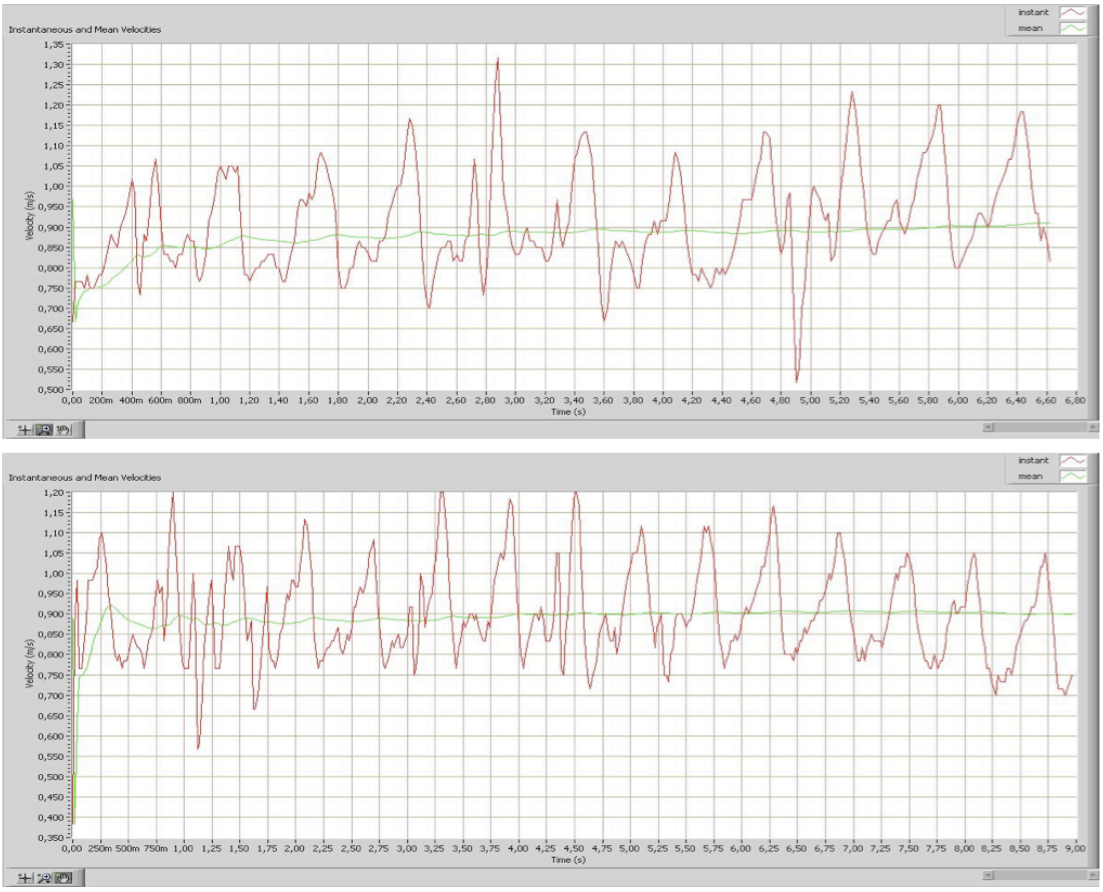
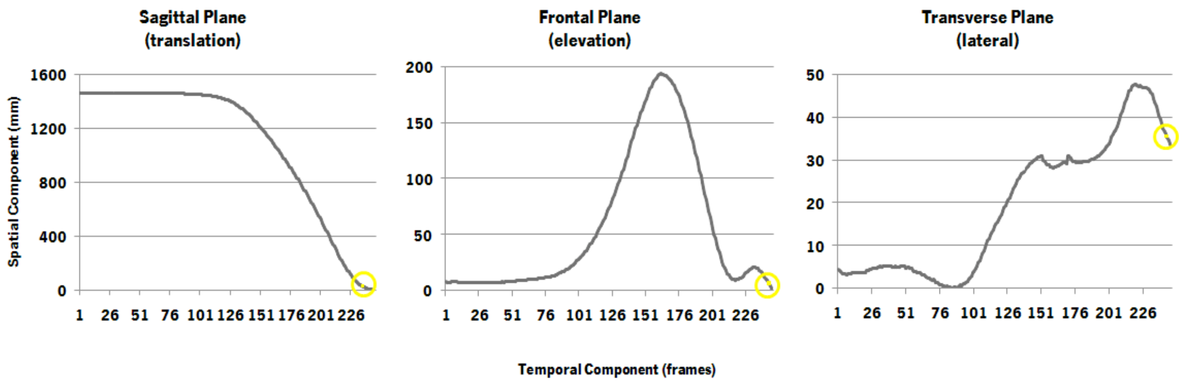


Figure 3.4 Sequence stages of motion capture.



3.3 Creating Point-light Walkers

The point-light figures are more than a number of dots attached to the main joints of a person, even if we can recognize biological motion. After capture, we need to transpose the data from human motion capture to point-light stimuli, which presumes some kind of data manipulation. Nevertheless, as we stressed in the last section, fewer manipulations in the captured data mean more naturalness of motion. Despite the procedures and options discussed before, to preserve the quality of the motion data itself, we need to ensure that the stimuli accurately reproduce the movement that was captured. In other words, it is a construct validity concern – one must be able to ensure that the PLW stimuli accurately reflect the properties of human motion captured previously. A different, but related, problem that we will discuss in the end of this chapter refers to ecological validity.

In this section, we present the options to preserve all motion properties, the routines implemented and the consequences for visualization. It is important to note that, despite the options taken and the arguments provided, we preserve the raw data intact, which allows us, depending on the research's goals, to use the data in a different way.

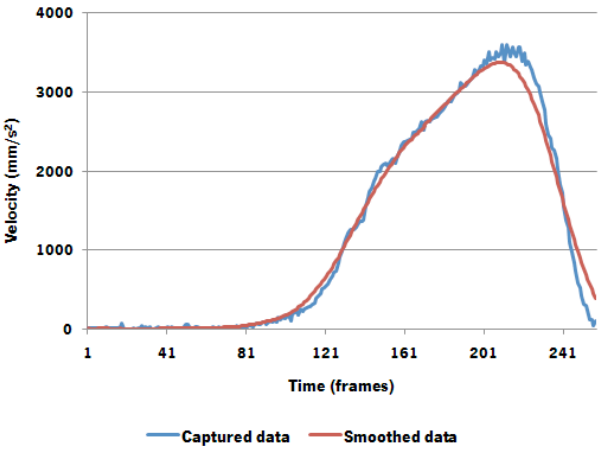
3.3.1 Noise signal, data filtering and smoothing

All measures are contaminated with noise. In the study of biological motion this represents a problem because human motion patterns are complex, but mainly because of the associated research techniques used, such as point-light figures. This problem is intensified when techniques imply dynamic patterns and their properties, such as velocity and acceleration patterns (Winter, Sidwall, and Hobson, 1974). The noise itself is not a problem when we know its dimension and influence in the real signal. For that, we have presented in section 3.2.2 the spatial and temporal accuracy and the errors associated. So, as we defended during the capture process explanation, the best option is to minimize the error and therefore avoid the "correction" of the data.

The data used to create point-light walkers is commonly filtered and smoothed. Firstly, the application of filters and smoothing routines reduce the time needed and make the PLW construction easier. Secondly, because many researchers assume that data filtering and smoothing only removes signal noise, they also assume that filters and smoothing routines don't affect the kinematic stimuli properties. In chapter 4, we will show evidence that this is not the case. To preserve the kinematic properties, we discarded filtering or smoothing processes, even if it does make the whole process more time consuming. Figure 3.5 illustrates an example of smoothing by using a moving average. The graph represents the velocity pattern of the marker attached to the ankle for one step (captured at 240Hz).

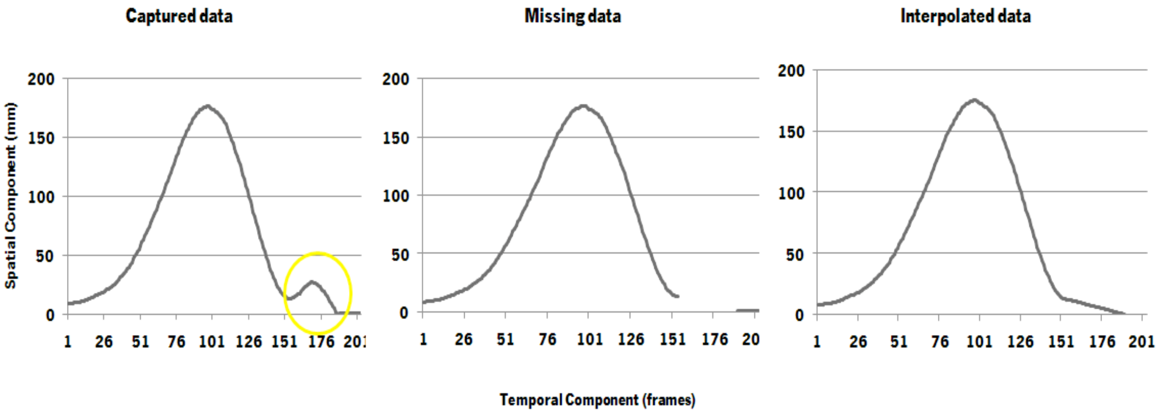
The blue line represents the captured data and the red line represents the smoothed data, using a 36-bar moving average. For the construction of point-light stimuli we used the raw data.

Figure 3.5 Differences between captured data and smoothed data.



Another issue is related to the missing data, typically caused by occlusion problems or system failure. During capture some markers disappear once in a while and reappear again, meaning a loss of data for a period of time. It is possible to reconstruct the missing values, by interpolating values between frames. Of course, when large gaps affect the capture, the option is almost always to reject the data, but when only some frames are missing, interpolation is commonly used. Depending of the frame rate chosen, one frame missing probably won't modify the curve shape significantly. However, the interpolation can generate a natural-looking motion but, in fact, the kinematic properties may have been destroyed, as illustrated in figure 3.6. The first graph represents the swing phase and the beginning of the stance phase of the marker attached to the ankle. This movement is easily recognized because of the curve drawn between the heel-strike and the foot-flat, as pointed by the yellow circle. If we have a gap between these points we lose this typical feature, as illustrated in the second graph. We can interpolate the data and, consequently, eliminate the gap and reconstruct the

Figure 3.6 Interpolation.



movement. But, when we try to resolve the missing data by interpolation, the process does not take into account the ankle pattern, as we can see in the third graph. We just applied a linear regression (y=ax+b) as an example, despite the existence of some kind of algorithms of human motion that can minimize the problem. Nevertheless, we are talking again about motion synthesis, and our approach rejects captures with gaps. Therefore, in this case, this is not an issue.

Table 3.4. Match between motion capture markers and PLW dots.

Markers	Calc	PLW dots
LFHD RFHD LBHD RBHD	divided	Head
C7 T10 CLAV STERN RBAK	deleted deleted deleted deleted deleted	
LSHO		Left shoulder
LUPA	deleted	
LELB		Left elbow
LFRA	deleted	
LWRA LWRB	divided	Left wrist
LFIN	deleted	
RSHO		Right soulder
RUPA	deleted	
RELB		Right elbow
RFRA	deleted	
RWRA RWRB	divided	Right wrist
RFIN	deleted	
LASI LPSI	divided	Left Hip
RASI RPSI	divided	Right Hip
LTHI	deleted	
LKNE		Left knee
LTIB	deleted	
LANK		Left ankle
LTOE LHEE RTHI	deleted deleted deleted	
RKNE		Right knee
RTIB	deleted	
RANK		Right ankle
RTOE RHEE	deleted deleted	

3.3.2 Number of dots

The number of dots comprising the point-light walker is not consensual and differs according to the experiment's purpose. This disagreement is related with the structural cues carried by the number of dots chosen. The more dots the PLW has, the more structural cues are available, and consequently we have more than just motion variables. In his work, Johansson manipulated the number of "lights" available and concluded that observers can easily perceive human motion from a PLW with a number of dots ranging form five to twelve. We can argue that different cues have a specific contribution on perception and that structural cues provided by the number of dots are one of them. Still, the amount of variables involved recommends some kind of compromise. Perhaps this can explain the recent growth of integrated approaches (Thrikettle et al., 2009; Troje, Westhoff, & Lavrov, M., 2005).

There is an advantage in being able to easily manipulate the number of dots available. The thirty-nine markers used in the capture process can be transposed to stimulus dots. LabView routines, developed exclusively for this purpose, compute the captured markers' coordinates into stimuli dots faster. These routines can make all markers available but the researchers can choose the default option, as illustrated in table 3.4. We opted for a PLW with thirteen dots (ankles, knees, hips, hands, elbows, shoulders and head), similar to Johansson's twelve dots PLW plus the head marker. The table shows the eliminated markers (the markers not used directly), the markers directly used as dots and the markers that, after calculations, generated a new dot.

The new dots computed are not human motion itself, since they are created after some calculations and, in this way, they generate artificial motion. Nevertheless, the new dots preserve all the kinematic motion properties, because we are just reallocating the dots. In other words, the two markers attached to the wrist (or to the hips) describe an imaginary straight line, defined by a linear function such as y=ax+b, on which each point preserves the relation between the markers during movement. So, we can compute the new dot without neglecting any kinematic property. Figure 3.7 shows this assumption. The two markers attached to the front of the head describe the

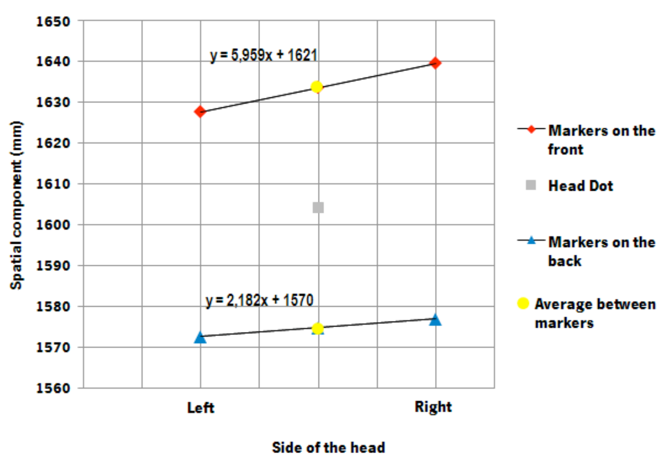


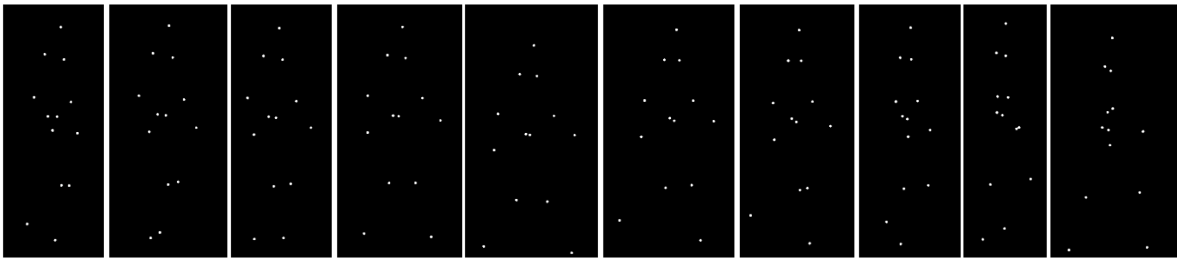
Figure 3.7 Head dot computation.

function present in the graph, making it possible to determine the virtual point between them. By applying the same process to the back of the head markers, we have two new points that define a new straight line, containing the point-light walker's head dot. Aggarwal and colleagues (1998) applied this method to non-rigid objects when they tried to investigate the influence of articulated structures in motion perception, an idea later explored in the study of local and global cues in motion perception by Troje and Westoff (2006). A different issue about the dot's location is related to the "inside articulation location" as opposed to the "outside body location": in other words, we attach the marker on the skin instead of attaching it to the joint. We will address this question at the end of this chapter, when we discuss the study of biological motion with solid bodies.

3.3.3 Translational component

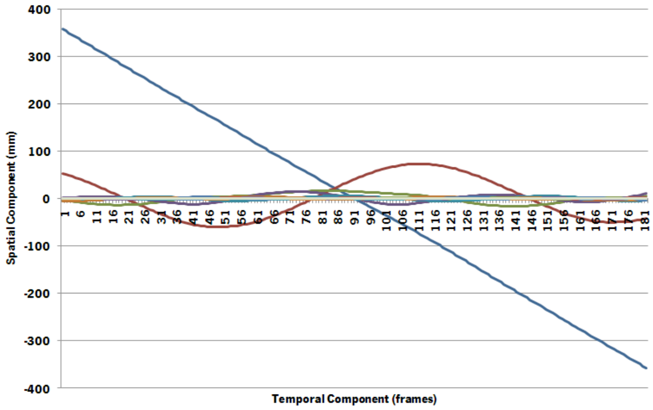
The stimuli translational component (Figure 3.8) is the greatest advantage of this work. Effectively, as we pointed out in the introduction, research on biological motion has neglected this important pattern. The experiments presented in the next chapters would not be possible without translational motion patterns. The capture design allows the construction of stimuli with several gait cycles, more than ten in some cases.

Figure 3.8 Stimuli translational component.



Nevertheless, it is possible to remove the translational component and see the PLW as if walking on a treadmill. Basically, we remove a principal component of motion: the common translational vector. When we apply the Principal Component Analysis to human motion, we can easily identify translational patterns, as illustrated by the blue line in the graph of figure 3.9. By removing it, the interference in other components is minimized and, consequently, in the motion itself as well. The LabView routine developed removes the translational component, but provides the data in a separate output file (Aragão et al., 2009b; Mouta et al., 2011).

Figure 3.9 Human Motion Principal Components.



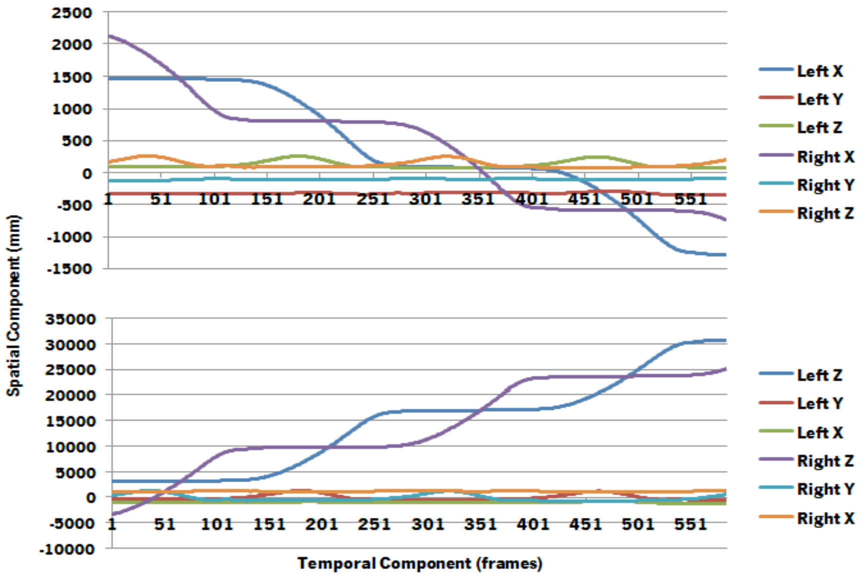
3.3.4 Visualization settings

After motion capture and PLW construction, we need to ensure that the characteristics discussed above remain the same when we transpose them to the visualization systems. In fact, the settings of visualization systems can degrade the stimuli's properties – not the system itself, but the differences and incompatibilities between capture system, stimulus construction routines, and visualization systems. Two main issues are stressed and solutions proposed.

The first issue refers to frame rate differences. Such as pointed out in the chapter introduction, we know that, even with the high frame rates of capture systems, the visualization systems work at low frame rates, commonly from 60 to 90 Hz. In this sense, we need to ensure that no data are lost, no slow or high motion occurs and all kinematic properties are preserved, ideally using the same frame rate or controlling the re-sampling process. Because it is expensive and time consuming to capture at different frame rates, we capture human motion with high frame rates (240Hz) and modify it according to the visualization system's frame rate and the research aim, using LabView routines. The high frame rate makes it possible to calculate sub-multiple re-samples, such as 30, 60 or 120Hz, without any kind of data manipulation. On the other hand, the interpolation process is more accurate when we need to operate with high frame rates. Effectively, we can prevent the problems evident in figure 3.6 (page 32) by re-sampling with higher frame rates. Obviously, the smaller the spatial difference between frames is, the greater the interpolation precision. Relating to this issue, chapter 4 will discuss the importance of frame rate on biological motion research.

The reorientation of the movement axes is the second issue. The incompatibility between systems produces perspective errors, generated by different 3D axes. With the motion capture system we operate with virtual and invisible 3D axes and small deviations occur. Transposing the data directly from the motion capture to the visualization system modifies the virtual reality system parameters and, consequently, decreases the immersive feeling. Deviations under an angle of 2° can change the results of the visual perception experiments, even if the observers are not aware of them. Figure 3.10 illustrates this process. Both graphs show the ankle movement (frontal, sagittal and transverse), the first for raw data and the second for data after re-orientation. To preserve the relation between the stimuli dots, the reorientation is computed from one specific dot or group of dots. For example, we can move the axes assuming the origin in the feet, as demonstrated in the graphs.

Figure 3.10 3D axes reorientation.



3.4 Discussion

More than 30 years of studies in biological motion with point-light figures, after many studies with brilliant conclusions, why develop a new approach to create Point-light Walkers? Which particular advantages compensate the efforts and the time consumption? To put it simply, because the methods commonly used neglect important biological motion kinematic properties, which forbids experimenting with these properties. The new approach to PLW enables the possibility to carry out research with these properties, as is presented in other chapters, mainly chapters 5 and 6. It is not only an issue of manipulation, but also the development of a new approach that enables the control of the whole process. Nevertheless, in the end, we can identify unresolved problems and we admit different perspectives, some of which have been discussed above.

Beyond the motion capture procedures, the kinematic properties of biological motion are affected by the subjects' characteristics. The gait pattern's specificities are carried by the PLW stimuli if the option is one per one, in other words, if the animation is supported by the motion data of one subject. This is one of the most discussed problems and, consequently, the easiest argument against our work. The option for avoiding any kind of smoothing techniques and creating the stimuli with one subject might preserve his abnormal gait specificities and, because of that, the percept might be the result of some kind of extraneous variables instead of the general human motion patterns. To decrease or control the influence of extraneous variables, other solutions have been proposed, such as the mixed models. Here, multiple subjects generate the motion data for PLW animation, creating a new pattern based on the average of the multiple subjects' motion. The argument is that Point-light stimuli should be a prototype of the human motion, without any kind of individual features. In fact, we can extrapolate Runeson's critiques to computer animated displays, because mix models reflect the same central issues: "the animations are purely geometric/kinematic with no involvement of dynamic factors such as mass, elasticity, energetic processes, or neural mechanisms [...]" (p.392). Based on the motion pattern of an individual subject, Point-light stimuli preserve more informative kinematic details and the unexpected patterns of individual motion have important features that explain the facility with which biological motion is perceived (Brudelin & Calvert, 1991; Proffit, Bertenthal, & Roberts, 1984). In summary, the individual features of motion are, in this case, the most powerful advantages of the proposed approach and their manipulation will enable the study of how they are used by the visual system.

However, the age of the subjects can be an issue, if we consider that their physical development is not yet finished and the biological motion pattern captured doesn't reflect the mature motion pattern. Obviously we can argue that we are always talking about human motion but, in fact, if the body structure is not totally developed, the motion captured can be characterized by different patterns of movements. Effectively, the skeletal maturation occurs between 18 and 25 years old (Gentry Steele & Bramblett, 1988), but the mature walking occurs earlier (Austad & van der Meer, 2007; Vaughan, 2002) and it is not exclusively dependent on the bones' maturation (see Sutherland et al., 1988) for a complete review of the development of mature walking). In this sense, the subjects' age range can represent a bigger problem than the ages' mean itself, because the differences between subjects are more significant during the development, decreasing in adulthood. Again, this represents a main problem if you try a human motion prototype based in a mix model, but not when motion of one subject is used to create one point-light stimulus. Even here the argument remains valid and we can say that in typical developing children, gait characteristics are matured by 7-8 years old (Assaiante & Ambalard, 1992).

Nevertheless, if we covet an exhaustive study about biological motion, or at least a database of movements that can easily be used at any time for different experiments, we are restricted to walking patterns. This frustrates the research with different patterns, such as running or dancing, just to name a few, and represents the most severe limitation to our purpose. The time consumption to capture motion discourages the capture of different patterns of movements, despite the procedures now being already developed and implemented, as shown in section 3.2 and 3.3. With this assumption, the option for capturing walking patterns is explained by their ecological value or, in other words, by their frequency, and the conclusions on biological motion research are easy to generalize. The ecological value of the stimuli is precisely the starting point for discussing the arguments against point-light stimulus, or if not against, at least in defense of different stimuli methods. Three issues deserve our attention, one related to the ecological validity of the captured patterns, another about the relation between human joints and point-light walker dots and the third related to stick figure implicit in the stimulus and the use of solid body models.

As pointed out in the introductory paragraph to section 3.3 in defense of construct validity, a different question is the ecological validity. In effect, we ensure that the point-light stimuli created represent the motion captured with a residual pattern variation, but the naturalness of the stimuli can be undermined when we have someone in the laboratory and we instruct them to “walk naturally”. Of course, biomechanically the movements are always defensible, but the dynamic patterns of human motion presented in natural motion are not, and they make a great difference in the perception of biological motion (Berry, 1991; Bingham, 1993). Actually this is a resolved issue, because the alternative would be to capture human motion in real life. High-speed cameras make it possible to capture in natural environments, but the data analysis strongly discourages it. The solution could be to conduct ghost trials – trials with motion capture without the knowledge of the subjects, allowing the subject to relax and perform more naturally.

The relation between human joints and point-light walker dots are another issue of discussion. For practical purposes, the markers attached to the joints of subjects are directly swapped to point-light stimuli dots, despite the markers being attached to the outside of the body. In other words, the dots represent the skeleton, but the markers actually reflect the body volume, changing the stick figure implicit on the stimuli. The procedures adopted to compute the wrists and the head should be applied to other dots, particularly to hips and knees because the changes in body dimension are greater than in the shoulders or elbows, for example. Of course this is an old argument and we find solutions in the literature (Cheung, Baker, & Kanade, 2003), such as the use of algorithms that in our opinion interfere with kinematic properties. Anticipating this problem, the anthropometric measures taken in the capture process are the best answer: we can, in the future, easily apply the same procedure that we have applied to the head and wrist.

The use of solid body models is a large topic, firstly because it has stimulated discussion over the years and secondly because many authors have tried to show the advantages of these models (Reed et al., 2003; Thornton, 2006; Troje, 2002). When talking about solid models we are talking about stimuli that contain dynamic and structural cues, that is to say that they contain motion patterns and body volume. The argument is that, despite the existence of different visual pathways for processing these cues (Goodale & Milner, 1992), in real life form and motion interact all the time and are interdependent. So, the ecological value of biological motion depends on the interaction of both and ideally they should be investigated together. A methodology contemplating one of them will be, necessarily, insufficient. In defense of our work we can say that the methodology used allows for the construction of solid models and this is the main reason behind the existence of an extensive anthropometric database. We have the intact motion information and the relevant body measures, which enable the reconstruction of the solid figure. However, as we stressed in the introduction, the argument that structure and motion interact in real life doesn't mean the abandonment of point-light stimuli, especially if we understand that the structure information is reflected in motion. Probably, the best choice is to reject the typical research dualism (form vs. motion), arguing that hypothesis guide the method's option. Here, our approach has multiple advantages: we have both information and we can easily relate them.

In conclusion, the methodology developed to construct biological motion stimuli clearly assumes the importance of dynamic properties of motion without neglecting other sources of information, such as structure cues. The new perspective about these dynamic properties is reflected in the procedures for the capture process, but mainly in the techniques for manipulation of the motion data. For all these options, we have presented valid arguments that, even if questionable, are always defensible. Now, it is possible to manipulate the spatial and temporal components of biological motion and to understand their contribution to visual perception. This work and the database developed will enhance the research on biological motion, as the experiments already published or about to be published prove (Mendonça, Santos, & López-Moliner, 2011; Mouta, Santos, & López-Moliner, 2012). Point-light stimuli, after more than 30 years, are a powerful resource in the study of biological motion and only the suggestions that we made here make the experiments presented in chapter 4, 5 and 6 possible.

4. Temporal Sampling in the Perception of Biological Motion

4.1 Introduction

As previously stated, one of the most remarkable examples of the resourcefulness of human vision is the ability to perceive biological motion, as supported by the works presented in previous chapters. The information provided by biological motion stimuli is sufficient to discriminate gender, emotions, dynamic and structural properties, direction and other specific properties. Moreover, this perception is so vivid that it can be interpreted by young infants (Fox & McDaniel, 1982). Trying to demonstrate that the perception of biological motion is an intrinsic capacity of the visual system, these authors showed that infants 4 to 6 months of age reveal a preference for biological motion patterns over other kind of movements. However, despite our stunning capacity to recognize biological motion and retrieve important information on the biological stimuli, research on visual perception pointed to a much larger temporal summation for biological motion than for other kinds of motion, such as object's motion. In other words, the high capacity to recognize biological motion (Johansson, 1973) is not reflected in a high capacity to integrate the signal – biological motion is a more time-consuming type of perception.

Theoretically, we can hypothesize that something in biological stimuli generates this kind of response: easy to recognize, but taking longer to integrate the kinematic properties. Citing Lakoff (1993, p.218), "in our visual system, we have detectors for motion and detectors for objects/locations. We do not have detectors for time (whatever that could mean). Thus, it makes good biological sense that time should be understood in terms of things and motion". Again, motion and its properties can explain this sensitivity to biological stimuli and simultaneously the large temporal summation. The common argument - the biological motion complexity - can justify both results. On the one hand, complexity generates unique patterns that, for survival reasons, explain the high accuracy and, on the other hand, the same complexity implies more resources (and more time) to process and integrate the motion signals. However, the methods used in the research on biological motion do not find support in that argument, because observers can easily recognize biological motion despite manipulations that degrade the information available. That is to say that even when we simplify the stimuli, we find the same results. In fact, the perception of biological motion remains robust even when manipulation on the stimuli degrades, neglects or changes important features and specific motion information, such as the kinematic biological properties, while keeping temporal summation unaffected. This evidence is true, regardless of the nature of the manipulation being spatial or temporal. Let's examine this in more detail.

Spatially, masking techniques probably represent the most used technique in biological motion research. Basically, these consist in surrounding the point-light stimuli with a set of dots identical to the point-light stimuli's dots so that in a static position the stimulus remains invisible (Cutting, Morre, & Morrison, 1988). However, when animated, the observers can easily perceive biological motion and recognize the stimuli hidden in the tangle of dots (Cutting et al., 1988; Thornton, Pinto, & Shiffrar, 1998; Thurman & Grossman, 2008). The most powerful example is the scrambled walker mask, in which the surrounding dots mimic local motion, which is to say, the mask contains not random motion but biological motion dots, such as movement of the limbs (Mather, Radford, & West, 1992; Thornton, Resink, & Shiffrar, 2002). Again, the perception of biological motion is clear, independent of the stimuli's ambiguity, such as in other kind of manipulations that involve blurring the dots, changing the contrast of dots or simply turning the stimuli upside-down (Ahlström, Blake, & Ahlström, 1997; Pavlova & Sokolov, 2003). We find other techniques that show the same evidence, such as manipulating the direction of the stimuli so that the top (head, shoulders, arms) and bottom halves (hips and legs) move in different directions. These incoherent point-light-stimuli don't destroy the local structure of the stimuli and observers can easily recognize biological motion, even though the global figure does not represent a coherent walking human being (Mather, Radford, & West, 1992). Manipulating the direction, but in a different way, Thornton and colleagues (2003) developed a stimulus with equal local motion in both directions, demonstrating that subjects show preference to perceive rightward motion versus leftward motion, an idea that Vanrie and colleagues (2004) adopted to study the stimuli's ambiguity and demonstrate the bias to perceive motion rightwards rather than leftwards. Also Beitema and Lappe (2002) changed the position of dots frame by frame, destroying the motion vector, and the results were impressive: subjects could still recognize the stimuli and perform the task easily. Moreover, the perception of biological motion is strong even when we use caricaturized motion (Calder et al., 1996; Pollick, Fidopiastis, & Braden, 2001), as demonstrated by accurate discrimination of point-light walkers.

Temporally, the manipulation of lifetime is certainly the most common technique. For instance, Johansson (1976) presented stimuli of 200 milliseconds and naïve subjects easily recognized the actions performed by point-light walkers. Mather and his colleagues (1992) used stimuli with similar duration, around 240 milliseconds, but we can also find numerous studies where observers can see the stimuli for several seconds (Heptulla-Chatterjee et al., 1996; Shiffrar et al., 1997). Other kind of temporal manipulations imply changing the temporal profile of trajectories, varying the interstimulus intervals to create apparent motion or alter the duration of each dot of the point-light stimulus differently (Hill & Pollick, 2000; Neri, Morrone, & Burr, 1998; Thornton et al., 1998). Actually, the option for short-time or long-time presentations is frequently related to the study of low level or high level motion mechanisms, even though the results are similar: high accuracy and high temporal summation. In their work about visual perception of human locomotion, Thornton and colleagues (2008) are very explicit: "the results (...) clearly demonstrate that observers can perceive human locomotion under both long-range and short-range apparent motion conditions" (p.544). However, unlike spatial tools, temporal manipulations can generate different results not justified by the manipulations *per se*, but by the nature of the biological motion or, in a different way, because of the temporal summation needed to process the biological patterns, which is precisely what we will try to demonstrate. As Cutting and his collaborators (1988) hypothesized, when displays are presented briefly, subjects report poor perceptual judgments of masked human locomotion. The most common interpretation is that the perception of biological motion involves integrative signal processes, which suggests high-level processes and temporal global analysis (Shiffrar & Freyd, 1990; Thornton et al. 1998), a conclusion contested by evidence that observers judge motion direction with short-time presentations easily (Mather, Radford, & West, 1992). Brilliantly, Thornton and colleagues (1998) conciliate the two approaches, showing that both kinds of processes are involved in biological motion processing. The evidence suggests, however, that "high-level mechanism, rather than low-level motion processes alone, underlies the visual perception of human movement" (p.545).

Neuropsychological evidence support these results, demonstrating that low-level and high-level mechanisms are implied in biological motion processing and that the distinctive pathways involved can explain why short and long stimuli presentation justify different but solid results (Grossman & Blake, 2001, 2002; Saygin, 2007). Effectively, the ventral and dorsal pathways seem to process different temporal and spatial properties of biological motion, the first processing information about "what" and the second about "how" (Goodale & Milner, 1992; Grèzes et al., 2001; Thornton et al., 1998). In other words, regarding biological motion, perception information should be processed by the ventral stream and action information by the dorsal stream, an idea that, however, seems to be difficult to prove experimentally (see Cardoso-Leite & Gorea, 2010, for an exhaustive review). In this sense, we can defend the hypothesis that the ventral pathway explains the easy recognition of biological motion, and the dorsal pathway the need for time to process this kind of motion patterns. Making it simple, the area STS receives input from both pathways, integrating the signal in a coherent perception of biological motion. This integration might be responsible for longer temporal responses for biological motion, an assumption that has yet to be fully demonstrated.

The idea of integration was explored by Nery and colleagues (1998) in a widely cited study. The authors measured the ability of the visual system to integrate biological motion information, comparing it to the ability to perceive and integrate other kinds of movements. They concluded that integration of motion components depends on the nature of the stimuli, with a non-linear integration for biological motion, as occurs for other kinds of complex motion, but not for simple translational patterns. The results demonstrated that observers perform differently in detection and direction discrimination of biological motion, but not in a simple translational pattern. For simple translation the temporal summation was near 600 milliseconds, and 2800 milliseconds for biological motion. However, the temporal summation was invariant for simple translational patterns, but not for biological motion. This means that non-constant temporal summation depends on the motion's velocity and is related with the cycles present rather than with exposure time and, according to the authors, indicates that we have very sensitive, but flexible, detectors to biological motion.

More recently, Thurman and collaborators (2010), trying to analyse the critical features of biological motion, suggested that both form and motion cues are relevant in the perception of biological motion, but their significance varies according to the exposure time. As claimed by the authors, form cues are primarily relevant for short presentations, although observers appear to use them during longer presentations, and dynamic features represent the most important source of information for longer presentations. The data showed that transition from form to dynamic features, as a main source of information, occurs around 200-300 milliseconds. The visual system seems to prefer dynamic information when temporal duration is sufficiently long because, as the authors pointed out, motion information is more readily available. So, keeping in mind the arguments discussed in previous chapters, where we had clearly assumed the importance of dynamic properties in the perception of biological motion, the longer temporal summation for dynamic features, in spite of the common argument for their complexity, appears to not make much sense. Why does the processing of relevant information for survival take so long? Can we accept that something in motion patterns explains the complexity of motion (Ilg et al., 2003; Thornton et al., 2003; Jastorff, Kourtzi, & Giese, 2006) and that this complexity justifies the large temporal summation? It's possible, but we can find evidence that refute this argument. For instance, Hunt and Halper (2008) concluded that complexity *per se* is not sufficient to explain the disruption in the perception of biological motion, proposing that the visual system prefers simple and uniform information rather than complex motion patterns.

Actually, the complexity argument, whatever the stimulus's feature that explains this complexity, keeps our assumption unresolved: why does biological motion have large temporal summation if it carried out a high survival value? Considering that the results mentioned above are valid, it is plausible to hypothesize that methodological questions can explain the data. This is precisely the idea of this chapter. Can we expect that larger temporal summation might just be a consequence of an insufficient temporal sampling of the stimuli? In other words, the lower the frame rate is, the less information is available in the stimuli and, consequently, the more time it takes to integrate the signal. With this assumption, we can argue that the difference in temporal summation between simple translational patterns and biological motion is better explained by the impoverish stimuli caused by lower frame rate. Effectively, in the cited studies of Neri and Thurman and their collaborators, temporal sampling of the stimuli varied between 30 and 60 Hz, and these are not exceptional examples. In spite of the frame rate used in the experiments in recent years being higher, it is still frequent to use low frame rates near 30Hz (e.g., Bruggeman & Warren, 2010; Thurman et al., 2010) or more recurrently 60Hz (e.g., Bruggeman & Warren, 2010; Schlack, Krekelberg, & Albright, 2008) or 75Hz (e.g, Thornton et al., 1998). In most cases the native monitors or projectors refresh rate probably explains the option by one or another frame rate and usually researchers don't mention the stimuli's frame rate, but only the monitor's frame rate. It is granted, however, that the great capacity to recognize biological motion can justify less attention being paid to the frame rate problem. It is no longer remembered that Johansson's stimuli (1976) were presented at 24Hz.

Nevertheless, the definition of frame rate and the hypothesis that temporal sampling can explain the temporal summation of biological motion implies that we take into account the human visual system's refresh rate. In a historical note, in their studies about silent films, in the dawn of cinema, Thomas Edison had defined that a frame rate below 46 frames per second "strained the eye" (Brownlow, 1980). Nowadays we know that it is not a question of strain, but rather of the visual system's (eye and brain) capacity to process a set of independent and discrete images (frames). In other words, the possibility to transform discrete signals in a vivid perception of a continuous signal, a phenomenon well described by Max Wertheimer (for a complete revision about the phi phenomenon see King & Wertheimer, 2005; Sekuler, 1996; Westheimer, 1999). In this sense, it is important to consider the visual system's refresh rate, to ensure the preservation of motion properties. Studies with critical flicker frequencies (CFF) showed that for 95% of the population the CFF of a CRT monitor (cathode ray tube) falls between 60 and 72Hz, meaning that CRT monitors that exceed this frequency can have benefits to visual perception (Curry, Martinsen, & Hopper, 2003).

In the present chapter we will try to dismiss this question, by understanding its real implication in the perception of biological motion, if it exists at all. In fact, because we will investigate dynamic features of biological motion, as described in the next chapter, we need to know if frame rate is an extraneous variable. For that, we describe in the first part of this chapter an experiment in which subjects need to discriminate the direction of motion in stimuli at different frame rates. Then, and after discussing the results, we propose a different manner of looking at the motion stimuli, demonstrating that mathematically we can change the nature of the stimuli when we choose the frame rate. In this sense, we performed a second experiment to answer the issues raised. Only after this methodological discussion are we prepared to investigate the variables proposed in the next chapter and to understand their effect in biological motion perception.

4.2 Experiment 1

The main goal of experiment 1 was to understand the effect of different frame rates on the perception of biological motion. The same motion stimulus was presented at two possible frame rates and participants had to discriminate the direction of motion. If the visual system's capacity to discriminate biological motion depends on the temporal sampling, participants should perform differently according to the stimuli's frame rate. Specifically, the results should show a better performance and lower reaction time for high frame rates.

4.2.1 Method

4.2.1.1 Participants. Nine volunteers took part in the study, all of them naïve as to the purpose of the experiment. Participants were all students with an average of 24 years old, ranging from 19 to 27 years old. All had normal or corrected-to-normal vision based on the automatic screening test and kinetic tests (dynamic visual acuity with moving stimuli varying direction, speed and spatial frequency) of the equipment for visual screening (Essilor, Ergovision).

4.2.1.2 Apparatus and Stimuli. The stimuli were presented on an Apple G5 Macintosh Dual Core computer equipped with a 2.3 GHz processor, 2.5GB of RAM, and an NVIDIA GeForce 6600 graphic board with 256 MB of VRAM. Images were displayed with OpenGL/GLUT software through a Samsung 2233RZ monitor with a spatial resolution of 1680x1050 pixels, a horizontal viewing angle of 170° and a vertical viewing angle of 160°, with a refresh rate of 120Hz.

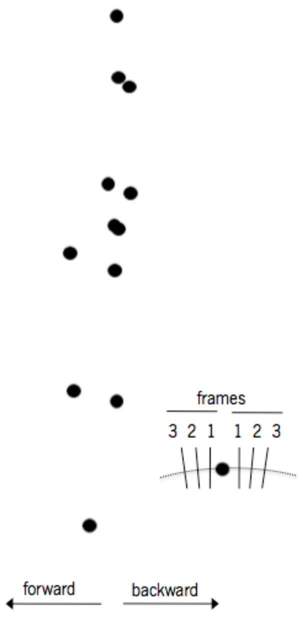
A white PLW of thirteen dots against a black background was presented laterally to the observer, during 100ms, with a visual vertical angle of 4°. The PLW was moving without translation, corresponding to a walking speed of 1.3 m/s and the temporal sampling was of 30Hz or 120Hz. In other words, 3 and 12 different frames were presented per stimulus, respectively. The stimuli were prepared from the human movements captured previously at 240Hz, as explained in chapter 3. The re-sampling was calculated for 100ms and the first and last frames were the same for both frame rates. To maintain the monitor's frame rate constant, we repeated the frames when the stimuli had 30Hz. So, we presented 12 frames per stimuli, but in fact for the stimuli at 30Hz we repeated each frame four times (see the illustration in figure 4.2 presented in the procedure).

To eliminate other cues of direction, such as form, and ensure that motion was the only variable presented, two procedures were taken. First, the stimuli were moving either forwards or backwards, and for that the biological direction was not relevant information. Secondly, we selected one step, meaning that one foot was in stance phase and the other was in swing phase. The first motion frame was the frame corresponding to the higher value in elevation (frontal plane) of the ankle, because the difference between the forwards and backwards motion is minimal. In other words, the frames previous to the beginning of the swing phase are in stance phase, and the amplitude in the sagittal plane (translation) is lower. Here, for backwards stimuli the motion was minimal and located in the upper body. To animate the backwards stimuli we inverted the order of the frames presented. Figure 4.1 illustrates the stimuli

Table 4.1 Stimuli used in Experiment 1. For each of the four possibilities we varied the frame rate: 30 Hz or 120 Hz.

		Kind of movement	
		Backward	Forward
Direction	Left	stimulus 1	stimulus 2
	Right	stimulus 3	stimulus 4

Figure 4.1 Stimuli construction.
(stimulus's face turned left; forward and backward ankle frames illustrated, with the backward frames inverted; 30Hz [3 frames])



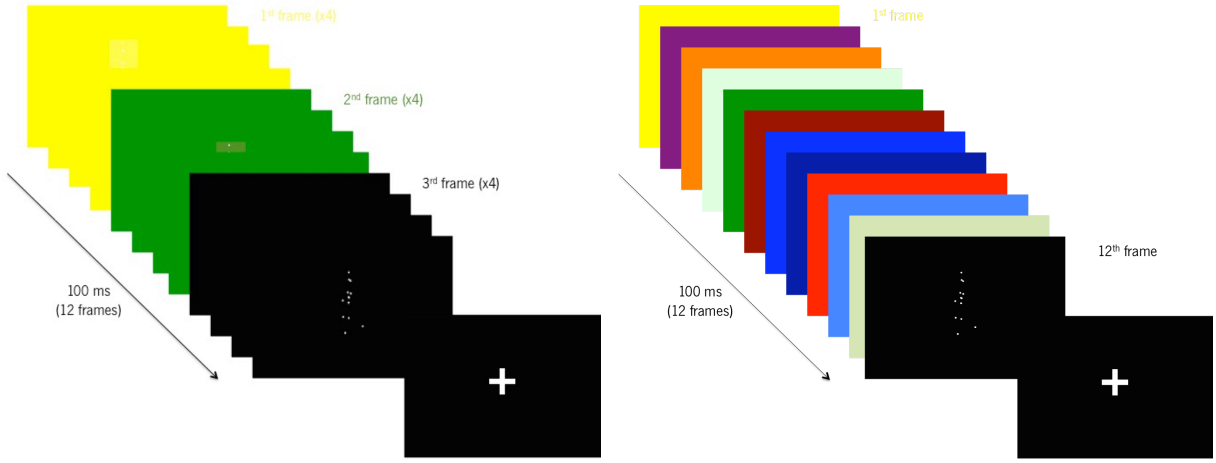
construction. In summary, the participants saw a total of eight different stimuli, depending on the direction of the stimuli, the kind of movement and frame rate, as showed in table 4.1

4.2.1.3 Procedure. Participants were asked to report the movement's direction. They responded by pressing the corresponding mouse buttons connected to the computer: left if the stimulus was moving to the left side and right if the stimulus was moving to the right, thus performing a two-alternative forced-choice task. No feedback was provided. Participants were seated in a dark room, with a head fixation system, 2 meters away from the display. The stimuli were presented randomly and participants gave the answer by pressing the mouse button when a cross was displayed. Figure 4.2 shows frame presentation for 30Hz and 120Hz, revealing the process that ensures the same refresh frame rate of the display (same number of frames presented), but making reference to the number of different motion frames, i.e., frames that carry out motion cues. Participants took part individually in one session, each lasting about 20 minutes and comprising of 800 trials, 100 trials per stimulus. The stimuli were presented for 100ms followed by an inter-stimulus interval of about 1400ms, during which the participants gave their answer. In the results we present the percentage of correct responses and the reaction time for each condition.

Figure 4.2 Experiment 1's procedure and stimulus presentation.

Stimuli at 30Hz

Stimuli at 120Hz

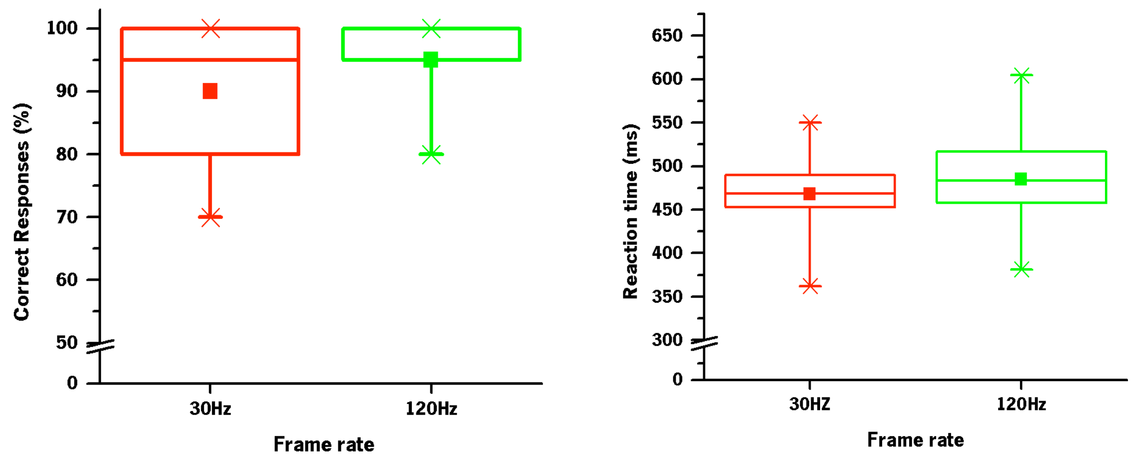


4.2.2 Results

An exploratory analysis allowed the assumption of normality, demonstrating that all data fall in the normal range, according to the Kolmogorov-Smirnov normality test. Furthermore, results better explained by the direction of the stimuli (facing right or left), the kind of motion (backwards or forwards) or the option for one of the mouse buttons are discarded and no significant results were found. Having confirmed these assumptions we performed analyses to confirm the existence of a significant effect of frame rate conditions. We present the t-test for paired samples for reaction time and accuracy.

Figure 4.3 shows the percentage of correct responses and the reaction time for both frame rates (30 and 120 Hz). The percentage of correct responses was greater for higher frame rates (M_{120Hz}=95%, SD_{120Hz}=6%; M_{30Hz}=90%, SD_{30Hz}=12%), although the reaction time was slightly higher too (M_{120Hz}=485ms, SD_{120Hz}=64ms; M_{30Hz}=467, SD_{30Hz}=50ms). However, the dependent t-test for paired samples found no effect for reaction time and accuracy (t(8)=1.52, n.s. and t(8)=1.46, n.s., respectively). The difference in frame rate didn't influence the discrimination of motion direction, i.e., no differences between conditions were found.

Figure 4.3 Results of Experiment 1.



Percentage of Correct Responses by Frame Rate

Reaction Time by Frame Rate

× minimum and maximum values; ⊥ 5th and 95th percentile; ■ mean

4.2.3 Discussion

The stimuli's temporal sampling did not influence thresholds and reaction times, which probably means that this factor cannot explain the large temporal summation of biological motion perception. In spite of the stimuli having been displayed for only 100ms, most participants showed a percentage of correct responses above 90% and the reaction time was similar for both conditions and much smaller than the temporal summation values referred in this chapter's introduction. However, these differences are not significant to explain the higher temporal summation for biological motion, and the temporal sampling does not appear to be a critical variable. The mean of the reaction time is similar for both frame rates and, curiously, it is closer to the temporal summation for simple translational motion (600ms) showed by Neri and colleagues (1998), than to temporal summation for biological motion (1200ms). Against our work, we can say that we presented insufficient motion cues or, in other words, not the motion cues themselves but their biological nature. Effectively, in a short presentation the biological nature is neglected or absent, as is the case of the stimuli present at 30Hz. Here, during 100ms, we presented only 3 frames, the minimum number of points to define a curve. But with 12 frames at 120Hz, although we can spatially define a curve or a shape, we can also argue that in a biomechanical perspective we cannot temporally define a biological human motion curve. So, in spite of having presented a point-light walker moving forwards or backwards, we actually presented only a point-light figure moving like an object to the left or to the right. Note that we are not saying that we presented a simple translational motion or a point-light walker moving as an object. We are saying that during 100ms the information available from 30Hz or 120Hz can be similar to an object moving. The difference here is not in the motion patterns but in form cues, in other words, the few frames available carried out structural information and, as demonstrated by Thirkettle, Benton and Scott-Samuel (2009), the old idea that an observer cannot perceive a PLW from one single frame is erroneous. Contradicting Johansson's over-cited work (Johansson, 1973), the authors showed how the reduction of motion information could result in a significant reduction of the capacity to perceive biological motion. They demonstrated how visual systems integrate motion and form cues, explaining how observers can perceive biological motion from one single frame but, simultaneously, why the perception is better when both cues are available.

With this assumption, we can propose a reasonable explanation that sustains the hypothesis, despite the results: we presented subjects with sufficient cues for the perception of motion and this explains their high performance. However, the information provided by frame rate needs more presentation time to express biological properties. Curiously, experiment 1 allows us a different interpretation of the results of Thurman and colleagues (2010), better explaining why visual systems prioritize form cues to perceive biological motion in short presentations and motion cues in long presentation, switching the priority at around 200-300ms. In this sense, it is not a question of priority but of availability. In short presentations the form represents the most salient information, because there are few differences between biological and non-biological entities in the beginning of any movement pattern. Furthermore, as pointed out by these authors, after 200-300 ms the observers prefer the motion cues as their first source of information but don't neglect the form cues, combining both in an integrated percept. Continuing our argument, after 200-300ms, both cues are available, but motion represents perhaps the most salient of them because we can extract significant information from it. In other words, the temporal component of biological motion implies, necessarily, more time to express the specific patterns. In the next topic (4.3) we will present arguments in our defense, demonstrating this explanation mathematically. However, we can say right now that the relation between temporal summation and gait cycle duration is probably not a coincidence.

In fact, we are discussing the argument that temporal summation is explained by the temporal biological component, not by the biological nature of the stimuli. Therefore, to investigate this argument we need to use longer presentations, to allow for the perception of the temporal component of motion. Recent work from Mouta and colleagues (2012) can shed a new light on this problem. Although the authors' main goal was to investigate time-to-passage issues, the stimuli used in their work illustrate better than others that non-intuitive difference between accuracy and reaction time. They presented observers with five kinds of stimuli: a classic PLW, constructed from the database and the methodology described in chapter 3, an inverted PLW (upside-down), a scrambled, a rigid (frozen) PLW moving like an object, and a PLW moving like a robot (complex non-biological stimulus), with local motion patterns moving at constant velocity. The stimuli were moving forward to the observer and were displayed between 500 and 700ms. One auditory beep was presented 1000 ms after the visual stimuli started to be displayed and subjects had to judge the stimuli's passage at the beep. The results were very interesting. The classic PLW (biological motion) presented simultaneously a time-to-passage anticipation and the higher reaction time, comparing to the rigid motion that had the opposite pattern. But the surprise is in the complex non-biological stimulus that had the form of a PLW, but not the motion component. This stimulus had a time-to-passage anticipation similar to classic PLW, but a reaction time analogous to rigid PLW. It appears that the nonexistence of the biological motion component affected the subjects' performance, but not in the same way. Reaction time-wise, the constant velocity in complex non-biological stimuli made them more similar to rigid motion than to biological motion, as if they had the same kind of processing.

The experimental conditions in experiment 1 did not actually include biological motion information. For 100 ms we presented motion information, not necessarily biological as explained, but mainly we presented form cues. If we are considering that temporal summation is better explained by the temporal component of biological motion, we need to change the methodology by increasing the duration of presentation. However, this is not sufficient. If we sustain the hypothesis that large temporal summation for biological motion might be just a consequence of an insufficient temporal summation, we need to present not only longer stimuli but at the same time stimuli that allow us to understand the influence of the temporal component. This proposal is explored in the next topic.

4.3 Interpreting the data differently

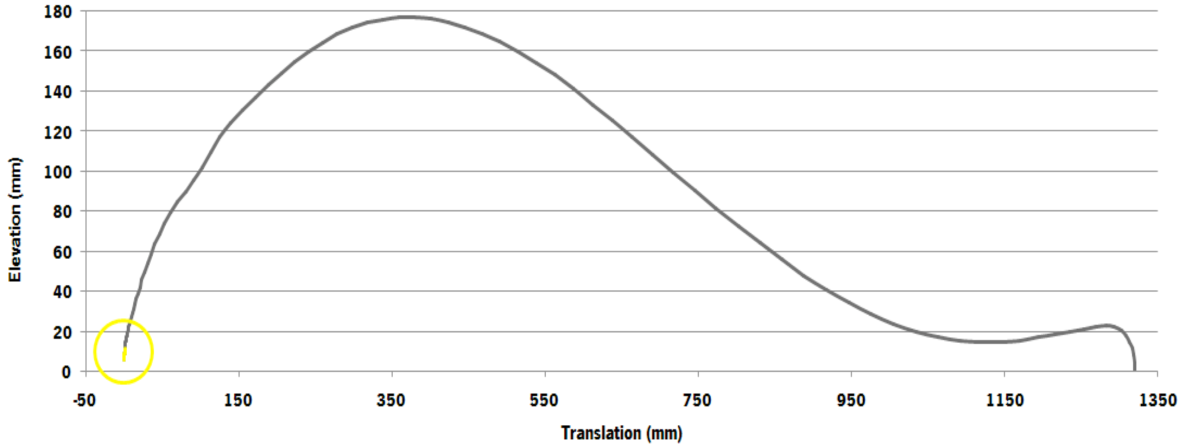
When we talk about motion we are talking necessarily about time, one of two motion components: space and time (Newton, 1729, pp. 9-12). In this sense, in the discussion of motion perception we need to analyse the temporal series behind the motion. In other words, we need to know what is being displayed when we choose a specific duration of presentation. In fact, the option for short or long presentations means more or less motion cues, which affects the temporal and the spatial motion components. Although the intrinsic properties (the capture properties) of a stimulus remain intact independently of the time span of presentation, the meaning that an observer can retrieve from it could be different, not because of the properties themselves, but due to the quantity of information provided. Figure 4.4 illustrates this argument; let's analyse it in more detail.

All graphs in figure 4.4 represent the ankle movement. Graph a) represents one full step, starting with the first frame of the swing phase and finishing with the last frame of the stance phase, and we can see all their movement in two dimensions (translation and elevation). The yellow circle signalizes the first 100 ms of motion that were displayed in experiment 1 (the ankle of the point-light walker) and, as we can see, represents a minor percentage of ankle motion. This percentage is expanded in graphs b) and c) for 120Hz (12 frames) and 30Hz (3 frames), respectively, and showed in graphs d) and e) for all frontal planes (elevation). We can conclude that the biological motion's pattern displayed is similar to an object moving linearly and, thus, can assume that form or form and motion together explain the results (Thirkttle et al., 2009). Effectively, the stimuli were poor in biological kinematic properties, as is well illustrated in graphs b) and c), and the temporal component is crucial to express these properties (graphs d) and e)). So, in biological terms, we cannot guarantee that we were presenting biological motion, despite having motion and a biological representation of a walker. It is important, in this sense, to ensure that subjects observe the kinematic components of biological motion, as shown by the graphs and according to the explanations given in chapter 3, section 3.1.2.

By increasing the stimuli's duration, 1) we ensure that kinematic properties of biological motion are being displayed but, at the same time, 2) we need to demonstrate that stimuli have different properties when displayed at different frame rates, despite their common origin. With this assumption, the arguments deserve a more detailed discussion, by analyzing the mathematical relation between different frame rates and how this relation can help us understand the influence of this variable on biological motion perception.

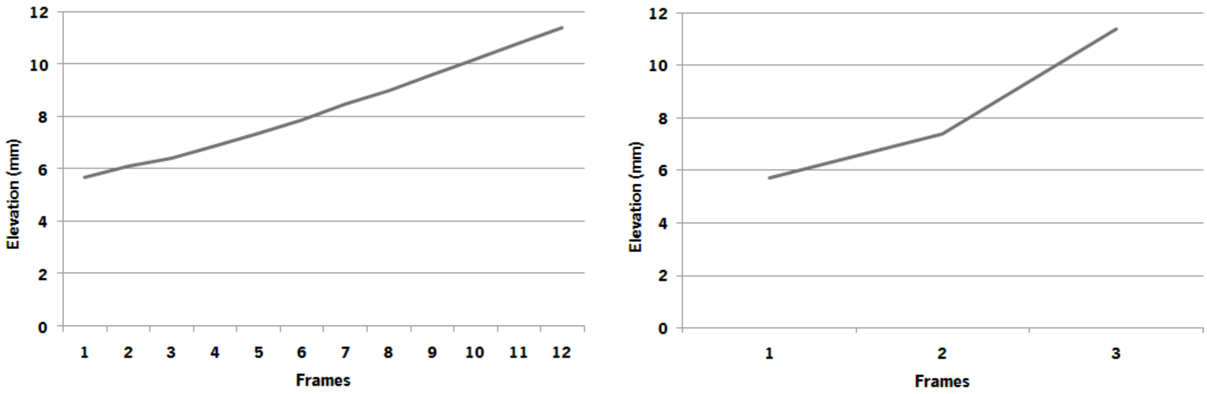
Figure 4.4 Motion's mathematical differences at different frame rates.

a) 2D space Ankle Movement at 120Hz



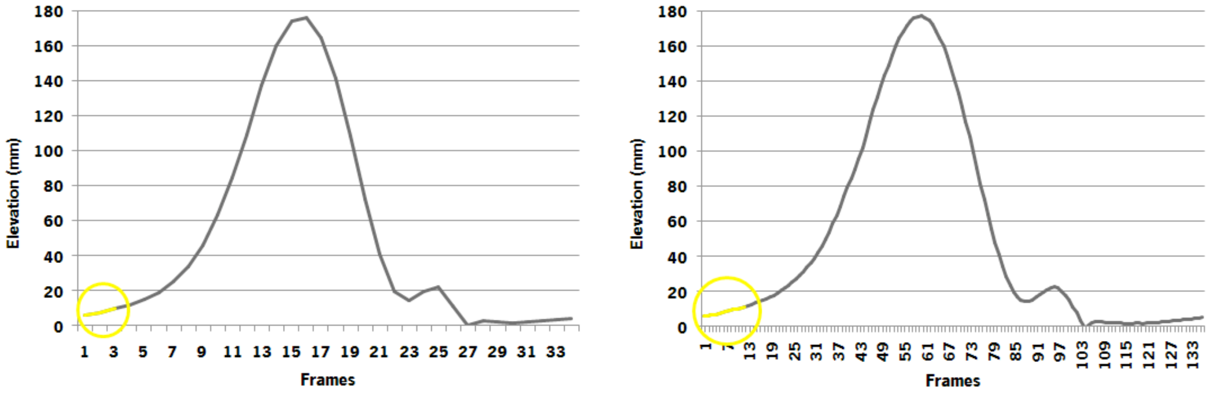
b) Ankle Movement at 120H
(swing phase's first twelve frames)

c) Ankle Movement at 30Hz
(swing phase's first three frames)



d) Ankle Movement at 120Hz
(all frames of the swing and stance phase)

e) Ankle Movement at 120Hz
(all frames of the swing and stance phase)



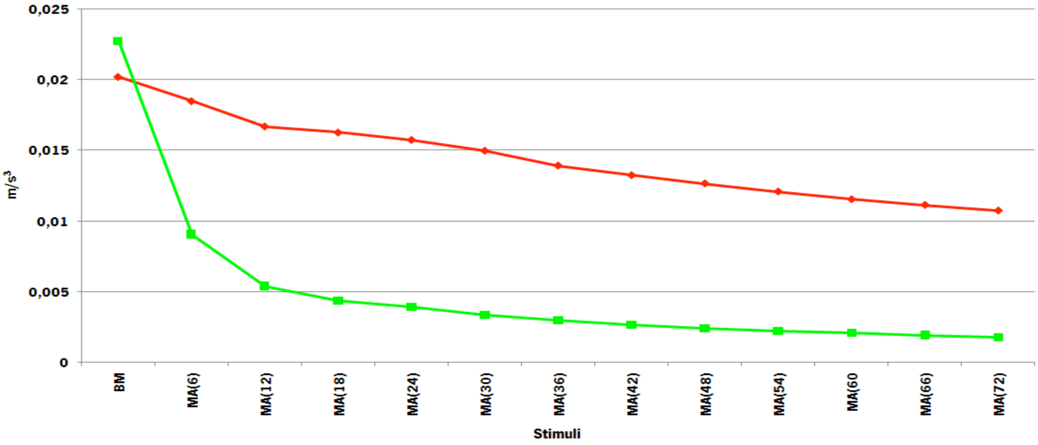
The first argument was addressed in chapter 3, when we explained the relevance of frame rate to capture human motion and to construct point-light stimuli. As we pointed out, the smoothness of relevant kinematic properties, among other factors, is caused by frame rate manipulation, and for that we could expect different reaction times and accuracy depending on the frame rate displayed. But the differences between stimuli cannot be sufficient to answer our question, which is, the smoothness of each stimuli compared with each other. So, consider the movement of an ankle without any kind of manipulation, as shown in graph a), figure 4.4. Then, consider the smoothness of the velocity pattern by manipulating the average of different subsets of the full discrete data with a simple moving average, also assuming the same process at 30Hz and 120Hz. If we use multiple values of six to compute the moving average, ranging from 6 to 72, we have thirteen stimuli: the biological motion stimulus and the twelve stimuli from moving average calculations (in chapter 5 we will describe in detail these stimuli and their construction process). The relation between them is shown in the graphs of Figure 4.5 by mean, standard deviation, and maximum jerk. As we can see, the difference between both frame rates is clear and statistically significant ($F(1,11) = 83.54$; $p<0.01$). Stimuli at 30Hz fit linearly and stimuli at 120Hz fit with a logistic regression. Therefore, if subjects are sensible to these differences, we can hypothesize that they perform differently if the task is to compare the different motion patterns with the same frame rate. We would expect that the curve of results would be specific for each frame rate. We will explore this assumption in experiment 2.

4.4 Experiment 2

Experiment 2 tries again to answer the main issue of this chapter: can we expect that larger temporal summation for biological motion might be just a consequence of an insufficient temporal sampling of the stimuli? According to the discussion above, participants observed a set of stimuli that we had previously smoothed, ranging from a biological motion pattern to 72 moving averages of the velocity pattern. Each set was presented with a specific frame rate in two distinct sessions. If the visual system's capacity to discriminate biological motion depends on the temporal sampling, the subjects should perform differently according to the stimuli's frame rate.

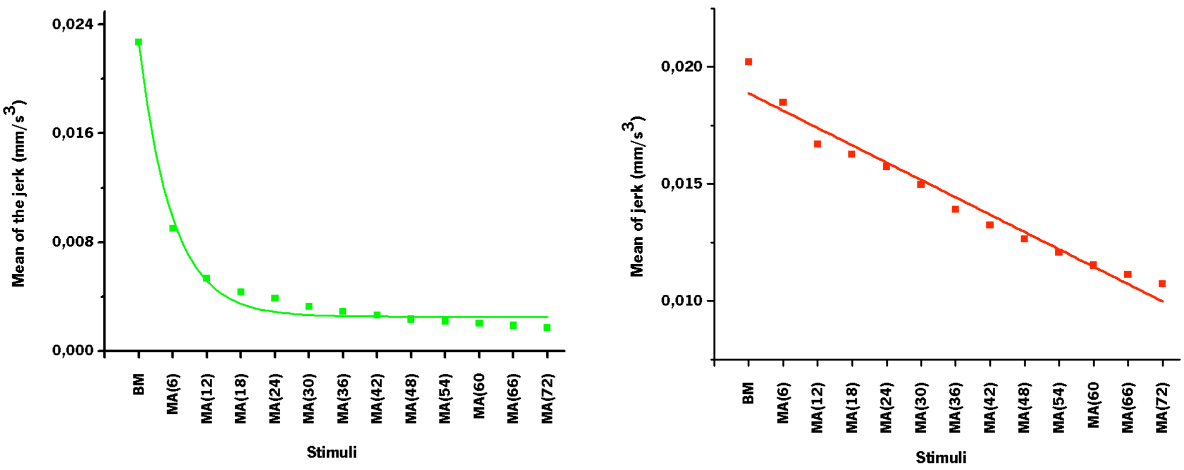
Figure 4.5 Relation between degrees of smoothness of the stimuli at different frame rates.

Mean of Jerk



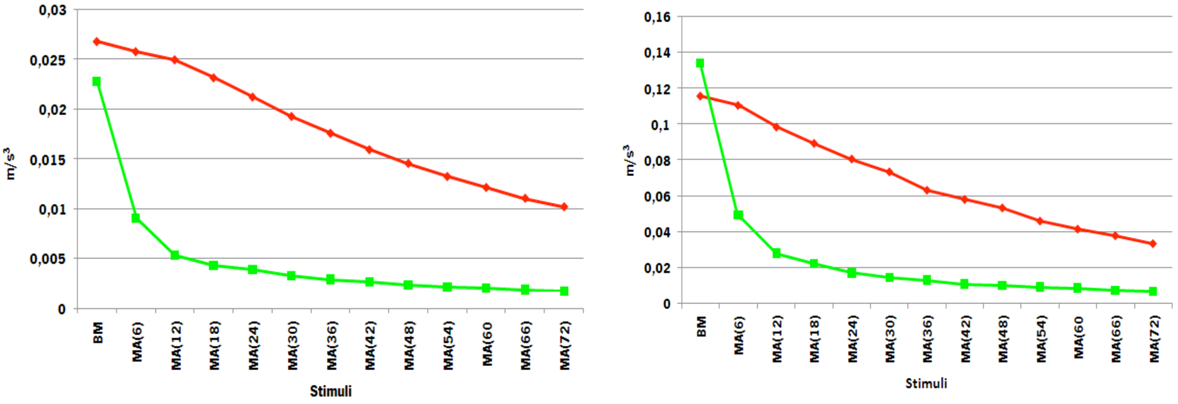
Exponential regression for stimuli at 120Hz

Linear regression for stimuli at 30Hz



Standard Deviation of Jerk

Maximum of Jerk



🟥 —— 30Hz 🟩 —— 120Hz

4.4.1 Method

4.4.1.1 Participants. Seven volunteers took part in the study, all of them naïve as to the purpose of the experiment. Participants were all students with an average of 25 years old, ranging from 22 to 26 years old. All had normal or corrected-to-normal vision based on the automatic screening test and kinetic tests (dynamic visual acuity with moving stimuli varying direction, speed and spatial frequency) of the equipment for visual screening (Essilor, Ergovision).

4.4.1.2 Apparatus and Stimuli. The stimuli were presented by a 3-chip DLP projector Christie Mirage S+4K, with a spatial resolution of 1400x1050 pixels and a refresh rate of 60Hz or 101Hz, as explained bellow. Images were displayed with OpenGL running over a Vr/Net Juggler software on a computer with a graphic board NVIDIA Quadro FX 4500. The stimuli were projected on a surface 2.10m high and 2.80m wide. This apparatus was possible in the Laboratory of Visualization and Perception of the University of Minho, in an immersive virtual environment, as shown in Figure 4.6.

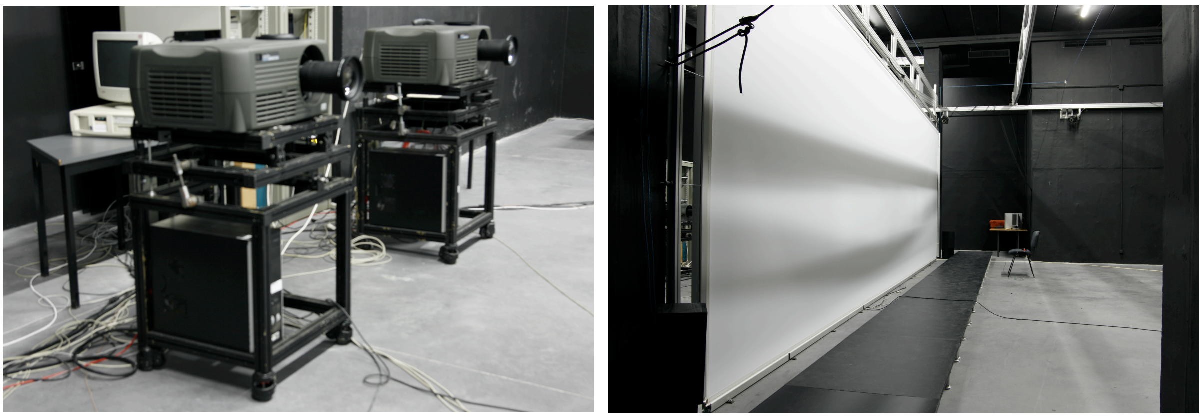


Figure 4.6 Laboratory of Visualization and Perception, University of Minho.

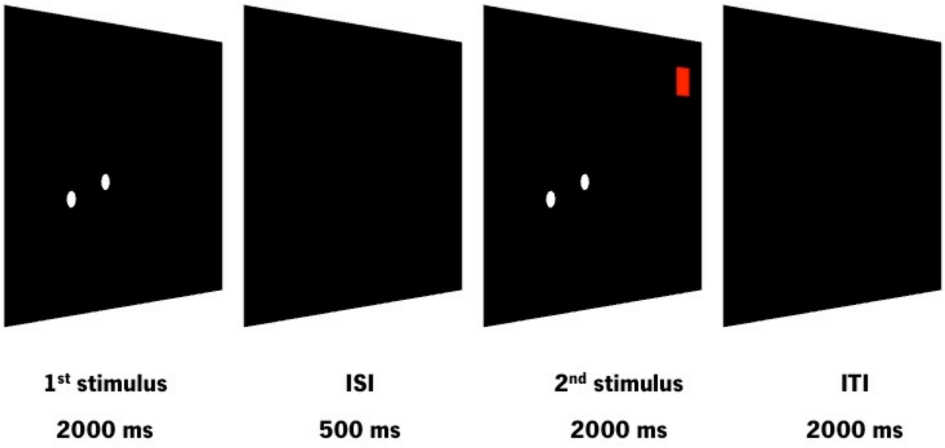
3-chip DLP projector Christie Mirage S+4K

Projection surface

The stimulus was a PLW of two dots. The typical dots of the head, shoulders, elbows, wrist, hips and knees were removed and only right and left ankles were presented, representing the feet of a walker. The stimuli were presented for 2000ms, corresponding to four gait cycles. We presented 13 stimuli: one of them was the biological motion without manipulations and the other twelve corresponded to different degrees of smoothness of the velocity pattern. The smoothness was computed for each step and didn't affect the spatial component. For that we used a simple moving average to calculate the velocity pattern of each stimulus, considering multiples of six, according to the previous discussion (see Figure 4.5 in the previous section). The entire process is better described in experiment 1, chapter 5, because these stimuli were developed for that experiment and, after the arguments presented previously, reused here. For now, it is important to realize that we had thirteen stimuli whose velocity pattern was gradually smoothed from biological motion to MA(72) in multiples of six, all of them corresponding to a walking speed of 1.3 m/s. The stimuli had a temporal resolution of 30Hz or 101Hz, although the projector's refresh rate was of 60Hz and 101Hz. The option for 60Hz and 101 Hz to display the stimuli at 30Hz and 101hz, respectively, is justified by the projector's technical specifications. In fact, theoretically, the projector had been prepared to frame rates up to 120Hz, but actually we could only ensure frame rates up to 101Hz, with the best spatial resolution (1400X1050 pixels). Simultaneously, the projector's native temporal resolution is 60 Hz and is not prepared for lower temporal resolutions. The solution for stimuli at 30Hz, as in experiment 1, was to repeat the frames twice.

4.4.1.3 Procedure. Participants were seated in a dark room, 2 meters away from the display and were asked to choose the most biological of two stimuli presented sequentially, with one of them always being the biological motion (standard stimulus). A black frame was presented for 500ms between the first and the second stimuli. Participants responded by pressing the corresponding mouse buttons connected to the computer, with the left button if the first stimulus was the most biological and the right button if it was the second stimulus, performing a two-alternative forced-choice task. No feedback was provided for correct responses. The stimuli were presented pseudo-randomly and participants gave the answer by pressing the mouse button after the second stimulus started to be presented. A red square on the top right corner signalized the second stimulus and a long black frame

Figure 4.7. Experiment 2's procedure and stimulus presentation (one trial).



with 2000ms signalized the inter trials interval (ITI). Participants took part individually in four sessions, each lasting for about half an hour and with 125 trials, 10 trials per stimulus (5 trials for standard stimuli when displayed in the first and second presentation simultaneously). Two sessions were presented at 30Hz and the other two at 101Hz, in other words, 20 trials per stimuli for each frame rate. Figure 4.7 illustrates the procedure described.

4.4.2 Results

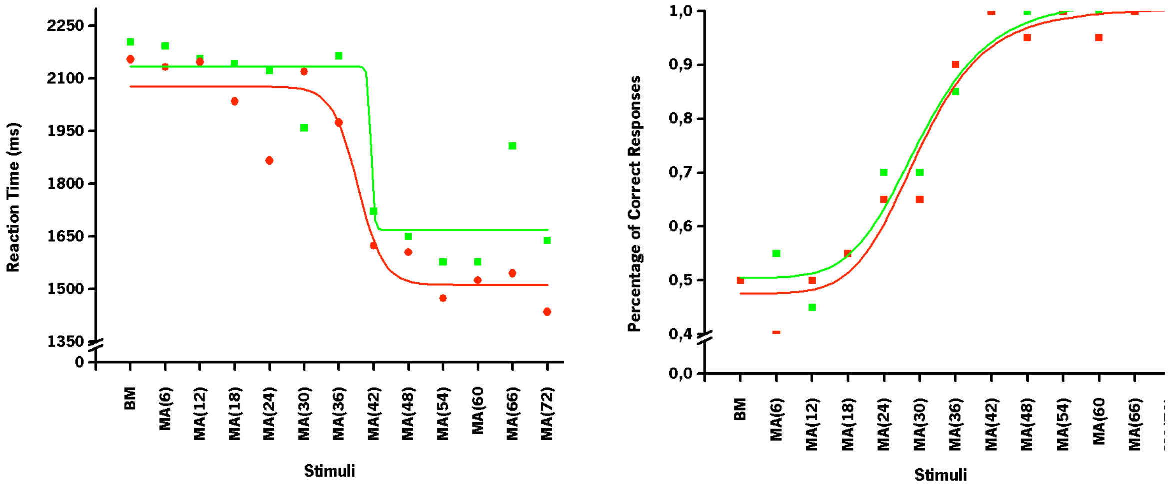
An exploratory analysis allowed the assumption of normality, demonstrating that all data fall in the normal range, according to the Kolmogorov-Smirnov normality test. Furthermore, results better explained by the presentation order (first or second stimulus) or the option for one of the mouse buttons are discarded and no significant results were found. Having confirmed these assumptions, we performed statistical analyses to confirm the existence of a significant effect of frame rate conditions.

Figure 4.8 shows the percentage of correct responses and the reaction time for each stimulus for both frame rates (30 and 101 Hz). For each frame rate taken independently, the difference between stimuli is a matter of discussion and in-depth analysis in chapter 5. Here, and according to the arguments presented in section 4.3, the difference between the curves is the relevant question. The percentage of correct responses was similar in both conditions (M_{101Hz}=77.3%, SD_{101Hz}=23.3%;

Figure 4.8 Results of experiment 2.

Percentage of Correct Responses

Reaction Time



🟥 30Hz —— 30Hz Regression Curve 🟩 101Hz —— 101Hz Regression Curve

M_{30Hz}=79.2%, SD_{30Hz}=22.3%), and the regression curves overlap. The ANOVA two-way found no effect (F(1,11)=1.76, ns). Contrariwise, a different pattern can be observed for reaction time. The reaction time is lower for the 101Hz condition than for 30Hz (M_{101Hz}=1818ms, SD_{101Hz}=288ms; M_{30Hz}=1924ms, SD_{30Hz}=256ms) and the difference is statistically significant (F(1,11)=8.84, $p < 0.01$). The logistic distribution applied to the results adjusts better to the condition at 101Hz than to the condition at 30Hz.

4.4.3 Discussion

The results were clear: the subject's response was influenced by the stimuli's frame rate, but not in the same direction. Both frame rates have a similar accuracy, but the same is not true for reaction time. Like in experiment 1, subjects demonstrated a great capacity to recognize biological motion and the stimuli's frame rate, duration or the interaction between these two conditions appears to not be a variable. The observers' capacity to recognize biological motion is similar in both experiments and consistent with the studies presented previously (Neri et. al, 1998, Thurman et al. 2010). However, when we analyse the reaction time a difference interpretation is possible. Retrieving the arguments presented in section 4.3, we had proposed that more motion information would be necessary to understand the real influence of the frame rate. In other words, the frame rate increases the quality of the motion signal (D'Amico and G. Ferrigno, 1990), the stimuli's duration improves the motion cues available (Thurman et. al 2010), the motion cues available make them more salient and the observers tend to use the most relevant information. In this sense, two major methodological changes introduced in experiment 2 appeared to be fruitful. Firstly, by increasing the stimuli's duration we presented subjects with real human motion information and real kinematic properties. Secondly, by choosing to present a range of motion stimuli, and comparing them at different frame rates, it was possible to effectively understand the influence of frame rate on the kinematic properties. In fact, experiment 2 was an experiment of signal processing. With the argument that frame rate changes the signal properties, only by presenting these changes at different frame rates is it possible to understand their influence.

At this level, we need to be careful with the conclusions. The differences in reaction time comparing the frame rate conditions allow us to propose that the quality of signal justifies the results. However, we cannot say that temporal sampling explains the large temporal summation for biological motion, as we had hypothesized in the introduction of the chapter. Being parsimonious, we can defend that frame rate influences the response to biological motion in long stimuli's presentation and that high frame rates appear to be the best option. But, we can submit the question again: can temporal sampling explain the large temporal summation for biological motion? In a restrict result analysis we can simply say that we don't know. The percentage of correct responses does not give an answer and just confirms other studies that had shown the human capacity to recognize biological motion. The reaction time was greater for stimuli more similar to biological motion and lower to the stimuli with motion patterns close to a rigid object, as expected. Subjects could respond after the start of the second stimulus and, adding the inter-trial-interval (see figure 4.7), they had 4 seconds to give an answer and press the button. Because they needed to choose between two stimuli it was expectable that presentation of similar stimuli lead to higher reaction times, and that the easier comparisons allowed for lower results. But if the frame rate had no influence, then both conditions should be comparable. We found, however, that they are not and the analysis of variance distinguishes two factors clearly.

Nevertheless, even though the experiment does not answer the chapter's main question, the results allow for new interpretations and new hypothesis about the large temporal summation that characterizes the perception of biological motion. Note that even for easier comparisons the reaction time was higher than 1400 ms and remember that we presented stimuli for 2000 ms, corresponding to four gait cycles. If the frame rate influences the observers' response we can argue that the motion signal presented explains the differences between frame rate conditions. In other words, we cannot say that temporal sampling explains larger temporal summation but we can hypothesize that the signal originated by the temporal sampling can explain that. So, it could be a question of signal properties that are implicit in the sampling process, but not with the sampling *per se*. Actually, considering the arguments presented along the chapter and the results of the two experiments, we are proposing that temporal summation could be better explained by the signal processing theories and, in this sense, the temporal sampling is a secondary question to the problem.

Effectively, when we capture human motion and construct biological stimuli we are reducing a continuous signal into a discrete signal (see details in chapter 3, section 3.2 and 3.3). This process influences the signal properties as we have shown above, but this influence does not indicate changes in main signal properties and does not mean that the signal's receptor (the observer in the perception experiment) perceives those changes. Put simply, the reduction of a continuous signal to a discrete signal can preserve the signal properties in a way that the receptor can reconstruct and interpret the original signal (the human motion observed directly) (Winter, 2009). The sampling process here is crucial to guarantee that the original signal preserves its properties and the Nyquist-Shannon Sampling Theorem, despite not being a theorem developed to explain human behaviour, can adequately answer the temporal sampling question (Marks II, 1991, 2009). According to Marvasti (2001), Shannon was probably aware of Cauchy's work about sampling problems, as quoted by Black (1953): "*If a signal is magnitude-time function, and if time is divided into equal parts forming subintervals, such that each subdivision comprises an interval T seconds long where T is less than half the period of the highest significant frequency component of the signal; and if one sample is taken from each subinterval in any manner; than a knowledge of the instant within each subinterval at which the sample is taken contains all of the information of the original signal*". The end of the quote, "*contains all of the information of the original signal*", can be demonstrated by the differences between frame rate conditions in experiment 2.

With these assumptions, it is defensible that high temporal summation is intrinsic to biological motion perception because the temporal component carries out relevant information. However, this relevant information or, in other words, "all of the information of the original signal", preserved by high frame rates, needs to be demonstrated. In Chapters 5 and 6 we will try to understand which signal properties are relevant to the perception of biological motion and, consequently, to the large temporal summation presented in many studies.

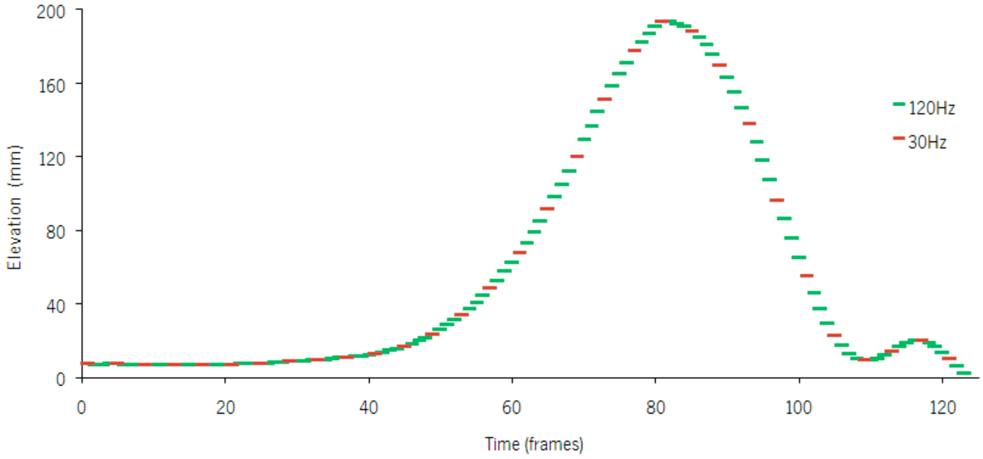
5. Perceiving Acceleration

5.1 Introduction

The perception of biological motion can be seen as an issue of signal processing, and the study of signal properties can allow for a deeper understanding about the mechanisms involved. As seems to be evident from the experiments with frame rate presented in chapter 4, small changes in signal properties can result in a different response from the subjects. So, we can theorize that signal properties carry with them the relevant information to biological motion perception, and that these properties can better explain many evidence found on biological motion perception, such as the high temporal summation, the old question about form and motion contributions, the relevant cues to perception depending on the duration of the presentation, just to mention a few. In fact, the argument is not new but perhaps it hasn't been actually applied to biological motion perception. In other words, the distinction made by Frederiksen, Verstraten and Van de Grind (1994) between *temporal integration* and *temporal summation* allows for a clear definition of concepts. In their work, the authors presented an integration temporal model that better explains, in their opinion, human motion perception (note that they investigate motion in general, not biological motion specifically). The central difference is that temporal summation models (Quick, 1973; Watson, 1979) use stimuli duration as independent variables, whereas the integration model uses the signal's properties. This appears to be crucial if we argue that biological motion perception is time-varying, that frame rate changes the signal and consequently its processing, and that the capture methods proposed in chapter 3 change the nature of biological motion stimuli. In sum, signal properties, more than the exposure time, are crucial and determinant to perception. Citing Smith (2003), "since the frequency domain is continuous, the synthesis equation must be written as an integral, rather than a summation" (p.207). Keeping in mind the discussion in the previous chapter, the manipulation of frame rate gives us an example of how an equation can be written as an integral or, in an opposite direction, as just a simple summation. When we increase the frame rate we are trying to transform a discrete function so that, in its greatest extent, a high frame rate will correspond to a continuous function. As illustrated in figure 5.1, the same ankle movement can be seen as a discrete function (30Hz (red markers)) or can be approximated to a continuous function (120Hz (green markers)). In this sense, signal processing is not a simple summation process, but the limit of a sequence of summations, in other words, integration. Here, the signal properties are preserved and consequently, we can investigate their real influence on perception.

So, the study of motion signals and their most salient properties (see chapter 2, section 2.2) can have many advantages, as we will try to demonstrate along the chapter.

Figure 5.1 Ankle elevation movement during one step at different frame rates.



Biological motion signals are characterized by acceleration and deceleration patterns (Calderone & Kraiser, 1989; Schmerler, 1976)), globally or locally distributed (Beitema & Lappe, 2002; Neri, Morrone & Burr, 1998; Troje & Westhoff, 2006). In activities such as walking or running, these signals are "regular in their irregularity", that is, we can find a periodical pattern that differs from period to period in terms of instantaneous acceleration and deceleration. Effectively, we can consider a prototypical pattern of biological motion, taking into account biomechanical constrictions of the human body (Crowninshield & Brand, 1981), and draw a perfectly periodical function of velocity or acceleration. However, in spite of the subjects' capacity to recognize biological motion here, we would be presenting something like a biological pattern that, as Runeson (1994) said, "only mimed the motion properties" (p.386). During the gait cycle, each foot has a particular pattern of acceleration and deceleration that differs from step to step, creating a specific kinematic pattern. Biomechanical properties, such as skeletal and muscle structures, originate a regular alternation between swing and stance phases. However, the degrees of freedom in the skeletal and muscle structure combined with gravitational forces produce an irregular pattern inside that regularity. This irregularity is precisely the biological component of motion or, in other words, its kinematic signature, as shown by Bingham, Schmidt, and Rosenblum (1995). In their study, these authors investigated the role of dynamics on perception by presenting subjects with animate and inanimate events, such as a tree falling, a hand-moved spring, a hand-moved pendulum, a pendulum, a rolling ball, a splash or falling leaves. The stimuli represent different types of dynamics: rigid-body dynamics, biodynamics, hydrodynamics and aerodynamics. At the same time, they manipulated the display's orientation and asked participants to describe events in a free-response task or to circle properties in a checklist. The results showed that participants were able to distinguish kinematic properties and identify various events, as reflected by the observers' descriptive patterns. As the authors pointed out, citing one of the participant's response about the hand-moved pendulum stimuli, "person holds one [end] and mimics a swinging motion by moving the bottom with his hand"(p.1483). They also showed that perception depends on the direction of the stimuli, when related to the gravitational direction. Nevertheless, the most important conclusion was that the energy flows are the feature of kinematic properties that allows for the identification of different types of dynamics. In other words, the perception of motion is dependent on the dynamics' properties and changes in the motion's velocity allow for the event's identification.

Effectively, the human capacity to discriminate different types of dynamic patterns had been study before by Birgham (1987) and by Runeson (1974), in a relevant and original work about the perception of velocity. In spite of Runeson's work not having been the first work on this theme, it was probably the first that investigated the perception of velocity as an issue of signal properties, considering these properties as independent variables. Previously, as the author points out, the research on perception of velocity was restricted to the invariance of perceived velocity under different retinal velocities or to the problem of constant angular or linear velocity. In general, and independently of the research concerns, the main assumption was that the velocity was perceived as such (*velocity-seen-as-such*) (see Bloch & Bonnet (1966) for an exhaustive review). However, contradictory evidence demonstrated that observers perceived constant velocity in stimuli moving with non-constant velocity (Johansson, 1950b) and that dots moving at constant velocity were perceived as moving at non-constant velocity (Goldstein & Wiener, 1963). Curiously, both studies mention the sinusoidal velocity pattern as a possible explanation for the perception of motion. Moreover, Goldstein and Wiener argued that sinusoidal motion could be an optimal stimulus to perceive constant velocity, an idea that Johansson (1950b) had explored in his work.

Considering these opposite evidence and the predominant idea that constant velocity is seen as such, Runeson (1974) developed a set of experiments where he tried to demonstrate that the perceived velocity can be related to the physical velocity but not, necessarily, in a linear way. Citing the author, "*the validity of this procedure [the author was referring to the common procedure adopted in studies on the perception of constant velocity] rests upon the implicit assumption that perceived velocity relates to physical velocity by a function, the parameters of which remain constant during the course of the* *movement. Thus, only situational /actors such as background conditions, type of target and track, plus an ordinary psychophysical magnitude relation could affect perceived velocity. Therefore, both constant and non-constant velocity would, in principle, be perceived as such. However, it is not necessary to make this assumption. The function relating physical to perceived velocity (if any) may also contain parameters which vary with time and/or distance traversed.*" (pp.3-4, square brackets added). In these experiments subjects compared objects moving linearly according to different velocity patterns. The results were impressive. Observers reported constant velocity when stimuli were moving with non-constant velocity and perceived non-constant velocity for stimuli moving with constant velocity patterns. Moreover, the results also demonstrated that to be seen as constant velocity the stimuli needed to be moving as a natural stimuli (natural motion), that is, starting to move smoothly and then stabilizing at a constant velocity. Runeson's work allows for two important conclusions to be drawn. Firstly, the visual system appears to be responsive to velocity patterns, and secondly, this sensibility appears to follow a specific pattern related to natural movements. So, we could expect that biological motion perception observes the same response pattern and, with this assumption, that the study of signal processing appears to be relevant.

In spite of the works presented above and the evidence that the human visual system can perceive acceleration/deceleration patterns, it is easy to find contradictory results in the literature or, at least, contradictory conclusions. Two main reasons can explain this. On the one hand, talking about motion, biological or not, implies discussing time and space, the two motion components. Although we can argue that they explain different levels of perception, these components are two parameters of a motion function. As defined by Runeson (1974, p.4), motion function means " a movement with physical velocity varying in a particular way along the track". In this sense, the translational component is implicit and velocity patterns, perceived or not, are also implicit. In a study about the role of spatial and temporal information in biological motion, Lange and Lappe (2007) presented stimuli where they manipulated none, one or both components: a classic PLW, a temporally scrambled PLW, a spatially scrambled PLW or a temporally and spatially scrambled PLW. The stimuli were presented laterally and participants had to report the direction the walker faced (left or right) and, in another task, the walking direction (forwards or backwards). Results showed that spatial but not temporal cues were crucial to detect the direction the walker faced. However, temporal and spatial information were required to correctly discriminate the walking direction. On the other hand, the second reason that can explain why we find contradictory evidence about the perception of velocity patterns is measure related. We can study velocity patterns or acceleration/deceleration patterns. Depending on the task and on the manipulation, different authors adopted one or another parameter. Strictly speaking they are related, but we can study them independently. Then again, a velocity value always has at least a corresponding acceleration value, which can be zero or no acceleration. Burker (1952) argued that the human visual system cannot perceive variations in acceleration and that we can only discriminate constant acceleration patterns. In spite of this, Schmerler (1976) concluded in his work that it is possible to detect changes in motion, but not for small velocity variations. To detect a 50% motion change it is necessary to increase or decrease velocity from 230 to 320%. In other words, the human visual system appears to be sensitive to velocity changes, but not highly sensitive. In another study, Muchisky and Bingham (2002) defended that we don't need to perceive velocity to detect variations in velocity patterns and that variations over space are sufficient. From another perspective, Brouwer, Brenner and Smeets (2002) tried to understand if we could use acceleration cues in interception with short time presentations. They presented two dots, one of them accelerated and the other decelerated, and asked subjects to judge which of the two was accelerated. In a second task participants were asked to adjust the velocity in order to perceive that dot as moving at constant velocity. The results showed that subjects didn't detect acceleration itself but they detected changes in velocity patterns. Finally, in a detailed study using only foot motion, Chang and Troje (2009) suggested that observers used acceleration cues to perceive motion. In their work about the local inversion effect in biological motion perception, the results demonstrated that the local inversion effect was carried by accelerations contained in the foot motion. Other evidence can be found in the studies of Babler and Dannemiller (1993), Casile and Giese (2005), Gottsdanker, Frick, and Lockard (1961) Port, Lee, Dassonville, and Georgopoulos (1997) or Schlack, Krekelberg, and Albright (2008).

As we said earlier, velocity and acceleration are related, but we can study them independently. Still, physically we can argue that velocity and acceleration are closely related and that discussing one requires discussing the other. Effectively, as velocity can be defined as the rate of change in space, acceleration can be described as the rate of change in velocity. In terms of equation of motion we know that velocity is the first derivative of the position of a moving object in respect to time, and acceleration is the second derivative (or the first if the original function is velocity). In this sense, we can argue that if acceleration affects perception, then perception is also affected by velocity. Taking into account the translation of an object, we can find different activities and, for each one, consider acceleration or velocity as the relevant cue to perform well. However, biological motion is temporally and spatially defined. Our biomechanical structure has limited degrees of freedom and, consequently, it forces the continuous relation between spatial and temporal components. So, it is expectable that, taking biological motion in itself, changes in the temporal component are followed by changes in space. If not, we can have something that appears to be biological motion but in fact is not. Therefore, changes in velocity are followed by changes in acceleration, with the same conclusion. In this sense, the definition of biological motion needs to preserve both parameters: natural velocity and natural acceleration. Therefore, we can argue that a third derivative will have to respect the previous derivatives. That is, by preserving the velocity and acceleration we can compute the natural acceleration and then compute the third derivative, or jerk. This derivative is simply the rate of changes in acceleration and, for biological motion, it has a predicted value, known by minimum jerk (Flash and Hogan, 1985). The minimum-jerk model proposed states that biological motion has a characteristic velocity pattern that can be mathematically defined. Quite simply, the minimum jerk is based solely on the motion's kinematic properties and it is a cost function that minimizes jerk value over a particular movement trajectory. Here we can hypothesize that the human visual system is sensible to minimum jerk (biological jerk) and, consequently, to acceleration and velocity biological patterns. Precisely, we will discuss this hypothesis in experiments 1 and 2 presented in the section below. In a curious study, Cook and colleagues (2009) compared the sensitivity to biological jerk in adults with autism spectrum conditions, by manipulating the velocity profiles of two conditions: minimum jerk (hand movement) and gravitational motion (falling tennis ball). For each condition they computed a range of velocity profiles ranging from 100% natural motion to 100% constant velocity. Participants were asked to report the less natural of the two stimuli in a forced-choice task. They found that participants with autism spectrum conditions didn't show sensitivity to biological or non-biological velocity profiles, when compared with control participants. In a control group they found not only sensitivity to the velocity profiles but also a lower threshold for the minimum jerk condition.

The jerk parameter necessarily encompasses velocity and acceleration parameters and their equations are always related. So, in biological terms, we can argue that manipulations on velocity patterns mean manipulations in acceleration patterns and, consequently, the participants' responses in a perception task can be compared with one of both parameters. In this sense, distinguishing the perception of velocity or the perception of acceleration can be redundant. Note that we are not saying that the visual system processes velocity and acceleration equally. The results presented earlier recommend caution. Instead, we are proposing that, to keep the biological characteristics of a stimulus, their kinematic properties need to be preserved, and for that, changes in velocity or acceleration affect the signal in the same way. So, the jerk parameter represents here a valid option. Considering the biomechanical constrictions and the logic sequence of space, velocity, acceleration and jerk, the jerk can give a biological signal value. In other words, considering the minimum jerk model, the value of jerk always represents the minimum value of rate changes in acceleration and velocity, for a specific object movement. The biological characteristics of motion signal can be measured with the jerk parameter, and the kinematic properties (velocity, acceleration, space-time relation, gravitational influence) will always be considered.

In this chapter we present a set of experiments about perception of velocity in biological motion perception. We show the human sensibility to perceive small changes in velocity patterns and, consequently, the capacity to recognize the biological specificities of motion signals. As we stated in the beginning, the perception of biological motion can be understood as an issue of signal processing. If it is an issue of signal processing and if the signal is characterized by velocity and acceleration patterns, the study of these parameters can give us a different understanding about biological motion. For that, for each experiment we discuss in detail the stimuli construction and the manipulations underlying the stimuli. In a first experiment we present subjects with a set of stimuli representing the feet of a walker, changing the velocity profiles of each stimuli. In a second experiment we reduce the cues available, presenting only one foot with a short duration. We discuss the results, proposing other experiments that may give us more evidence about the relevance of motion signal properties to perceive biological stimuli.

5.2 Experiment 1: perceiving motion patterns of the feet

In experiment 1 we changed the properties of the motion signal by manipulating the velocity patterns. The main goal was to understand the perception of velocity patterns in biological motion and, consequently, to understand the importance of motion signal properties. We presented observers with the feet of a point-light walker and they were asked to choose the most natural of the two stimuli. Differences in the participants' responses should show the sensibility to velocity patterns and the minimum physical changes needed to perceive signal differences. The results show the capacity of the visual system to perceive small physical changes and to recognize different biological motion velocity patterns.

5.2.1 Method

5.2.1.1 Participants. Nine volunteers took part in this study, all of them naïve as to the purpose of the experiment. Participants were students or researchers in the Laboratory of Visualization and

Perception with an average of 22 years old, ranging from 20 to 31 years old. All had normal or corrected-to-normal vision based on the automatic screening test and tests of kinetic (dynamic visual acuity with moving stimuli varying direction, speed and spatial frequency) of the equipment for visual screening (Essilor, Ergovision).

5.2.1.2 Apparatus and Stimuli. The stimuli were presented by a 3-chip DLP projector Christie Mirage S+4K, with a spatial resolution of 1400x1050 pixels and a refresh rate of 101Hz. Images were displayed with OpenGL running over a Vr/Net Juggler software on a computer with a graphic board NVIDIA Quadro FX 4500. The stimuli were projected on a surface 2.10m high and 2.80 wide. This apparatus was possible in the Laboratory of Visualization and Perception of the University of Minho, in an immersive virtual environment (see figure 4.6 in chapter 4).

The stimulus was a point-light figure of two dots. The typical dots of the head, shoulders, elbows, wrist, hips and knees of a typical PLW were removed and only right and left ankles were presented, representing the feet of a walker. The feet carry out relevant dynamic information, as shown by many studies (Casile & Giese, 2005; Mather, Radford, & West, 1992; Thurman, Giese, & Grossman, 2010; Troje & Westhoff, 2006), when compared with upper body parts that contain more structural or form information (Lange, George, & Lappe, 2006). This option reduces the number of available cues to recognize a point-light walker, but not to recognize biological motion properties and specific signal information.

Keeping intact the stimuli spatial component, we changed their temporal component by manipulating the velocity of the translational pattern. For that we smoothed the velocity of the translation pattern with a simple moving average (MA) (see Kendall & Stuart (1976) and Chatfiel (2004)), changing the order (q) in multiples of six, thereby creating thirteen stimuli ranging from biological to MA (72). For each frame we assumed that the new value of instant velocity would be the average of half of the previous values and half of the next values of the moving average value order of the biological values available in the database presented in chapter 3. As the q parameter gets larger the velocity curve approximates a linear function at constant velocity, i.e., the bigger the moving average order, the bigger the smoothness of the velocity translational pattern. The procedure to calculate the new velocity values is shown in table 5.1.

Table 5.1 Moving average procedure.

Frames	Biological Velocity	Smooth Velocity
f_1	21.4	
f_2	24.6	
f_3	15.7	
f_4	19.5	19.1
f_5	11.8	
f_6	22.6	
f_7	18,4	

Moving Average Formula

$$MA(q)_{fn} = \frac{f_{n-1} + f_{n-2} + f_{n-3} + f_{n+1} + f_{n+2} + f_{n+3}}{q}$$

Calculation's example

$$MA(6)_{f4} = \frac{21{,}4 + 24{,}6 + 15{,}7 + 11{,}8 + 22{,}6 + 18{,}4}{6} = 19{,}1$$

After calculating the new velocity pattern, we computed the new 3D coordinates (translation, elevation and sagittal). Considering a frame rate of 240Hz, we firstly computed the translational component, assuming that

$$v = \frac{d}{t} \Leftrightarrow d = vt\,,$$

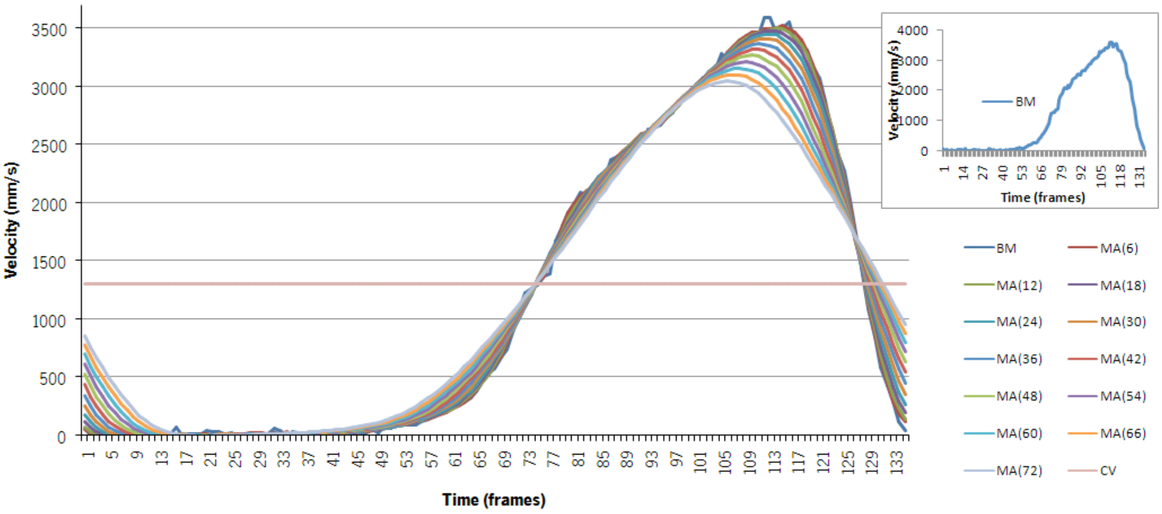
and that we know the variable v, calculated as shown in table 5.1, and that variable t is the same for each frame (240Hz/1000ms). Assuming an initial value to the trajectory, we computed the formula for each frame, considering its instant velocity and the same temporal differences between frames. Knowing the new translational pattern, we calculated the new elevation pattern. For that, we used the linear interpolation method because the differences between two consecutive values are small and the elevation values do not change rapidly (Billo, 2001). Assuming the general formula,

$$y_1 = y_0 + \frac{x_i - x_0}{x_1 - x_0}\left(y_1 - y_0\right),$$

and knowing that x_0 and y_0 are the biological values and x_1 is the previously calculated value, we obtain the new elevation value for each frame, y_1, and consequently the new elevation pattern. The sagittal axis was neglected because the deviation in one single step was inferior to 2 cm, a variation inferior to 4' of the vertical visual angle, a higher conservative value of visual accuracy (Verhoeff, 1933). Here, we considered that the foot was moving in the same plane, meaning that we had actually a 2D stimulus. However, the same process applied to the elevation axis could be used here.

All procedures were computed for one single step to one foot and then looped to obtain a sequence of steps to the same foot. After that, to get the feet of a walker during two gait cycles, the foot was duplicated and the difference between the feet's position was subtracted according to the captured biological data. By looping and duplicating the procedures applied to one foot during one step, we eliminated the differences between steps and the differences between feet. These differences could be an important source of information during the two-forced choice task because the moving average process does not equally affect the steps during the gait cycle and both feet. Depending on the raw data used to compute the stimuli, we could have obtained stimuli that differed not only in velocity pattern, but also in steps and between feet. Although we can argue that differences between steps and between feet are part of walking kinematic properties, they could be an extraneous variable in itself. The result was thirteen stimuli, all with the same spatial properties but different temporal characteristics, with the toe-off and heel-strike (see definition in chapter 2, section 2.1) being the same for each step and for both feet. Only the instant velocity differed according to the moving average order, smoothing the velocity pattern progressively, as shown in figure 5.2. The natural signal noise of biological patterns (BM), as we can see in the small graph, was progressively removed and the smoothness increased until MA (72), the most smoothed stimulus. The horizontal line (CV), illustrates the average velocity or, in other words, a stimulus at constant velocity with the q parameter equal to the total number of frames.

Figure 5.2 Velocity pattern for each stimuli (one foot, one step).

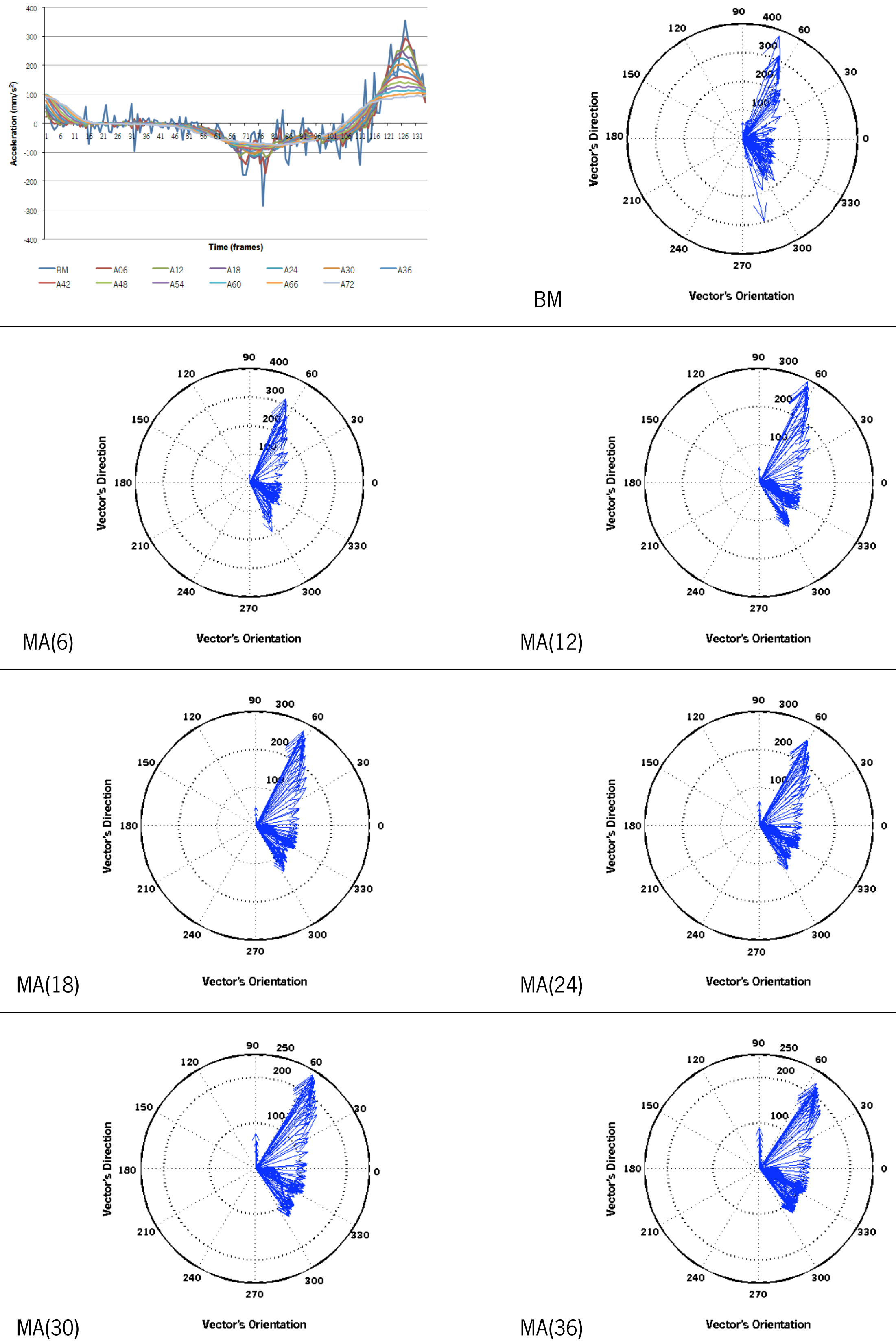


The similarity in the shape of the velocity curves can be better interpreted in terms of vectors' representation. The hodographs of figure 5.3 give us a visual representation of acceleration vectors for all stimuli, showing the three vectors' components: direction, orientation, and length. In spite of the velocity curves almost overlapping (figure 5.2), the vectorial representation of acceleration shows the differences between stimuli. Increasing the moving average's q parameter decreases all vectors' length, making them similar to each other. At the same time, vertical vectors, absent in biological motion, become common in the stimuli with a high moving average's q parameter. These vectors mean strong accelerations and occur in toe-off and heel-strike and, in spite of the fact that human gait can be viewed as a kind of controlled falling process, we do not find abrupt accelerations in the beginning and ending of each step. Nevertheless, when we smooth the velocity pattern, the typical smoothness of the heel strike disappears and the moving average process distributes the initial and final instant velocity in such a way that the dot representing the foot makes abrupt movements. In a different perspective, Johansson addressed this issue regarding the perception of cycloids' motion (see Johansson, 1973, for a complete review). On the other hand, the smoothness generates a more uniform pattern of movement that, *in extremis*, at constant velocity, means no acceleration. This pattern decreases the horizontal vectors found in biological motion, because the lower values of the stance phase increases at the time that higher values decrease. Comparing all acceleration patterns and the signal smoothness process, the biological stimuli and the stimuli near it, the irregularities are more salient and consequently, in hodographs, the dispersion of vectors becomes clear.

The stimuli had a temporal resolution of 101Hz, although the projector had been prepared to frame rates up to 120Hz, but actually we could only ensure frame rates of up to 101Hz, with the best spatial resolution (1400X1050 pixels).

5.2.1.3 Procedure. Participants were seated in a dark room, 2 meters away from the display and were asked to choose the most biological of two stimuli presented sequentially, with one of them always being the biological motion (standard stimulus). A black frame was presented for 500ms between the first and the second stimuli. Participants responded by pressing the corresponding mouse buttons connected to the computer, with the left button if the first stimulus was the most biological and the right button if it was the second stimulus, performing a two-alternative forced-choice task. No

Figure 5.3 Hodographs of acceleration for all stimuli.



BM

MA(6)

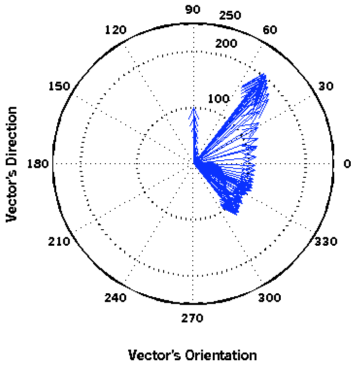
MA(12)

MA(18)

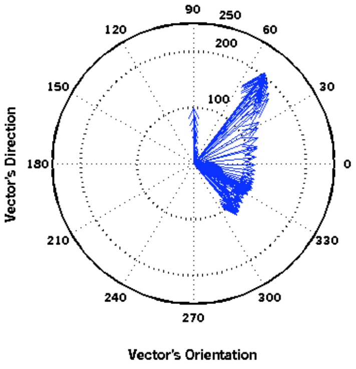
MA(24)

MA(30)

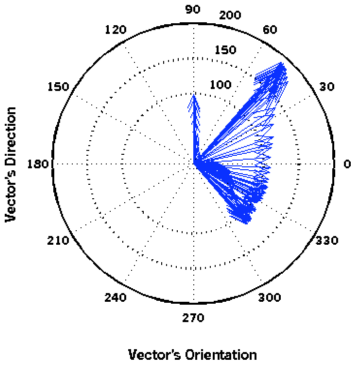
MA(36)



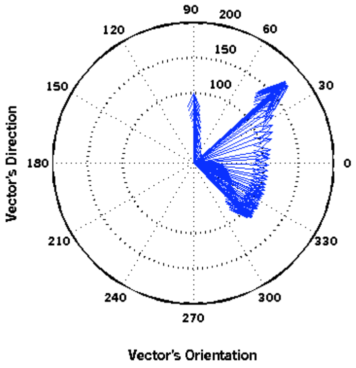
MA(42)



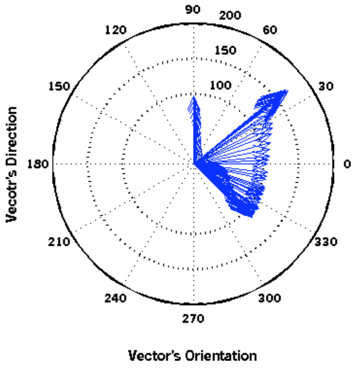
MA(48)



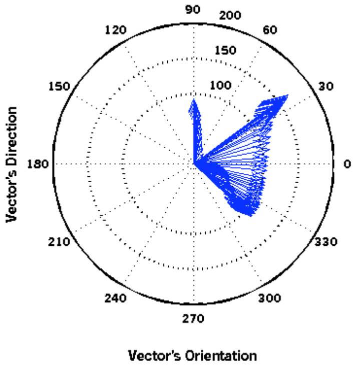
MA(54)



MA(60)



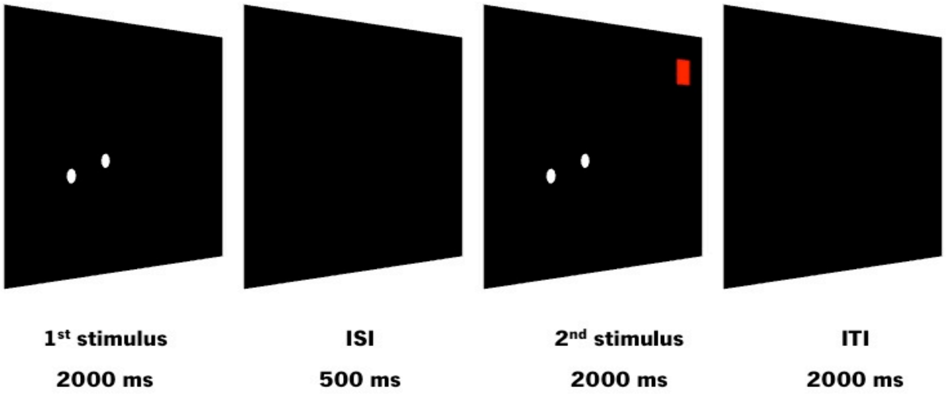
MA(66)



MA(72)

feedback was provided for correct responses. The stimuli were presented randomly and participants gave the answer by pressing the mouse button after the second stimulus started to be presented. A red square on the top right corner signalized the second stimulus and a long black frame with 2000ms signalized the inter trials interval (ITI). Participants took part individually in two sessions, each lasting for about half an hour and with 125 trials, 10 trials per stimulus (5 trials for standard stimuli when displayed in the first and second presentation simultaneously), 20 trials per stimuli for both. Figure 5.4 illustrates the procedure described.

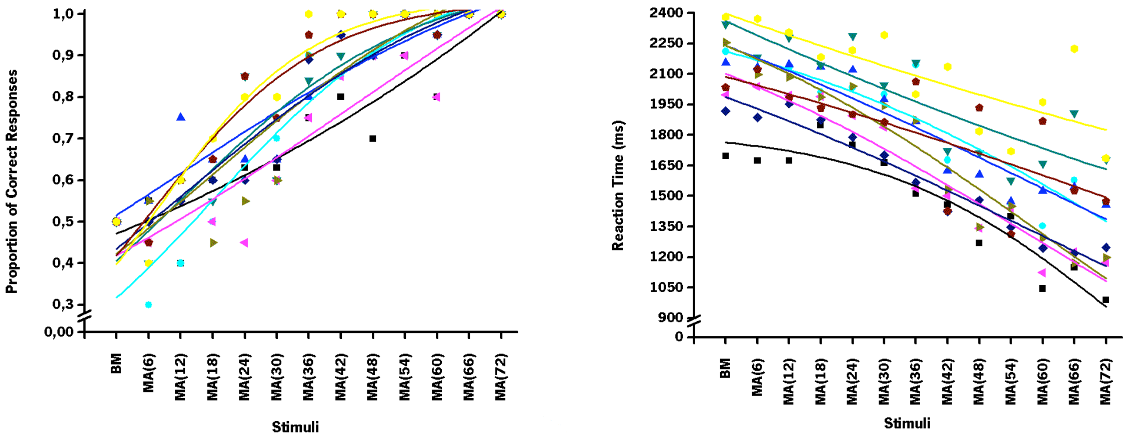
Figure 5.4 Experiment 1's procedure and stimulus presentation (one trial).



5.2.2 Results

An exploratory analysis allowed the assumption of normality, demonstrating that all data falls in the normal range, according to the Kolmogorov-Smirnov normality test. Furthermore, results better explained by the presentation order (first or second stimulus) or the option for one of the mouse buttons were discarded and no significant results were found. Having confirmed these assumptions, we performed statistical analyses to confirm the existence of a significant effect in the perception of biological motion velocity patterns.

Figure 5.5 Results per participant of experiment 1.

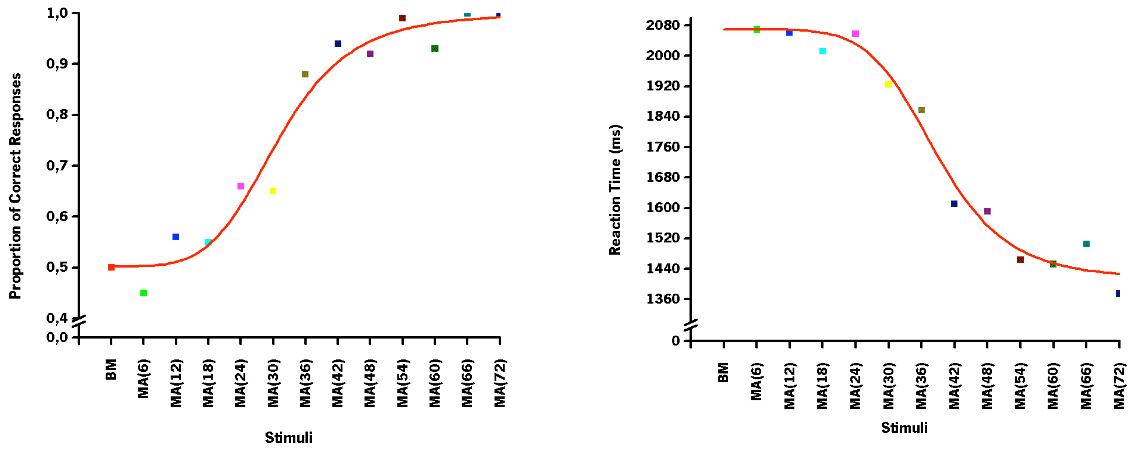

A) Proportion of Correct Responses

B) Mean Value of Reaction Time

The individual results for the proportion of correct responses (graph A) and reaction time (graph B) are shown in figure 5.5. A one-way ANOVA for repeated measures was conducted to analyse the effect of smoothness of the velocity pattern on the perception of biological motion. Considering the responses of all participants, there was a significant effect on reaction time and on the proportion of correct responses, with $F(12,8)=3.73$, $p < 0.01$ and $F(12,8)=29.14$, $p < 0.01$, respectively. The logistic fit conformed well for both measures and to most of the participants, with exceptions in reaction time for participants 8 and 9. Tables 5.2 and 5.3 discriminate the values per participant for reaction time and proportion of correct responses, respectively.

Figure 5.6 shows the mean of the proportion of correct responses (graph A) and the mean of reaction times (graph B) for each stimulus as a function of stimuli smoothness: from biological motion to less biological stimulus (MA[72]). The logistic regression applied to the aggregated data fits well to both measures, but the adjustment is better for the mean value of reaction time ($R^2=0.97$) than for the mean value of proportion of correct responses ($R^2=0.95$).

Figure 5.6 Aggregated results of experiment 1.



A) Mean value of Proportion of Correct Responses

B) Mean Value of Reaction Times

■ BM ■ MA(6) ■ MA(12) ■ MA(18) ■ MA(24) ■ MA(30) ■ MA(36)
■ MA(42) ■ MA(48) ■ MA(54) ■ MA(60) ■ MA(66) ■ MA(72)

Table 5.2 Mean, standard deviation and fitting of reaction time per participant and aggregated data (values in milliseconds).

	Stim. / Part.	BM	MA(6)	MA(12)	MA(18)	MA(24)	MA(30)	MA(36)	MA(42)	MA(48)	MA(54)	MA(60)	MA(66)	MA(72)	Logistic Fit *
■	1	1697 (454)	1672 (418)	1673 (429)	1847 (518)	1750 (415)	1663 (283)	1510 (446)	1457 (525)	1269 (464)	1399 (486)	1044 (544)	1149 (533)	989 (549)	adj. R^2= 0.87
●	2	2210 (196)	2118 (442)	2129 (308)	2011 (420)	2033 (317)	1999 (303)	2143 (243)	1677 (202)	1815 (207)	1460 (228)	1352 (387)	1578 (301)	1467 (216)	adj. R^2= 0.78
▲	3	2154 (529	2133 (393)	2146 (483)	2135 (291)	2119 (433)	1974 (380)	1866 (489)	1623 (426)	1605 (504)	1474 (428)	1524 (565)	1545 (336)	1457 (568)	adj. R^2= 0.88
▼	4	2345 (432)	2181 (411)	2278 (459)	2143 (530)	2287 (475)	2046 (570)	2156 (380)	1722 (355)	1711 (379)	1577 (528)	1659 (513)	1907 (570)	1678 (509)	adj. R^2= 0.68
◀	5	1996 (152	2039 (148)	1995 (263)	1990 (79)	1895 (121)	1839 (243)	1539 (330)	1502 (185)	1341 (170)	1439 (259)	1123 (172)	1226 (179)	1173 (194)	adj. R^2= 0.91
▶	6	2254 (223)	2098 (432)	2082 (393)	1986 (331)	2039 (529)	1943 (362)	1872 (506)	1531 (452)	1347 (363)	1449 (470)	1291 (409)	1170 (406)	1197 (453)	adj. R^2= 0.93
◆	7	1916 (183	1885 (418)	1952 (504)	1874 (331)	1788 (280)	1700 (632)	1566 (477)	1422 (468)	1479 (494)	1347 (538)	1245 (474)	1217 (538)	1246 (702)	adj. R^2= 0.94
⬟	8	2033 (284)	2123 (292)	1982 (262)	1932 (267)	1901 (243)	1863 (331)	2063 (292)	1427 (329)	1933 (463)	1312 (355)	1868 (465)	1527 (591)	1474 607)	adj. R^2= 0.41
⬢	9	2378 (176)	2371 (150)	2303 (280)	2182 (113)	2216 (134)	2291 (293)	2000 (376)	2135 (233)	1818 (209)	1719 (289)	1961 (209)	2223 (199)	1685 (225)	adj. R^2= 0.51
-	All	2109 (292)	2068 (345)	2060 (376)	2011 (320)	2003 (327)	1924 (377)	1857 (393)	1610 (353)	1590 (361)	1464 (398)	1451 (415)	1504 (405)	1374 (447)	adj. R^2= 0.97

* y = a / (1 + e^(- k * x- xc)))

Table 5.3 Mean, standard deviation and fitting of proportion of correct responses per participant and aggregated data (values in milliseconds).

	Stim. / Part.	BM	MA(6)	MA(12)	MA(18)	MA(24)	MA(30)	MA(36)	MA(42)	MA(48)	MA(54)	MA(60)	MA(66)	MA(72)	Logistic Fit *
■	1	0.5	0.55	0.4	0.6	0.63	0.63	0.75	0.8	0.7	0.90	0.8	1	1	adj. R^2= 0.85
●	2	0.5	0.3	0.4	0.5	0.6	0.7	0.9	0.85	0.9	1	1	1	1	adj. R^2= 0.90
▲	3	0.5	0.55	0.75	0.65	0.65	0.65	0.8	0.95	0.9	1	0.95	1	1	adj. R^2= 0.85
▼	4	0.5	0.4	0.55	0.55	0.85	0.6	0.84	0.9	1	1	0.95	1	1	adj. R^2= 0.84
◀	5	0.5	0.45	0.55	0.5	0.45	0.6	0.75	0.85	0.9	0.9	0.8	1	1	adj. R^2= 0.84
▶	6	0.5	0.55	0.6	0.45	0.55	0.6	0.9	1	1	1	1	1	1	adj. R^2= 0.78
◆	7	0.5	0.5	0.55	0.6	0.6	0.65	0.89	0.95	0.9	1	0.95	1	1	adj. R^2= 0.90
⬟	8	0.5	0.45	0.6	0.65	0.85	0.75	0.95	1	1	1	0.95	1	1	adj. R^2= 0.91
⬢	9	0.5	0.4	0.6	0.7	0.8	0.8	1	1	1	1	1	1	1	adj. R^2= 0.92
–	All	0.5 (0)	0.46 (0.09)	0.56 (0.11)	0.58 (0.08)	0.66 (0.14)	0.66 (0.07)	0.86 (0.09)	0.92 (0.06)	0.92 (0.1)	0.98 (0.04)	0.93 (0.08)	1 (0)	1 (0)	adj. R^2= 0.95

* y = a / (1 + e^(- k * x- xc)))

Consider now the proportion of correct responses as a function of the proportion of the reaction time for each stimulus. The proportion of reaction time for each stimulus (prt_s) is given by the equation,

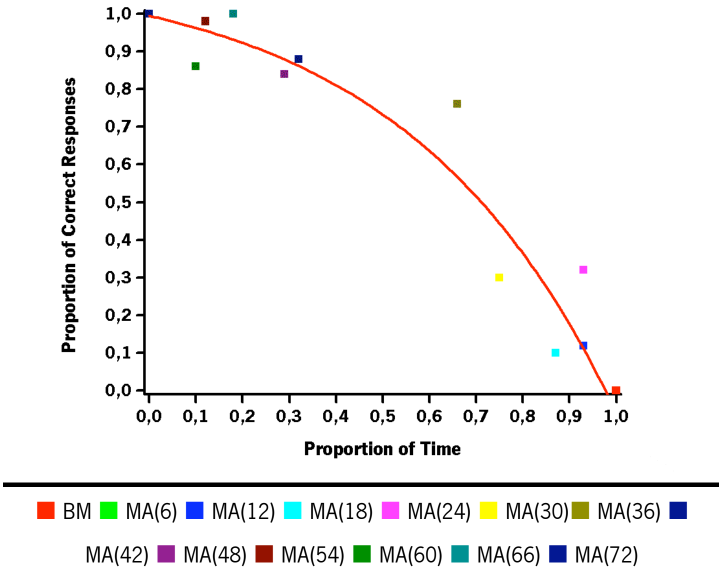
$$prt_S = \frac{|MA(72) - MA(q)|}{|MA(72) - MA(1)|}$$

where the numerator is the difference between the reaction times of the stimulus with the higher moving average order value (MA(72)) and one of the other stimuli, and the denominator is the difference between the reaction times of the stimuli with the higher and lower moving average order value (the stimulus with the lower moving average assumes the value 1 in the proportion, corresponding to 100%). The proportion of correct responses (pcr_s) is given by the equation,

$$pcr_S = \frac{|MA(1) - MA(q)|}{|MA(1) - MA(72)|}$$

where the numerator is the difference between the reaction times of the stimulus with the lower moving average order value (MA(1)) and one of the other stimuli, and the denominator is the difference between the reaction times of the stimuli with the lower and higher moving average order value (the stimulus with the higher moving average assumes the value 1 in the proportion, corresponding to 100%). q represents the parameter of the moving average (for the biological motion stimulus (BM) we can assume that q = 1, with each frame divided by 1). We can now compare the proportion of correct responses of each stimulus as a function for the difference of reaction time, i.e., the time difference considering the reaction time of the theoretically easiest stimulus (MA(72). Figure 5.7 illustrates this relation,

Figure 5.7 Proportion of Correct Responses as a function of proportion of reaction time (Exponential decay function).



showing that the easier the comparison between stimuli, the lower the reaction time. In other words, increasing the degradation of the biological signal, by increasing the moving average's q value, made it easier for the observers to identify biological motion. This relation fits better to an exponential decay function (adj.R^2=0.90) and, in this sense, the proportion of correct responses is subjected to exponential decay, meaning that the decrease in time is proportional to the signal degradation. The decay rate (λ) obtained is - 0.45 and given the equation

$$y(x) = y_0 + Ae^{\frac{-x}{\lambda}},$$

where y represents the proportion of correct responses and x represents the proportion of time, when y equals 0.5 (as we are working with the proportion of correct responses, 0.5 represents the absolute level of 0.75), x is 0.71 This means that responses higher than chance level occur near the stimulus with MA(36) (■).

Using the same procedure between the proportion of reaction time and each one of the motion signal parameters – velocity acceleration and jerk – we can see that the jerk parameter conformed better to the results. Figure 5.8 shows the relation between the proportion of reaction time, as explained previously, and the proportion of the difference of standard deviation ($p\sigma$) between the BM stimulus and other stimuli (assuming BM stimulus as the baseline and equalling 0), as given by the equation,

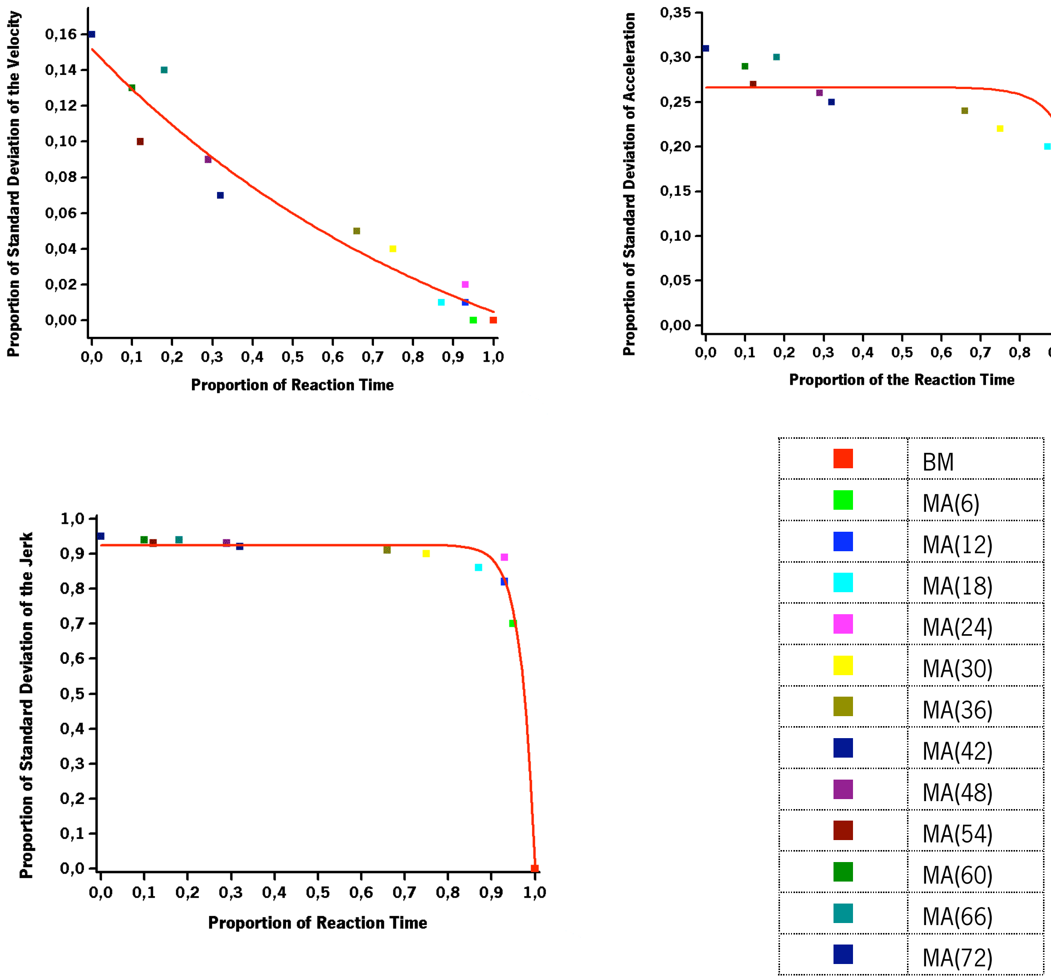
$$p\sigma = 1 - \frac{\sigma_{MA(q)}}{\sigma_{MA(72)}},$$

where q is the order of moving average and σ is the standard deviation of the stimuli in subscript. The graphs represent the standard deviation of the signal parameter: the lower the standard deviation, the more time is needed to give an answer and to choose the correct (biological) stimulus. The goodness of the exponential decay fit is better for the jerk parameter (R^2=0.98) than for velocity (R^2=0.93) or acceleration (R^2=0.87).

5.2.3 Discussion

The results clearly show that the perception of biological motion is influenced by velocity patterns - as the biological temporal component of the stimulus increases, participants perceive the stimulus as more natural, or more biological. Moreover, observers are sensible to small pattern

Figure 5.8 Signal parameters as a function of proportion of reaction time (Exponential decay function).



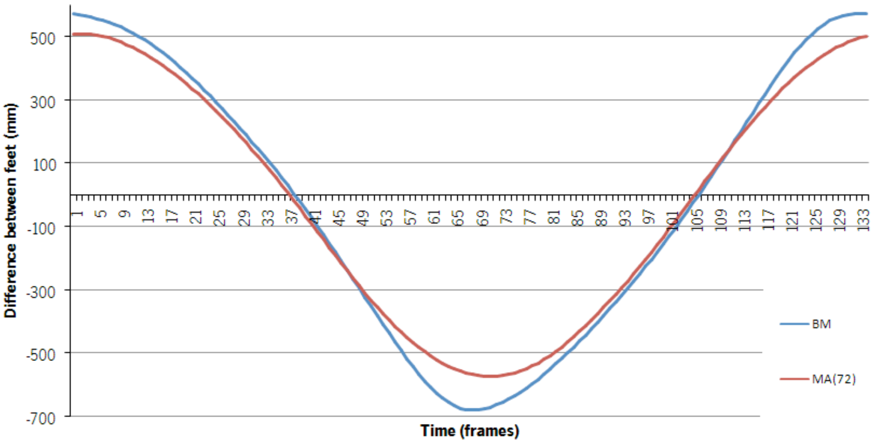
variations, as shown by the high proportion of correct responses for the stimuli with moving average higher than 36. In spite of the curves of velocity of BM and MA (36) stimuli overlapping, the small smoothness of the signal is sufficient to distinguish the biological stimuli from those near biological. Here it is important to explain what we mean by small smoothness. By analyzing the stimuli's velocity curves (figure 5.2) we can say that the temporal differences between them are small. In fact, if the average velocity is equal for all stimuli, the standard deviation decreases with the moving average's order value. However, this is a small decrease and the difference between the biological motion stimulus (BM) and the farthest stimulus (MA (72)) is no more that 16%. If we consider the MA (36) stimulus, above which the proportion of correct responses was higher than 0.75, the difference to the BM stimulus is around 5%. However, if we change the parameter we need to be careful when saying that temporally the stimulus do not differ much. As we can see in the hodographs (figure 5.3), different vectorial representations of the motion signal showed a distinctive pattern of acceleration, not with the same proportion of differences as in velocity. On the other hand, analyzing the jerk of the stimulus, a different relation between them is established, distinctive from both velocity and acceleration patterns. In this sense, the participants' responses can justify divergent interpretations if we make use of velocity, acceleration or jerk patterns. At the very least, this issue could explain the contradiction of some of the studies presented earlier in the introduction: the same results can yield different conclusions depending on the signal parameter chosen to analyse them. Because of that, but mainly because of the dependent relation between the parameters, it appears unreasonable to choose one of them. As they are related, all of them need to be considered. Effectively, the jerk parameter appears to explain the mean of reaction time better than both velocity or acceleration patterns, but more experiments need to be performed to explain the importance of each parameter or the predominance of one of them. As we proposed in the introduction, the jerk could be used as a biological measure and the results seem to justify it, but more evidence need to be collected. Ideally, the biological motion signal should be manipulated in terms of jerk, acceleration, and velocity independently. The same process applied in experiment 1 to velocity patterns could be applied to acceleration and jerk. This means that we would have three conditions, each one with many levels, in such a way that the parameters would be manipulated to generate equidistant levels between stimuli, for each of them. The participants would perform the same task and the results could be compared as proposed above: firstly deriving or integrating the equations depending on the parameter considered (jerk condition presupposes only integrative equations, acceleration presupposes integrate velocity and velocity only derivative equations). Then, it would be possible to compare each condition and their differential equations as a function of the reaction time. Independently of the manipulation that had been applied to velocity, jerk, or acceleration, if one explained the results better than the other, we would have more support to our hypothesis. Evidently, all three parameters would always explain a percentage of the results because, as we argued, they are related.

Degrading the biological properties, by smoothing the signal, made it easier to recognize the correct stimuli, looking at the proportion of correct responses and reaction times for each stimulus. Although the results showed that subjects performed better as the stimuli got easier, the difference between stimuli appears to be better explained by the mean of reaction times than by the proportion of correct responses. Even if not significant, the goodness of fit is better with the mean of reaction times. Here, the distinction between integration and summation, made by Frederiksen, Verstraten and Van de Grind (1994) and discussed in the introduction, can help us understand these results. In fact, if we consider that the perception of biological motion is analogous to signal processing, it is defensible that, independently of the capacity to recognize the correct stimulus, the integration of kinematic properties reflects the signal's smoothness. As their kinematic properties are temporally defined, the visual system needs to integrate the different parameters along time to perceive if a stimulus is natural or not. The higher the smoothing, the least respected the biological characteristics are and the easier it will be to perceive the difference. Recalling again Runeson's work (1974) and the argument that the visual system appears to be responsive to velocity patterns and that this responsiveness follows a specific pattern related to natural movements, the progressive smoothness of natural parameters influences the capacity to recognize biological stimulus and, equally, the time to do it.

Assuming that the visual system is prepared to respond firstly to natural movements, and that the jerk is one of the central parameters of the biological algorithm, it is possible to conciliate the results of many experiments in this area and to give them a new interpretation. For instance, the manipulation of stimuli as made by Lange and Lappe (2007), briefly described in the chapter's introduction, from which the authors had concluded that both temporal and spatial information were required to discriminate the walking direction correctly, is now justified. The temporal component is destroyed when the scramble is applied to the frame order, but not when it is applied to the different body parts, within the frames, as is done with spatial scramble. Here, in spite of the global cues not being represented, the local cues carry out the temporal information of biological motion. So, the temporal component is a necessary condition to perceive biological motion, but not necessary and *sufficient*, at least according to the authors. To be a necessary and sufficient condition, we need to eliminate all structure cues, a demanding experimental condition. The perception of biological motion presupposes some structure information, as is shown by the minimal number of dots required for a point-light walker (Johansson, 1973). Here, we consider the possibility that our stimuli carry out structure or spatial information. As we utilized the feet, the relation between them could be an extraneous variable. In spite of the spatial component having been preserved for each foot, by respecting the initial position (toe-off) and final position (heel-strike) between steps and the translational trajectory within steps, the relation between feet is only preserved in biological motion stimuli. For other stimuli, the variations in instant positions caused by the new coordinates of translational patterns originated from new velocity patterns generate a time lag between feet. The higher the moving average orders, the higher the time and the space lag. So, the capacity to distinguish the velocity pattern and to choose the biological stimuli can be facilitated, in particular for less biological stimuli, by the lag between feet. Figure 5.9 illustrates this relation for the BM stimulus and for the furthest stimulus (MA

(72)). The lines represent the distance in translation pattern between left and right foot for each frame for one step. As we can see, the difference is very clear. Actually, this is one of the stronger arguments against our procedure. On the one hand, the option for feet implies some level of structure cues and, on the other hand, this structure observes biomechanical conditions that constrain the degrees of freedom available to the feet relation. The time lag between feet produces another biological cue that can be interfering on participants' responses, and even more because we presented stimuli for 2000 ms, corresponding to two gait cycles, making that cue more salient. In particular, a final issue concerns to time span.

Figure 5.9 Distance difference between left and right foot in translation pattern (one step).



Despite several studies reporting a long integration time for biological motion (Burr & Santoro, 2001; Neri, Morrone & Burr, 1998; Watamaniuk & Sekuler, 1992), the option for short or long stimuli duration is not a solved question. We find conflicting evidence and opposite arguments defending one or another option. Frequently, the problem is related to levels of processing and the processes involved. The different stimuli durations are used to explain high-level and low-level processes and the common argument is that long presentation can justify high-level processing and short stimuli duration can be explained by low-level (firstly proposed by Braddick, 1974, see Cavanagh and Mather, 1989, for a review). Thornton, Pinto and Shiffrar (1998) tried to understand the problem of stimuli duration and to conciliate apparently inconsistent evidence. In a set of experiments they presented stimuli with different durations and concluded that participants perceived biological motion in all conditions, although the results for long presentations were more consistent. They also concluded that high-level processes are involved in the perception of biological motion, but still noting that their results could not be interpreted as if only high-level mechanisms were being used. However, the authors concluded that, independently of the kind of processes involved, performance was better for long durations, meaning, in the authors' perspective, that participants can integrate motion correctly over long presentations.

Nevertheless, if we consider that the perception of biological motion is signal-dependent, then its quantity (in terms of long vs. short presentations) should influence the participants' performance - longer presentation times imply more information available, which in turn can require longer processing times. Still, the participants' rationale remains the same, as it is always dependent on the signal. In sum, motion signal properties are crucial to perceive biological motion and high or low level mechanisms operate under that information, albeit with different assumptions.

5.3 Experiment 2: perceiving motion patterns of the foot

Experiment 2 followed the same rationale and the same procedure of experiment 1, but using a more impoverished stimulus: one foot walking one single step. Basically, we eliminated the structure cue maintained by the feet relation and reduced the duration of the stimuli, trying to demonstrate that the perception of biological patterns is signal-dependent and is a sufficiently robust percept. Such as in the previous experiment, here differences in the participants' responses should show the sensibility to velocity patterns and the minimum physical changes needed to perceive signal differences. Again, the results show the capacity of the visual system to perceive small physical changes and to recognize different motion velocity patterns.

5.3.1 Methods

5.3.1.1 *Participants*. Eight volunteers took part in this study, four naïve as to the purpose of the experiment and four with some background knowledge about the purpose of this study. Participants were students or researchers at the Laboratory of Visualization and Perception with an average of 25 years old, ranging from 21 to 31 years old. All had normal or corrected-to-normal vision based on the automatic screening test and tests of kinetic (dynamic visual acuity with moving stimuli varying direction, speed and spatial frequency) of the equipment for visual screening (Essilor, Ergovision).

5.3.1.2 Apparatus and Stimuli. The stimuli were presented by a 3-chip DLP projector Christie Mirage S+4K, with a spatial resolution of 1400x1050 pixels and a refresh rate of 101Hz. Images were displayed with OpenGL running over a Vr/Net Juggler software on a computer with a graphic board NVIDIA Quadro FX 4500. The stimuli were projected one a surface 2.10m high and 2.80 wide. This apparatus was possible in the Laboratory of Visualization and Perception of the University of Minho, in an immersive virtual environment (see figure 4.6 in chapter 4).

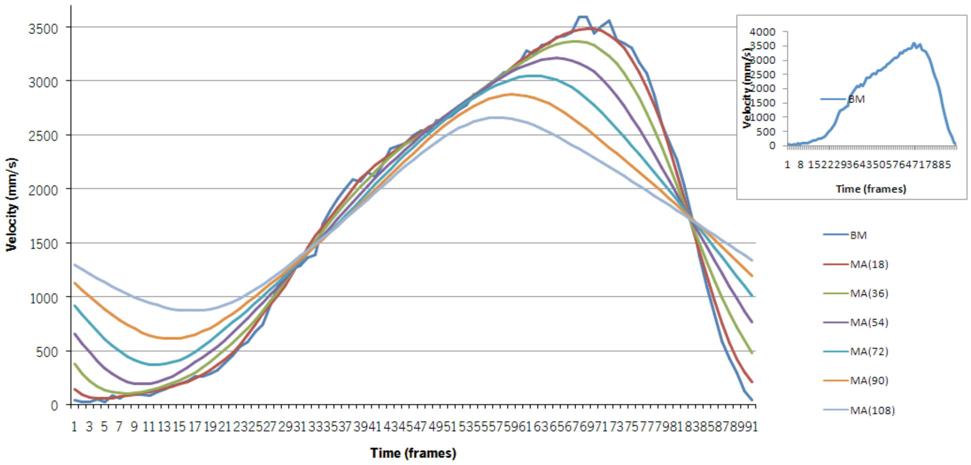
The stimulus consisted of a single dot representing one foot walking a single step. To eliminate the structure cue we removed the second foot, and initially presented a one-foot step, starting in swing phase and finishing in stance phase. However, without other visual cues, the stance phase originates a slide effect, an optical illusion in which the dot appears to be dragged during this phase, when actually it is in a fixed position. This visual illusion automatically disappeared when two feet were presented. To avoid this effect, we presented only the swing phase and, using the procedure described to the stimuli of experiment 1, we smoothed the velocity of the translation pattern with a simple moving average (MA), changing the order (q) in multiples of 18 and creating seven stimuli, ranging from biological to MA (108). With the velocity pattern smoothed, we computed the new translational pattern for each stimulus and then interpolated the new elevation values. Table 5.4 summarizes the procedures detailed in the stimuli description in experiment 1.

Table 5.4 Smoothness process and stimulus construction step-by-step.

	Component	Description	Formula
1	Velocity pattern	Smoothness of velocity corresponding to the instant velocity of translation pattern	$MA(q)_{fn} = \frac{f_{n-1} + f_{n-2} + f_{n-3} + f_{n+1} + f_{n+2} + f_{n+3}}{q}$
2	Translation pattern	Computing the new translation pattern from the new velocity pattern, maintaining the initial and final trajectory positions	$v = \frac{d}{t} \Leftrightarrow d = vt$
3	Elevation pattern	Computing the new elevation pattern by interpolating the biological values and taking into account the new translational pattern	$y_1 = y_0 + \frac{x_i - x_0}{x_1 - x_0}\left(y_1 - y_0\right)$
4	Sagittal pattern	According to the specificities of the experiment, performing again the previous step but now for sagittal pattern or assuming a unique value (for a 2D Stimuli).	———

Although only the swing phase was presented, the smoothness of the velocity pattern could be computed with or without the values of the stance phase. Two related issues should be taken into account, one of them spatial and the other temporal. Spatially, including the stance phase in the calculations means that the temporal moment of heel-strike differs from one stimulus to another. In this case, the swing phases have different durations and, to display the same spatial pattern, we need to present stimuli at different time spans. Temporally, to display stimuli with identical durations, there is the need to ensure that the toe-off and the next heel-strike are presented. However, because the heel-strike is not the same for all stimuli, we would have to change the spatial pattern. Thus, the option was to smooth the velocity pattern, considering only the swing phase values. The result was a foot that started moving in toe-off and stopped at heel-strike, with the same duration. The velocity pattern of each stimulus, ranging from biological stimuli to MA (108) stimuli, is compared in the graph of figure 5.10.

Figure 5.10 Velocity pattern for each stimulus (one foot).

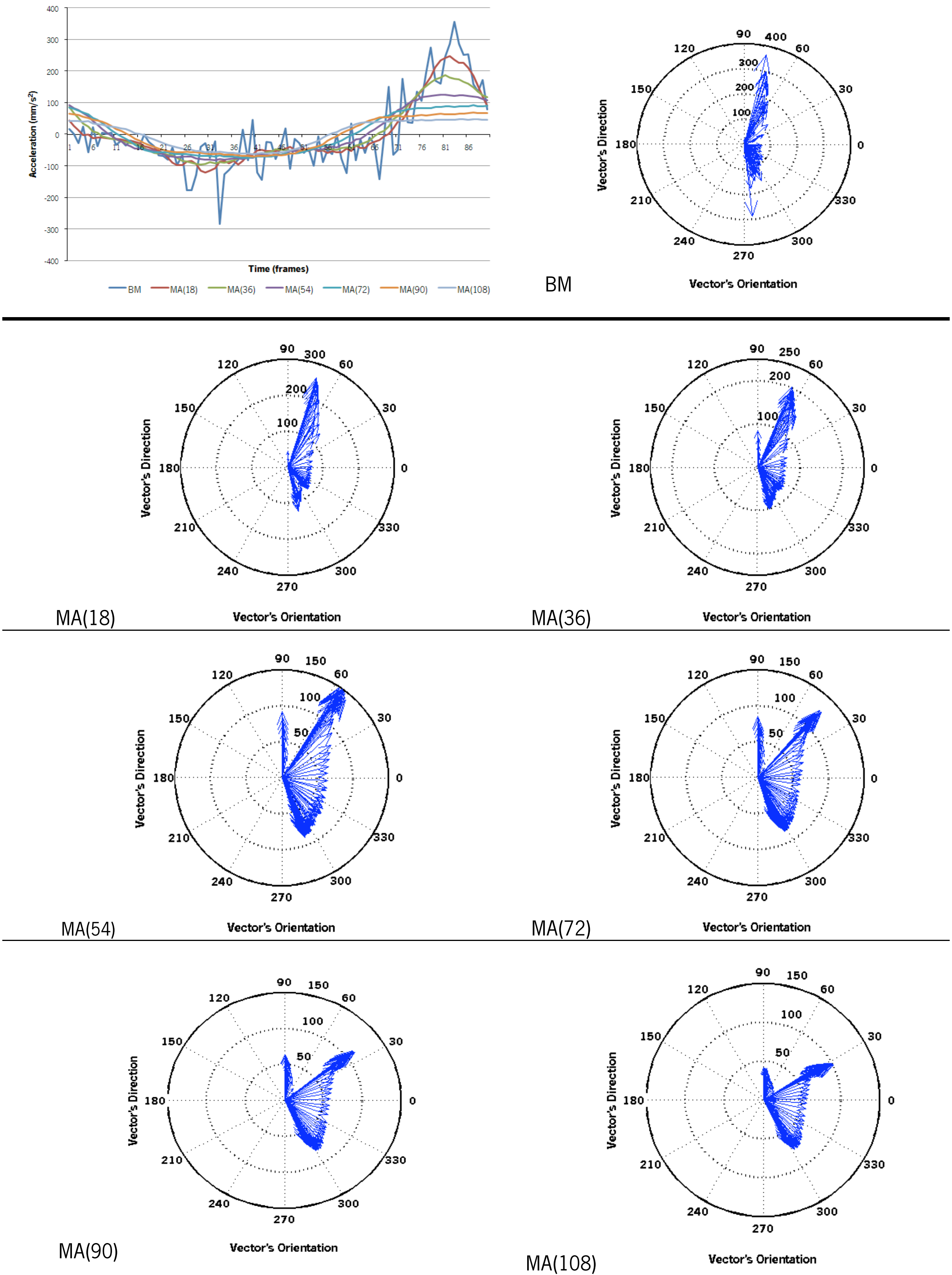


The stimuli can also be analysed in a vectorial perspective, as shown by the hodographs in figure 5.11, representing the acceleration vectors for all stimuli. The smoothed pattern, shown in the acceleration graph, has different vectorial configurations. As the stimuli in experiment 1, vertical vectors (90°), corresponding to jerking movements are inexistent in biological movements, where horizontal vectors (0°) are more frequent. The beginning and the end of the movement explains these differences, because the moving average process increases these values, making the foot start and end abruptly.

The stimuli had a temporal resolution of 101Hz, although the projector had been prepared to frame rates up to 120Hz, but actually we could only ensure frame rates up to 101Hz, with the best spatial resolution (1400X1050 pixels).

5.3.1.3 Procedure. Participants were seated in a dark room, 2 meters away from the display and were asked to choose the most biological of two stimuli presented sequentially, with one of them always being the biological motion (standard stimulus). A black frame was presented for 500ms between the first and the second stimuli. Participants responded by pressing the corresponding mouse buttons connected to the computer, with the left button if the first stimulus was the most biological and the right button if it was the second stimulus, performing a two-alternative forced-choice task. No feedback was provided for correct responses. The stimuli were presented randomly and participants

Figure 5.11 Hodographs of acceleration for all stimuli.



BM

MA(18)

MA(36)

MA(54)

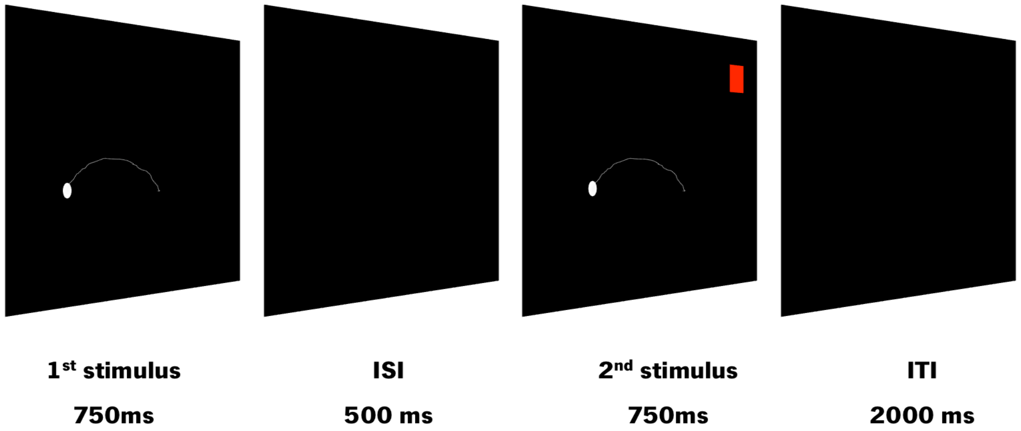
MA(72)

MA(90)

MA(108)

gave the answer by pressing the mouse button after the second stimulus started to be presented. A red square on the top right corner signalized the second stimulus and a long black frame with 2000ms signalized the inter trials interval (ITI). Participants took part individually in two sessions, each lasting for about half an hour and with 650 trials, 50 trials per stimulus (25 trials for standard stimuli when displayed in the first and second presentation simultaneously), 100 trials per stimuli for both. Figure 5.12 illustrates the procedure described.

Figure 5.12 Experiment 2's procedure and stimulus presentation (one trial).



5.3.2 Results

An exploratory analysis allowed the assumption of normality, demonstrating that all data fell in the normal range, according to the Kolmogorov-Smirnov normality test. Furthermore, results better explained by the presentation order (first or second stimulus) or the option for one of the mouse buttons were discarded and no significant results were found. Having confirmed these assumptions, we performed statistical analyses to confirm the existence of a significant effect in the perception of velocity patterns.

Figure 5.13 shows the individual results for each participant, with graph A plotting the proportion of correct responses and graph B the reaction times (ms) as a function of stimuli smoothness: from biological motion stimulus to less biological stimulus (MA (108)). The individual results are expressed in tables 5.5 and 5.6. All of them conformed well to a linear adjustment, except for the reaction time of participant 5 (◀). A one-way ANOVA for repeated measures was conducted to compare the effect of the smoothness of the velocity pattern on the perception of biological motion. Considering the responses of all participants, there was a significant effect on the reaction times and on the proportion of correct responses, $F(6,7)=149.72$, $p < 0.01$ and $F(6,7)=27.53$, $p < 0.01$, respectively.

Figure 5.13 Results per subject of experiment 2.

A) Proportion of Correct Responses

B) Mean Value of Reaction Time

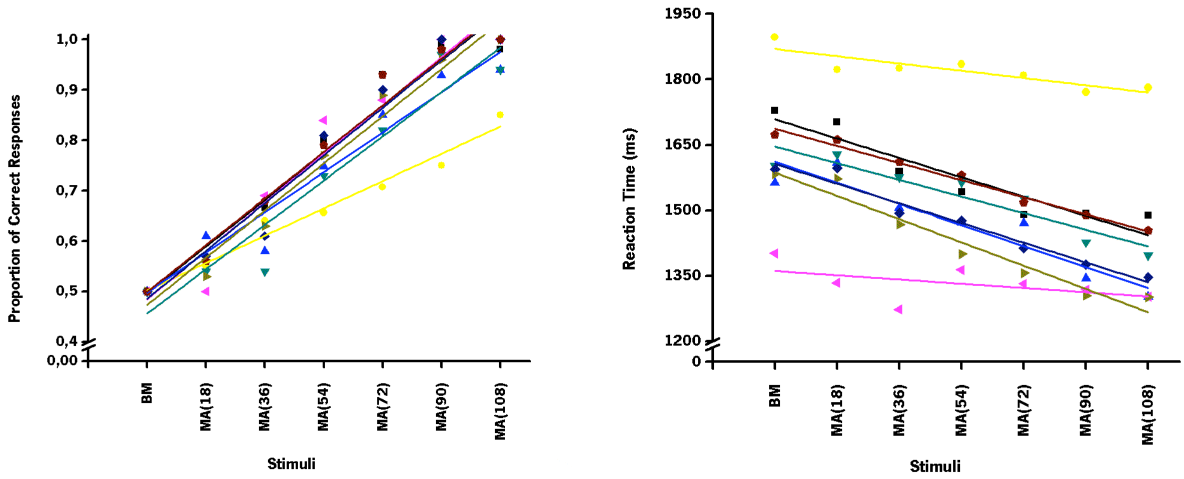


Table 5.5 Mean, standard deviation and fitting of reaction time per participant and aggregated data (in milliseconds).

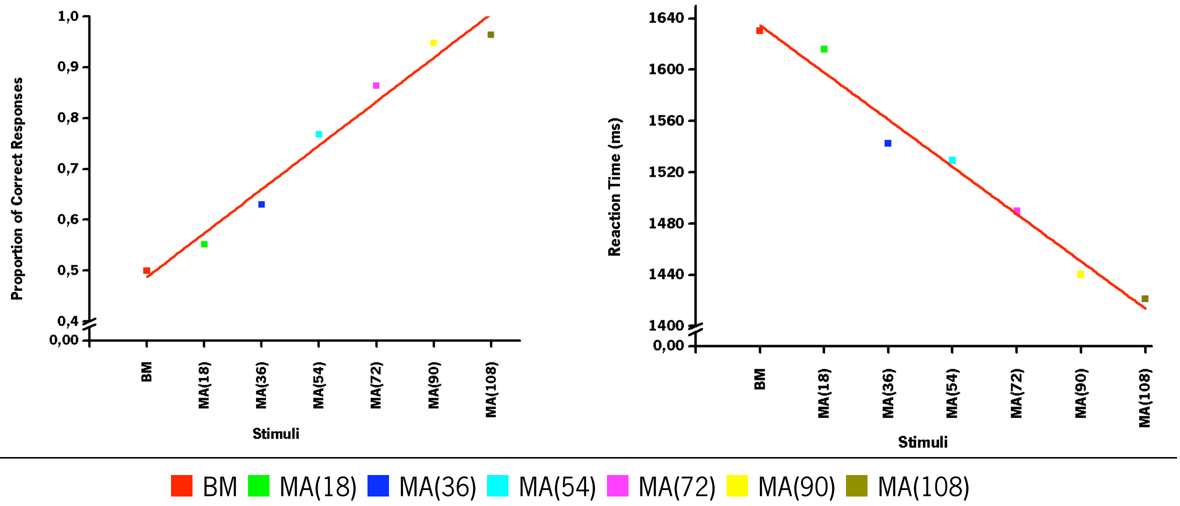
	Stim. Part.	BM	MA(18)	MA(36)	MA(54)	MA(72)	MA(90)	MA(108)	Linear Fit
■	1	1728 (405)	1702 (436)	1588 (370)	1542 (409)	1489 (317)	1492 (366)	1487 (338)	y=1753 – 44x (adj. R^2= 0.85)
●	2	1896 (391)	1822 (339)	1825 (342)	1834 (322)	1809 (377)	1770 (321)	1780 (310)	y=1886 – 17x (adj. R^2= 0.72)
▲	3	1563 (362)	1609 (340)	1505 (327)	1471 (322)	1470 (343)	1344 (271)	1301 (295)	y=1659 – 48x (adj. R^2= 0.86)
▼	4	1602 (298)	1628 (348)	1576 (283)	1564 (305)	1526 (258)	1427 (274)	1397 (281)	y=1685 – 38x (adj. R^2= 0.85)
◀	5	1401 (354)	1333 (361)	1272 (375)	1363 (366)	1331 (368)	1318 (346)	1301 (366)	y=1371 – 10x (adj. R^2= 0.10)
▶	6	1583 (401)	1572 (431)	1467 (401)	1400 (366)	1356 (347)	1305 (299)	1301 (277)	y=1640 – 53x (adj. R^2= 0.94)
◆	7	1594 (283)	1596 (341)	1493 (280)	1476 (303)	1413 (241)	1376 (266)	1346 (266)	y=1652 – 45x (adj. R^2= 0.96)
⬟	8	1672 (351)	1661 (328)	1611 (318)	1580 (305)	1517 (330)	1488 (325)	1453 (256)	y=1726 – 39x (adj. R^2= 0.98)
–	All	1631 (356)	1616 (366)	1543 (337)	1529 (338)	1489 (323)	1440 (309)	1422 (299)	y=1672 – 37x (adj. R^2= 0.97)

Table 5.6 Mean, standard deviation and fitting of proportion of correct responses per participant and aggregated data.

	Stim. Part.	BM	MA(18)	MA(36)	MA(54)	MA(72)	MA(90)	MA(108)	Linear Fit
■	1	0.5	0.55	0.67	0.8	0.93	0.99	0.98	y=0.4 + 0.09x (adj. R^2= 0.94)
●	2	0.5	0.55	0.64	0.66	0.71	0.75	0.85	y=0.45 + 0.05x (adj. R^2= 0.97)
▲	3	0.5	0.61	0.58	0.75	0.85	0.93	0.94	y=0.42 + 0.08x (adj. R^2= 0.93)
▼	4	0.5	0.54	0.54	0.73	0.82	0.97	0.94	y=0.37 + 0.09x (adj. R^2= 0.91)
◀	5	0.5	0.5	0.69	0.84	0.88	1	1	y=0.39 + 0.1x (adj. R^2= 0.93)
▶	6	0.5	0.53	0.63	0.77	0.89	0.96	1	y=0.38 + 0.09x (adj. R^2= 0.97)
◆	7	0.5	0.57	0.61	0.81	0.9	1	1	y=0.39 + 0.09x (adj. R^2= 0.95)
⬟	8	0.5	0.56	0.68	0.79	0.93	0.98	1	y=0.41 + 0.09x (adj. R^2= 0.96)
–	All	0.5 (0)	0.55 (0.03)	0.63 (0.05)	0.77 (0.05)	0.86 (0.07)	0.95 (0.08)	0.96 (0.05)	y=0.4 + 0.09x (adj. R^2= 0.97)

The linear functions for aggregated data are shown in Figure 5.14, with graph A displaying the mean of the proportion of correct responses and graph B the mean of reaction times. The linear adjustment applied to the results fits well to both measures (R^2=0.97).

Figure 5.14 Results of experiment 2.

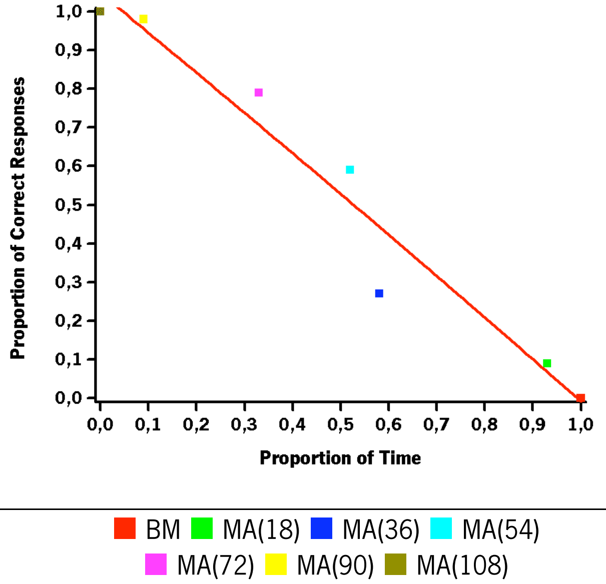


A) Mean value of Proportion of Correct Responses

B) Mean Value of Reaction Times

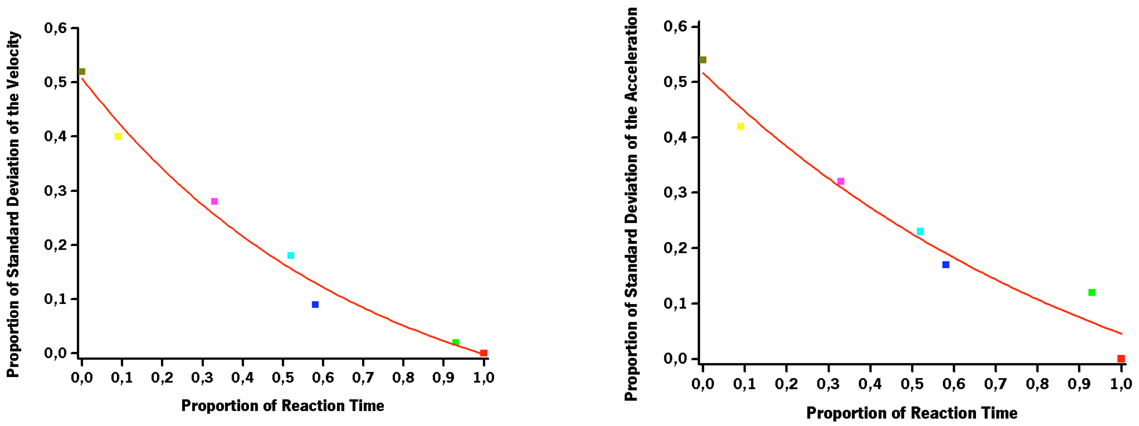
Consider again the proportion of correct responses as a function of the proportion of the reaction time for each stimulus, as proposed in experiment 1's data analysis. The graph of figure 5.15 shows this relation and the exponential decay adjustment. Assuming a decay rate (λ) equal to -15.29, for a proportion of correct responses of 0.5 (chance level), *x* assumes a value near 0.53, corresponding to a stimulus near MA (36), as obtained in the experiment with the feet.

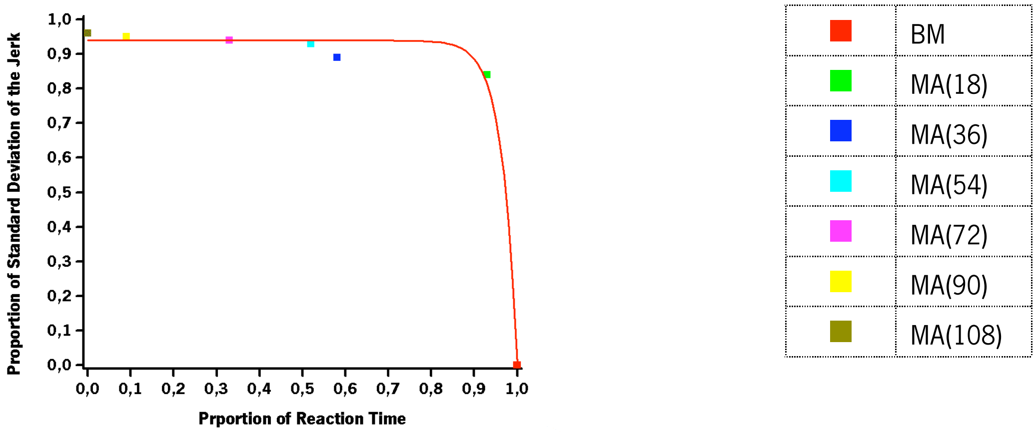
Figure 5.15 Proportion of correct responses as a function of proportion of reaction time (Exponential decay function).



Applying the same rationale, as described earlier, we analysed the standard deviation of the biological motion signals – velocity, acceleration and jerk – as a function of the proportion of reaction times (Figure 5.16). All parameters conformed well to an exponential decay. Acceleration had the lower adjusted value of R squared (R^2=0.95), followed by velocity (R^2=0.97) and the jerk parameter (R^2=0.99).

Figure 5.16 Signal parameters as a function of proportion of reaction time (Exponential decay function).





5.3.3 Discussion

The results show clearly that participants distinguished and perceived small changes in velocity patterns. The proportion of correct responses increases while the reaction time decreases as the smoothness increases. This progressive pattern is demonstrated by the liner adjustment and higher values of adjusted R-squared obtained for both. Even if we can note more individual differences in reaction time, including a bad adjustment for one participant, individual and aggregated data conformed well to a linear function and the curves' slop in both analyses were very close. The proportion of correct responses superior to 0.75 occurred slightly above the MA (36) stimulus, between MA (36) and MA (54) stimuli. Here, the difference in terms of the velocity's standard deviation ranged from 8% to 17%, respectively. So, in a condition where the available cues were reduced to the minimum, one foot and one step, the observers can still distinguish small differences in the biological signal. In fact, the higher the smoothness of the biological properties, the better the proportion of correct responses and the lower the time needed to discriminate it. But several considerations can be taken, both theoretical and methodological.

Firstly, the accuracy and reaction time appear to be related, as shown by the linear fit obtained (figure 5.14), demonstrating that apparently the assumption that biological motion perception has high levels of accuracy but contradictory higher reaction time needs to be revised. As we exposed in the introduction, the integration processes implied in biological motion perception commonly justify the differences in accuracy and reaction time. Here we tried to show that this integration process is not a question of complexity of the signal, but of its properties. As a time-varying function, the signal properties are being revealed to the visual system over time. A good hypothesis is that the smoothness process progressively destroys the biological parameters and, consequently, the lower the biological information is, the earlier the discrimination of the differences. The linear adjustment obtained appears to demonstrate that lower biological properties affect perception progressively, as if the visual system is responding directly to the moving average's order. If it was a question of biological or non-biological, we should expect a sinusoidal response where we should easily identify the value between biological and non-biological. If not for reaction times, that reflect more the difficulty of the task, at least for the proportion of correct responses. But more evidence need to be collected and the study of the brain processes involved can help to explain and demonstrate our assumption. If brain areas implied on biological motion and motion processing respond as the psychophysical results show, we are not proving that the hypothesis is true but at least, that it pays to be investigated. We dedicate chapter 6 to explore this idea.

The results show also a close relation between reaction time and motion parameters – velocity, acceleration and jerk, as demonstrated by the goodness of fit. All parameters fit well and the easiest explanation could be arguing that, as motion functions, they are related. However, the moving average process does not affect all parameters in the same proportion. As defended in the discussion of experiment 1, we should apply the same process directly to acceleration and jerk and then analyse if the participants perform equally for both. But the idea that the visual system does not process velocity or acceleration is getting weaker. Probably the best approach is saying that the visual system processes space-time signals, corresponding to specific parameters of velocity, acceleration and jerk, for instance. So, the definition of motion stimuli in terms of average velocity, as found in the majority of articles, can be insufficient if we are studying motion perception. For example, the discussions around artificial motion algorithms can be better understood here. It is possible that some parameters are being considered, such as the walker's average velocity and the spatial component, but that does not mean that we are observing biological stimuli. All stimuli presented had 1.3m/s of average velocity and the same spatial component, but they differed significantly and, if in terms of velocity patterns we can argue that the differences are minimal, the vectorial representation of acceleration patterns (see hodographs in figure 5.10) leaves no doubt.

A third consideration concerns the decay rate that associates the proportion of correct responses and reaction times. The exponential decay function showed that responses higher than 0.75 occurred for stimuli higher than MA (36), curiously the same value obtained in experiment 1. However, in that case, the standard deviation of the velocity pattern, at MA (36) stimulus, was about 5%, lower than the value of standard deviation in experiment 2. Actually, in this experiment the standard deviation of the velocity pattern of the stimulus after MA (36) (MA (54)) was of about 17%, precisely the value of the furthest stimuli in experiment 1 (MA (712)). This difference can be explained by the feet relation cue. If the processing of biological signals reflects their own kinematic properties, we could expect that when a *minimum quantum* changed in biological signals, a correspondent value of response would be affected. Assuming that the visual system had an algorithm to process biological motion signals, we should be able to calculate the decay response for all situations, when the parameters involved are known. Again, results bring strong evidence about the possibility of developing that algorithm, but in this stage there are insufficient data to propose one. Other reasons can be pointed out, but the first and main difficulty to develop an algorithm will be the parameters that will have to be considered. Note that we are not defending that other cues should not be taken into account, and the evidence easily showed the opposite. On a different perspective, we are proposing that only the signal properties should be manipulated if we are trying to understand the phenomenon. For instance, in experiment 1 the stimulus was the feet of a point-light walker and, as we note, the relation between them could be used to disambiguate the participant’s choice.

The idea of a visual system that is able to recognize and react to motion stimuli versus stationary scenes is not a new one, as isn't the notion that the visual system is sensitive to acceleration and movement patterns, despite contradictory results presented earlier in the introduction. Crucial, in our work, is the demonstration that signal properties have a determinant role in perception and, for that, a survival value. Citing Burr (1981, p.337), “The natural visual environment is dynamic. One seldom views a totally stationary scene, and, typically, the objects in motion are those of greater interest, often of great importance to survival. If these moving stimuli are to be detected and resolved with the same efficiency as stationary ones, there must exist in vision a system capable of summating over time the signals emanating from their images. Without such summation sensitivity would inevitably suffer”. Our results appear to demonstrate, considering also the discussion taken in chapter 4 about the importance of frame rate and sampling process, that it is not an issue of summation but rather a specific case of summation. The visual system appears to integrate the signal properties, working on high temporal frequencies and processing biological space-time parameters.

Nevertheless, numerous authors propose that spatial (form) and temporal (motion signal) features are always being processed and it probably is reductive to overestimate the importance of motion properties. The most robust proposal is supported by the existence of different brain pathways for the processing of different motion properties, which would then be processed together at STS (superior temporal sulcus) level. We will discuss this argument deeply in chapter 6, but here it is important to note that this does not call into question the fundamental argument: that visual systems are able to process signal motion properties, that these signals are crucial to perception and facilitate the responses to biological motion stimuli. Eventually, the relation between the results of experiment 1 and experiment 2 could help us understand this argument better. We could compare the results of stimuli with equal levels of smoothness in both experiments, in this case, MA (18), MA (36), MA (54) and MA (72). The differences in participant's responses would be explained by the distinctive variable between them, i.e., the relation between feet.

However, the methodological options in stimuli construction do not allow this analysis. The stimuli in experiment 2, even if computed with the same moving average process, contemplate only the swing phase. So, we are not comparing the same signal if we compare the stimuli of both experiments. In the future, an experiment that manipulates both stimuli, with one or both feet, using the procedures described above, could give us interesting and new results.

A final word about the perception-action paradigm. We can find numerous evidence and suggestions that perceiving motion and acting in motion is considerably different. People appear to be more precise when they interact with the stimuli, compared to the typical perception tasks. In other words, when participants act during the visual task their performance could be better. In this sense, if participants are sensible to signal differences, it is expectable that smoothness in velocity patterns influences their actions. This not only explains the perception of signal properties but also gives a strong demonstration of the survival value of biological signal processing. We explore this assumption in chapter 7.

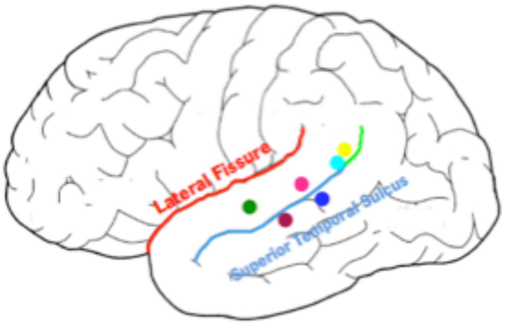
6. One small physical step. One great leap for perception

6.1 Introduction

The human capacity to perceive objects in motion seems to be perfectly demonstrated. The numerous studies described before and the results of the experiments presented in previous chapters provided strong evidence of that capacity. The human visual system, as in other animals, is remarkably adept at recognizing motion and its kinematic properties. As we demonstrated in chapter 5, subjects are able to recognize small physical differences in biological motion patterns, expressed by the high capacity to recognize different velocity and acceleration patterns. Moreover, the information provided by motion patterns appears to be so critical that even when it is portrayed by the few dots of a point-light figure, the perception of a living being is vivid and strong. In this sense, it seems reasonable to hypothesize that our brains developed specialized mechanisms to process motion information. In other words, the perception of motion patterns, whatever the source of information is, should be characterized by neural correlates that can better explain the mechanisms involved, specifically in biological motion perception. If kinematic properties are used in the visual perception of biological motion, we can expect that brain activity demonstrates that and, according to the brain areas implied, brings a new enlightenment about their relevance.

In fact, findings supporting the existence of a specialized mechanism to process biological motion have been proposed and demonstrated in the last few years. Neuroimaging and neurophysiological studies demonstrated that the Superior Temporal Sulcus (STS) is the brain region that responds better to biological motion stimuli, as shown by the selective neural signals found for body movements' perception (Grossman et al., 2000; Howard, et al., 1996; Kourtzi & Kanwisher), but also for the processing of social communication (Grèzes, Costes, & Decety, 1998; Puce et al., 1998; Rizzolatti et al., 1996b). The STS is a large sulcus that extends from the most anterior part of the temporal lobe to the most anterior part of parieto-occipital lobe. Anatomically it is easily identified because it is the first sulcus inferior to the lateral fissure. Various

Figure 6.1 Superior Temporal Sulcus (STS): selective neural signal in different studies.

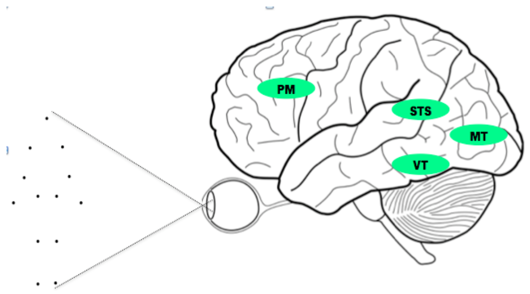


● Howard et al. (1996)
● Rizzolatti et al. (1996b)
● Grèzes, Costes, & Decety (1998)
● Puce et al. (1998)
● Kourtzi & Kanwisher (2000)
● Grossman et al. (2000)

studies identified different localizations for biological motion perception and social communication along the STS, as shown by figure 6.1.

In spite of the STS being commonly referred as the biological motion area, numerous evidence have shown a strong interconnection with other areas. Together, they form a specialized network that plays a central role in biological motion perception, action understanding and social information. This network comprises middle temporal (MT) areas and parietal attention areas, responsible for motion computation and attention (Grèzes et al., 2001; Vaina et al., 2001), ventral temporal (VT) areas, involved in form and face processing (Lesli, Johnson-Frey, & Grafton, 2004; McCarthy et al., 1997), and premotor (PM) areas, implied in action imitation (Rizzolatti & Craighero, 2004; Bruce, Desimone, & Gross, 1981). Figure 6.2 illustrates the localization of these different areas.

Figure 6.2 Brain areas involved in the perception of biological motion.



MT - middle temporal area; PM - premotor cortex; STS - superior temporal sulcus; VT - ventral temporal cortex

After exiting the primary visual areas in the occipital lobe, the neural signal continues to the areas described above. A common explanation is that the neural signal follows two independent pathways or streams, one ventral and the other dorsal – the two-streams hypothesis. Firstly proposed by Mishkin and Ungerleider (1982), the argument was later revisited by Ettlinger (1990). Nevertheless, the most influential contribution was presented by Goodale and Milner (1992). These authors proposed that the *visual perception* and *visual control of actions* are mediated by distinctive processes in different brain areas. Visual perception would occur ventrally, from the striate cortex to the inferiortemporal cortex, as opposed to visual control action, that would occur dorsally, from the striate cortex to the posterior parietal. The ventral stream would be responsible for recognition and object identification, and because of that it is also named the "what" pathway. The dorsal stream operates the sensorimotor transformation for visually guided actions, and is also named the "where" pathway. In other words, the ventral stream processes form and structure information while the dorsal pathway processes motion and its spatiotemporal properties. For instance, in biological motion perception, using point-light walkers, this would mean that the point-light structure, such as body position, the different body parts, height and weight, would be processed through the ventral stream, whereas the motion information, such as direction, velocity or acceleration, would be processed trough the dorsal stream.

Many evidence support the existence of two separate pathways that process distinctive information independently (Culham et al., 2003; Shmuelof & Zohary, 2005). Moreover, research with patients suffering with schizophrenia (Foxe, Doniger, & Javitt, 2001) and autism (Spencer et al., 2000) appears to confirm this hypothesis. In their work, Goodale and collaborators (1994) were clear when they pointed out that "dissociation lends strong support to the idea that the visual mechanisms mediating the perception of objects are functionally and neurally distinct from those mediating the control of skilled actions directed at those objects. It also supports the recent proposal of Goodale and Milner that visual perception depends on a ventral stream of projections from the primary visual cortex to the inferotemporal cortex, whereas the visual control of skilled actions depends on a dorsal stream from the primary visual cortex to the posterior parietal cortex" (p.604).

However, in spite of these evidence, the existence of two separate pathways for recognition of form and motion is still a matter of controversy and different proposals can be found in the visual processing literature. Perhaps these proposals can be distinguished by the emphasis they put on the kind of pathways (dorsal-ventral or other) proposed or in the relation between them. On the one hand, some authors defend that object recognition and the encoding of object motion and position are supported effectively by independent pathways, but not in a dorsal-ventral perspective. In the experiment of Braddick and colleagues (2000), using functional magnetic resonance imaging (fMRI), participants observed arrays of line segments (form condition) or a sequence of a coherent motion with reversing or dynamic noise (motion condition). The results showed that the brain areas activated by form do not overlap with those activated by motion, thereby demonstrating an independent processing. However, the regions activated do not support the two-streams hypothesis, as showed by the activation of temporal, parietal and occipital areas for both conditions, but without overlapping. On the other hand, numerous authors have proposed that object recognition and motion encoding are processed in ventral and dorsal pathways, respectively, but not in a separate and independent way. The two streams are interconnected, forming a brain network that processes both object characteristics and motion properties (Farivar, 2009). Farivar, Blanke, and Chaudhuri (2009) showed that the dorsal visual areas might participate in object recognition, defending a dorsal-ventral integration rather than a dorsal-ventral separation.

In biological motion studies the argument of a network of interconnected dorsal and ventral areas has proved to be more consistent. The identification of the neurological basis for the structure-from-motion (SFM), which is the ability to recognize objects on the basis of their motion patterns, conforms better with a network of interconnected areas than with separate systems. Bradley, Chang, and Andersen (1998) localized SFM in the MT, an area of the dorsal processing that is therefore involved in object perception. Furthermore, different single-cases demonstrated that both pathways can develop an important role in the perception of biological motion properties. Vaina and colleagues (1990) described a patient, A.F., who had lesions in the posterior parietal pathways. In spite of his incapacity to perceive coherent motion in random noise, he was able to identify objects defined by biological motion and other SFM. On the other hand, Cowey and Vaina (2000) observed the patient A.L.'s capacity to perceive form and motion, but simultaneously the incapacity to recognize biological motion. His lesion in the ventral temporal cortex allows him to see motion, but not what it represents.

Together, these evidence support the argument in favor of a network of interconnected ventral and dorsal pathways that process biological motion stimuli. In this network, the STS is a critical area that, in spite of the activated pathway, is always activated in biological motion perception (Allison, Puce, & McCarthy, 2000). The activation of the STS, independently of the biological characteristics and the pathway involved, can mean that the STS plays a central role in the integration of form and motion properties that were processed separately. As proposed by Cusick (1997), the STS receives neural signals from both dorsal and ventral streams, integrating the information that was previously processed independently. According to the author, a specific area was identified in monkeys that functions as an integrator of both pathways – the superior temporal polysensory cortex (STP). Moreover, the STPa, another area of the STS, receives connections from the auditory, visual and somatosensory cortex, showing the STS's potential as an integrator of all neural signals (Desimone & Gross, 1979).

With this assumption, the argument discussed in previous chapters could be perfectly explained. If the STS or a specific part of the STS integrates the information processed by different brain pathways, it could explain the large temporal summation found for biological motion and simultaneously the higher performance of subjects in a perception-action task when compared with a perception task alone. In other words, in a perception-action task the information would be processed through the dorsal pathway, where the areas that process the visual guided tasks are located. Here, the information of ventral areas will be less important, at least in a first moment of the response process, such as in time-to-contact or time-to-passage tasks. This means that the integration process occurring in the STS would not be relevant and the reaction time would be lower. Conversely, the reaction time would be higher for biological motion, in spite of the high capacity to recognize it, when all the information is in use, because it needs to be processed in both pathways and then integrated in the STS. This is a hypothesis that needs to be confirmed and tested, but theoretically it conforms well to the arguments in favour of a network of areas that have the central area in the STS.

In spite of the need for further evidence to propose a biological motion brain network, the role of the different brain areas involved, as showed in figure 6.2, is reasonably known. Beyond the STS, the role of areas such as MT, VT and PM appears to be relevant and recent research has shown it.

The Middle Temporal area (MT), also known as V5, is recognized as a motion processing area that is strongly activated whenever subjects are seeing motion (Hulk & Heeger, 2002; Watson et al., 1993). Although different sub-regions appear to be responsible for the processing of different types of motion (Howard et al. 1996), a specific area is activated when subjects observe stationary body postures that have implicated motion (Kourtzi & Kanwisher, 2000). The authors presented participants with photographs of athletes in motion, photographs of athletes without motion or photographs of people at rest or houses. The results showed that the MT+, an area of the MT, was more activated, probably meaning that the MT is engaged in processing kinematic implied information.

The MT is the first area that processes motion information or, at least, the first area specialized in motion perception. In fact, neurons in the MT recognize direction and process speed, but there are no evidence that they distinguish biological motion from other types of motion (Grossman, 2006). However, we can hypothesize that, if the encoding of kinematic properties occurs in earlier processing stages, this kind of information is relevant to process motion and SFM. That is, the signal's properties are critical to perceive motion. More than an issue of types of motion, it can be an issue of signal properties expressed in terms of spatiotemporal characteristics.

Another relevant area in biological motion perception is the premotor cortex, located in the inferior temporal gyrus and considered the homologue area to F5 in monkeys. F5 is the region where the mirror neuron cells were identified (Gallese et al., 1996), a type of neurons that fire both when an animal acts and when the animal observes the same action performed by another. Typically, the majority of the studies about mirror neurons were performed with hand movement stimuli (e.g., Fogassi et al., 1998; Montgomery & Haxby, 2008; Iacoboni et al., 2005), what Molenberghs, Cunnington and Mattingley (2011) labelled in their meta-analysis about brain regions with mirror properties as “classical mirror studies” (p.344). As Grossman (2006) points out, the predominance of these studies is probably explained by the fact that the hand has one of the major representations in the premotor cortex.

The most interesting finding, however, is the relation between the premotor cortex and other areas, such as the MT and the STS, when subjects are performing or just observing a specific action. This relation appears to be a strong argument for the existence of a network between perception and action. In their study, Rizzolatti and colleagues (1996a) observed the brain activity in monkeys in distinct conditions: food grasping (e.g., presenting food or putting it on a surface), manipulation of food or other objects (e.g., breaking) or interaction with non-related objects. The monkeys grasped the objects actively, viewed a movie of a hand grasping the objects or just observed passively. The results showed activation in the premotor cortex when the monkey performed an action and when he observed a similar action made by another monkey or by the experimenter. The results also demonstrate activation in the premotor cortex, MT+, and posterior STS when the monkey observed a hand grasping an object compared to the passive observation of an object.

Lastly, the same activation was found for biological motion. When subjects observe a point-light walker, the neurons in the premotor cortex respond selectively (Saygin et al., 2004). According to these authors, this can mean that when we are observing or performing an action we are sharing the same brain network. That is, performing an action implies the same brain representations that are being elicited when we just observe that same action. This issue is better explored in studies about intentional action (see Pierno, Ansuini, & Castiello, 2007, for an exhaustive review).

In the present chapter we describe an fMRI experiment about perception of velocity patterns in biological motion stimuli. We try to understand the brain activity and the areas involved in the perception of biological motion stimuli and their kinematic properties. As we have been proposing, biological motion can be understood as an issue of signal processing, as the psychophysical results described in chapter 5 appear to demonstrate. If brain areas activated to discriminate different kinds of velocity patterns overlap with the areas involved in biological motion perception, and if this activation can be better explained by the different velocity patterns and not by the biological versus non-biological nature of the stimuli, we have new arguments to demonstrate our hypothesis.

6.2 Experiment 1: brain areas involved in the perception of biological motion

In experiment 1 we used the same procedure adopted in chapter 5. Basically, we presented subjects with a set of stimuli representing the foot of a walker, changing the velocity profiles of each stimuli, in such a way that only temporal but not spatial components were manipulated. The result was a set of stimuli ranging from biological to near constant velocity pattern. Participants were asked to identify the most biological stimuli, meaning that differences in the participants' responses should show the sensibility to velocity patterns and the minimum physical changes needed to perceive signal differences. The brain areas involved during the visualization should show how the human brain processed the velocity patterns associated to biological motion stimuli. Presenting only one dot representing a foot was sufficient to activate the areas involved in biological motion, demonstrating that the discrimination of velocity profiles was processed in areas involved in biological motion perception. The results also show activation in areas considered part of the dorsal pathway. We discuss the results and the new arguments that we can propose to understand the brain processing of biological motion stimuli and their kinematic properties.

6.2.1 Methods

6.2.1.1 Participants. Nine volunteers took part in this study, four naïve as to the purpose of the experiment and the type of stimuli used and five with some background knowledge about the purpose of this study and experience with point-light stimuli. Participants had an average of 27 years old, ranging from 22 to 37 years old. All had normal or corrected-to-normal vision based on the automatic screening test and tests of kinetic (dynamic visual acuity with moving stimuli varying direction, speed and spatial frequency) of the equipment for visual screening (Essilor, Ergovision).

6.2.1.2 Apparatus and Stimuli. The stimuli were presented using the Matlab psychophysics toolbox and were displayed with a VESA compatible SVGA projector, with a spatial resolution of 1024x768 pixels and a refresh rate of 60Hz.

The stimulus consisted of a single dot representing one foot walking a single step. We presented only the swing phase and, using the procedure described in experiments 1 and 2 of chapter 5, we smoothed the velocity of the translation pattern with a simple moving average (MA), changing the order (q) in multiples of 36 and creating six stimuli, ranging from biological to MA(180). With the velocity pattern smoothed, we computed the new translational pattern for each stimulus and then interpolated the new elevation values. Table 6.1 summarizes the procedures detailed in the stimuli description of the experiments of chapter 5.

Although only the swing phase was presented, the smoothness of the velocity pattern could be computed with or without the values of the stance phase. Two related issues should be taken into account, one of them spatial and the other temporal. Spatially, including the stance phase in the calculations means that the temporal moment of the heel-strike differs from one stimulus to another. In this case, the swing phases have different durations and, to display the same spatial pattern, we need to present stimuli at different time spans. Temporally, to display stimuli with identical durations, there is the need to ensure that the toe-off and the next heel-strike are presented. However, because the heel-strike is not the same for all stimuli, we would have to change the spatial pattern. Thus, the option was to smooth the velocity pattern, considering only the swing phase values. The result was a foot that

Table 6.1 Smoothness process and stimulus construction step-by-step.

	Component	Description	Formula
1	Velocity pattern	Smoothness of velocity corresponding to the instant velocity of translation pattern	$MA(q)_{fn} = \frac{f_{n-1} + f_{n-2} + f_{n-3} + f_{n+1} + f_{n+2} + f_{n+3}}{q}$
2	Translation pattern	Computing the new translation pattern from the new velocity pattern, maintaining the initial and final trajectory positions	$v = \frac{d}{t} \Leftrightarrow d = vt$
3	Elevation pattern	Computing the new elevation pattern by interpolating the biological values and taking into account the new translational pattern	$y_1 = y_0 + \frac{x_i - x_0}{x_1 - x_0}(y_1 - y_0)$
4	Sagittal pattern	According to the specificities of the experiment, performing again the previous step but now for sagittal pattern or assuming a unique value (for a 2D Stimuli).	———

started moving in toe-off and stopped at heel-strike, always with the same duration. The velocity pattern of each stimulus, ranging from biological stimuli to MA (180) stimuli, is compared in the graph of figure 6.3. The stimuli can also be analysed in a vectorial perspective, as shown by the hodographs in figure 6.4, representing the acceleration vectors for all stimuli. The smoothed pattern, shown in the acceleration graph, has different vectorial configurations.

Figure 6.3 Velocity pattern for each stimulus.

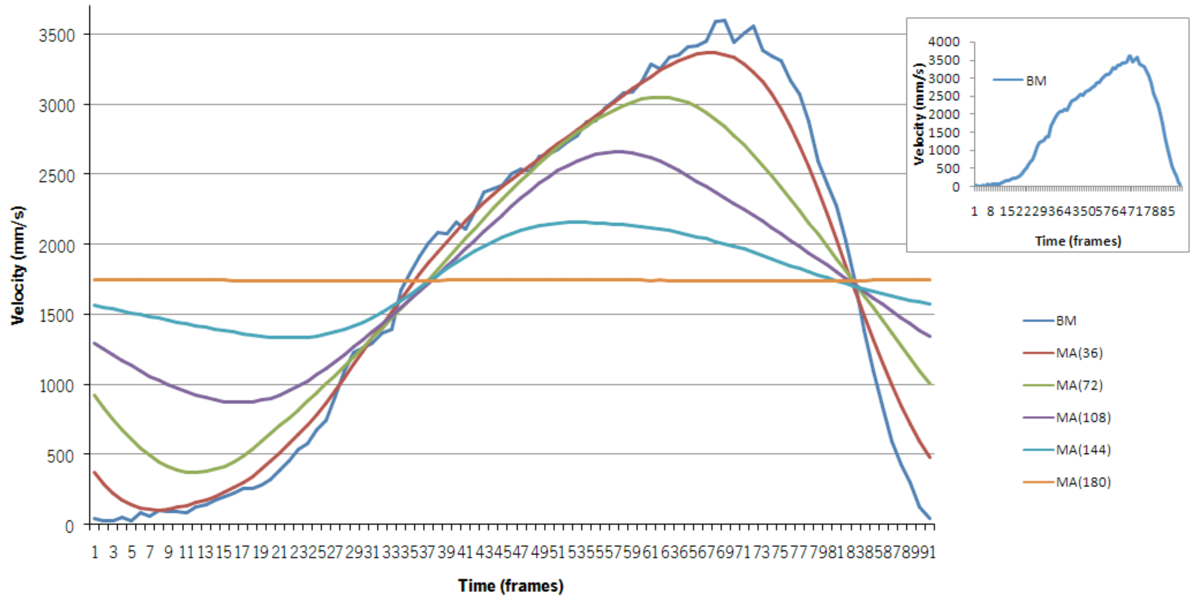
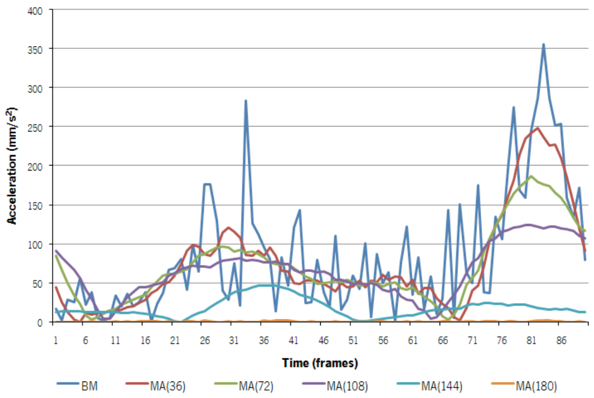
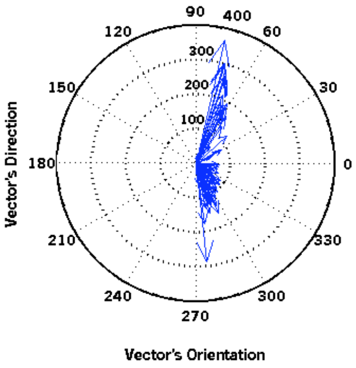
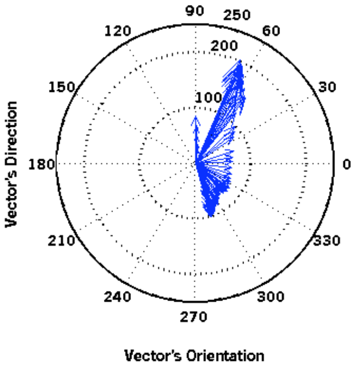


Figure 6.4 Hodographs of acceleration for all stimuli.

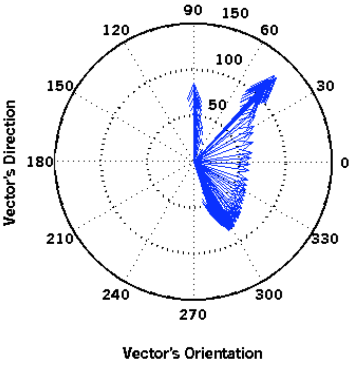




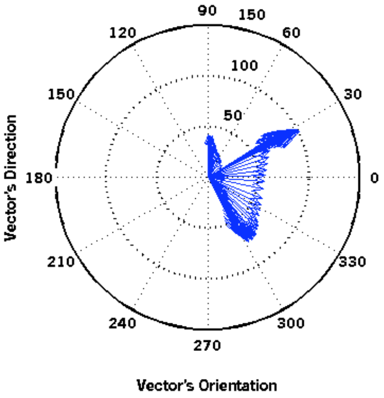
BM



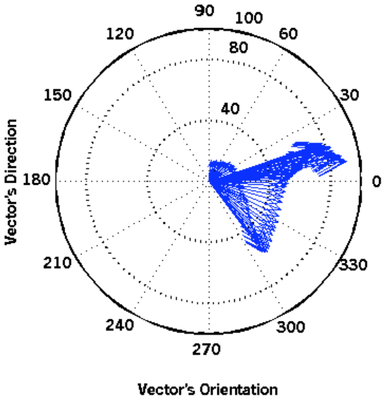
MA(36)



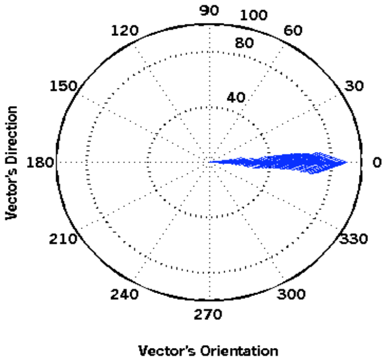
MA(72)



MA(108)



MA(144)

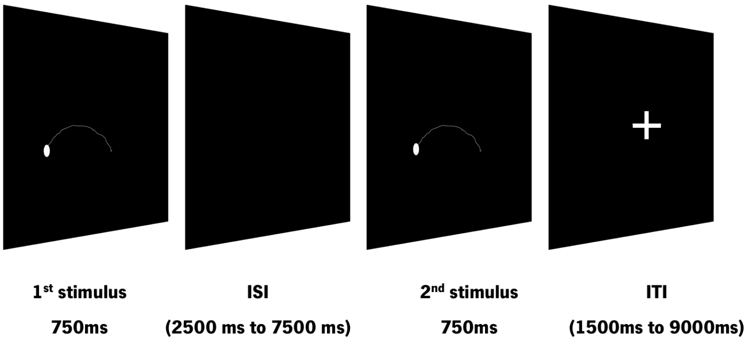


MA(180)

6.2.1.3 Data acquisition. FMRI data were collected on a Siemens TIM Trio whole body system (Siemens). Foam pads were used for positioning and immobilization of the subject's head within the head coil. Functional images were taken with a blood oxygenation level-dependent (BOLD) contrast (728 x 728 matrix, TR = 2500ms, TE = 37ms, FoV = 1790mm, in-plane resolution = 2.46 x 2.46mm, slice thickness = 3mm). Thirty-seven axial slices that covered the whole brain were obtained, a total of 405 volume images per run. Functional images were collect to localize the MT area (510 x 510 matrix, TR = 2000ms, TE = 47ms, FoV = 1275mm, in-plane resolution = 2.50 x 2.50mm, slice thickness = 3.5mm, 125 axial slices). A high-resolution anatomical T1-weighted volume scan (MP-RAGE) of the whole brain was acquired in the same session for anatomical localization and spatial normalization (256 x 256 matrix, TR = 2500 ms, TE = 4.3ms, FoV =256mm, in-plane resolution=1 x 1 mm, slice thickness = 1mm, 176 axial slices).

6.2.1.4 Procedure. Participants were asked to choose the most biological of two stimuli presented sequentially, with one of them always being the biological motion (standard stimulus). A black frame was presented for 2500ms, 5000ms or 7500ms between the first and the second stimuli. Participants responded by pressing the corresponding buttons connected to the computer, with the blue button if the first stimulus was the most biological and the yellow button if it was the second stimulus, performing a two-alternative forced-choice task. No feedback was provided for correct responses. The stimuli were presented randomly and participants gave the answer by pressing the mouse button after the second stimulus started to be presented. A white cross on the center signalized the inter trials interval (ITI). The ITI duration was defined by the start of the first video of the following trial, which could start 7500ms, 10000ms or 12500ms after the start of the first video of the previous trial. Participants took part individually in one session with two runs, each lasting for about twenty minutes and with 100

Figure 6.5 Experiment 1's procedure and stimulus presentation (one trial).



trials, 20 trials per stimulus, 200 trials per stimuli for both runs. Figure 6.5 illustrates the procedure described.

6.2.2 Results

Two analysis steps were conducted in this experiment. In the first step, the determination of neural signals in the regions capable of discriminating different stimuli was performed. An ANOVA repeated measures analysis was conducted using a Bonferroni correction for multiple comparisons. In the second step, the correlation between functional and psychophysical data was assessed with Pearson's correlation coefficient. All statistical analyses were performed using the BrainVoyagerQX software version 2.30. Statistically significant results were considered at a cut-off p-value of 0.05.

Averaging statistical maps for all nine participants in talairach space revealed the most significant areas of activation. A General Linear Model (GLM) analysis, contrasting all stimuli, found a higher significance effect for the middle temporal (MT) area, premotor (PM) area and primary Motor (PiM) area, as illustrated in figure 6.6. The talairach coordinates are shown in table 6.2. A region-of-interest analysis (ROI), using an independent localizer, found a higher activation for MT.

Figure 6.6 Three areas with higher activation in experiment 1.

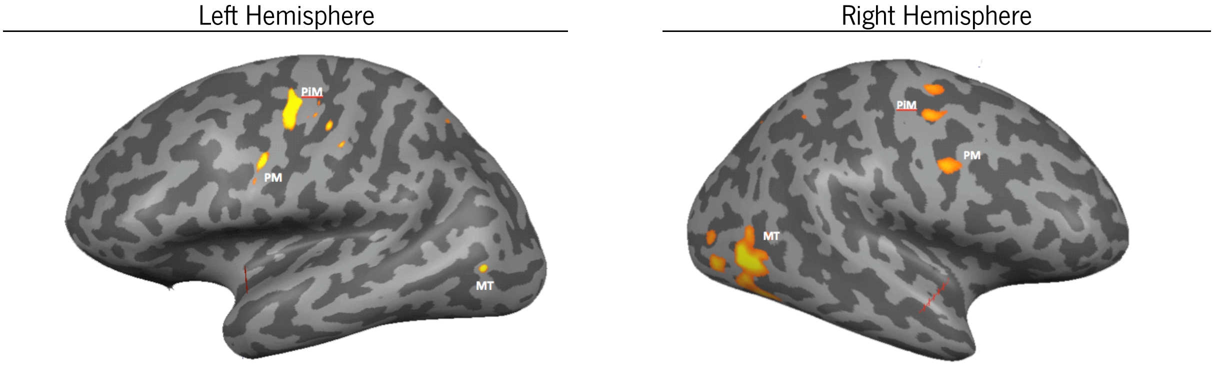


Table 6.2 Talairach coordinates for the three areas with higher activation in experiment 1.

		Talairach Coordinates		
		x	*y*	*z*
Middle temporal (MT)	LH	-46	-67	2
	RH	40	-67	0
Premotor cortex (PiM)	LH	-42	-13	52
	RH	34	-10	50
Primary motor cortex (PM)	LH	-57	-5	40
	RH	-46	-2	38

A significant effect was found in MT, PiM and PM when all stimuli were considered in the contrast effect, but not when we contrasted the biological condition (BM) with the non-biological conditions (other five stimuli). The ANOVA for repeated measures showed a strong effect in MT ($F_{LH}(6)=8.971$, $p< 0.000000$; $F_{RH}(6)= 4.813$, $p<0.000002$) and PM ($F_{LH}(6)=7.334$, $p< 0.000000$; $F_{RH}(6)= 4.543$, $p<0.000007$). The contrast effect in PiM presented high values for the left hemisphere ($F_{LH}(6)=3.704$, $p< 0.000004$).

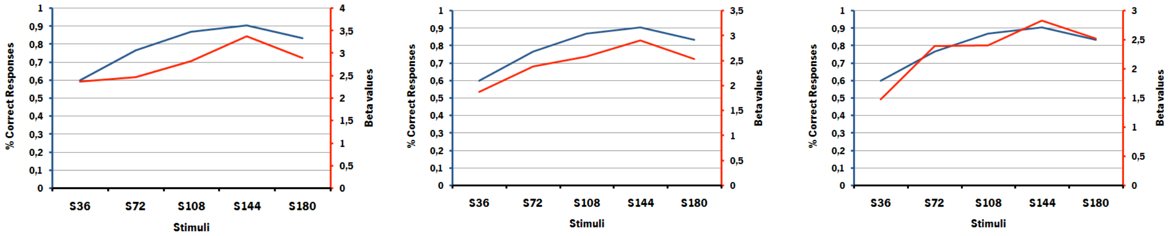
We also found great but not so high activity in other relevant areas for biological motion processing, such as in the STS. Table 6.3 describes the talairach coordinates and the ANOVA values for the six areas identified. All of these areas were significantly activated when participants observed the stimuli but no contrast effect was found.

Table 6.3 Other relevant areas involved in biological motion processing with statistical significance in experiment 1.

	Talairach Coordinates			t(7266)	p
	x	*y*	*z*		
Superior Temporal Sulcus (STS)	45	-43	13	2.332	0.020190
Cerebellum	17	-50	-16	2.465	0.014105
Anterior Cingulate	4	17	38	4.537	0.000008
Precuneus	17	-60	44	6.040	0.000000
Medial Temporal	44	-29	0	-2.328	0.020437
Fusiform gyrus	31	-58	-15	3.223	0.001373

As we collected the psychophysical responses, we compared them with the beta values for the areas where we found a significant contrast effect. To compute the beta values we just considered valid the activation for the stimuli correctly identified. A Pearson correlation superior to 0.9 was found for both areas (using the values of LF). Figure 6.7 shows the comparative graphs for the three brain areas.

Figure 6.7 Correlation between psychophysical and fMRI data for the three most relevant areas.



Middle Temporal	Primary Motor	Premotor
r = 0.943, p=0.016	r = 0.977, p=0.011	r = 0.977, p=0.004

The percentage of correct responses is represented in the blue y-axis and the beta-values for each stimulus is represented by the red y-axis. In this experiment we did not compare biological motion with biological motion, i.e., the possibility of the second stimulus being equal to the first. Because of that, just five comparisons are expressed in each graph of figure 6.7.

6.2.3 Discussion

The results show the activation of the different areas involved in biological motion perception (Grossman & Blake, 2002, Grossman et al., 2000; Montgomery & Haxby, 2008). Presenting briefly one dot representing a foot, we observed activation in the biological motion brain network, with higher significance in the middle temporal, premotor and primary motor areas. This appears to demonstrate that the recognition of biological motion patterns implies a network of areas, in spite of the existence of a specific area (STS) for biological motion stimuli. All relevant regions commonly referred to as forming the brain network involved in biological processing (MT, PM, VT and STS, see figure 6.2) are activated, but more significantly the MT and PM. As we presented stimuli with kinematic properties and no structural cues, it is expectable that ventral areas have a little involvement in the processing of our stimuli. Nevertheless, considering that our stimuli represent one of the most pure forms of biological motion signals, and considering that neurons in STS fire for human bodies in motion, the lower activation was unexpected. Eventually, if we consider that the neurons in the STS function as an integrator of form and motion properties, a lower activation could be expectable when an impoverished stimulus is presented. However, to test the hypothesis that the STS works as an integrator we needed to collect more evidence. It would be interesting to compare the response in three distinct conditions: one of them with our stimuli (only kinematic biological properties), another with frozen point-light walkers (only form features), and a third with form and motion properties. If the STS works as an integrator, it will be activated in all conditions, but more for the third.

Two other areas showed a strong activation: the anterior cingulate area and the precuneus. The anterior cingulate is involved, among others, in error detection (Pardo et al., 1990). It seems to be responsible not only for detecting errors, but also to monitor performance and signal when adjustments in control are needed (MacDonald et al., 2000). The participants' task was to choose the most biological of two stimuli or, in another perspective, to identify and reject the wrong stimulus. So, a strong activation can mean an involvement of this brain area in signal detection, a hypothesis that deserves to be explored. As pointed out by Carter and collaborators (1998), the anterior cingulate is activated when an error is detected but also when correct possibilities are in competition, a clear example of when two stimuli are spatiotemporally closer. With this assumption, these authors suggested that the anterior cingulate does not detect the errors themselves, but detects the conditions under which errors can easily occur. However, considering the argument of signal detection error, it is important to discard the effects of using a two forced-choice paradigm.

The precuneus is implied in motor coordination and, in articulation with the premotor cortex, it is involved in visuospatial tasks (Frings et al., 1996). It is more activated when observers are viewing more realistic spatial information than non-realistic (Mar et al., 2007). As our stimuli have the same global spatial component, it can suggest that the spatial differences during translation are being processed. Because these differences are a consequence of instant velocity patterns that derive from stimuli to stimuli, this can be an argument in favor of a capacity to process small signal motion properties and not an average velocity or global patterns. Here, it is important to remember that the stimuli presented in experiment 1 have the same average velocity, start and finish the motion in the same place and only the instant velocity and acceleration patterns are distinct (see figure 6.3 and figure 6.4.)

Another conclusion is concerned with the nature of the areas involved and which are more activated. They are considered part of the dorsal pathway. Considering the two-streams hypothesis described in the chapter's introduction, these results seem to be in agreement with the idea of a pathway sensible to spatiotemporal patterns. In fact, the stimuli have only kinematic properties, but not structural features, suggesting that the MT is more than a motion detector: it is sensible to and capable of distinguishing velocity patterns. In the same way, the effect found in the premotor area shows that mirror neurons are activated, suggesting that observers recognize the stimuli as a familiar observed and performed action. The activation in the primary motor cortex is also related to action recognition (Hari et al., 1998). Together, all of these areas are part of the action perception network (Gallese and Goldman, 1998; Gallese et al., 2004), which can explain the results in visual perception tasks when participants are acting simultaneously. The signal motion characteristics appear to be critical to activate the motor mechanism and the areas involved in the recognition of familiar executable actions (Kilner & Frith, 2008; Press, 2011). Alluding to the relation between the STS and premotor areas in the perception of action stimuli, Saygin (2007) recognized that, although the areas are part of a specialized network, the specific functional role of each region is not completely explained yet. Later, Saying and colleagues (2011) suggested that such areas, along with parietal and temporal areas, could be involved in the prediction error when the brain negotiates if an agent appears human or not, but does so without considering the biological properties of movement. According to these authors, the uncanny valley could be explained by this argument. However, our results suggest that the action perception systems are highly sensible to the kinematic properties and that kinematic properties can be necessary to recognize or perform an action. In spite of being a biological or not, our brain mechanism appears to be highly sensible to signal detection.

The relation between the psychophysical results, measured by the percentage of correct responses, and fMRI results, measured by the beta-values, showed a high correlation between the behavioural response and neural correlates. The sensibility to small physical changes in motion signal is observed also in neural correlates. These results have more interest if we consider that contrast analyses between stimuli show a significant effect when we considered all stimuli, i.e., the different velocity patterns. When we contrast biological (BM) against non-biological (other five stimuli), no effect was found. This suggests that participants processed the signal motion properties, expressed by the velocity and acceleration patterns, and not the stimuli category, i.e., if they are biological or not. Moreover, the predominance of areas belonging to the perception action system, and their capacity to distinguish different velocity patterns, constitute another argument toward an ecological theory of motion signal processing. In other words, if critical cues to process dynamic stimuli are given by kinematic properties and not by stimuli category, it can mean an earlier and faster processing of this kind of features, making a rapid reaction in an interactive environment possible and explaining the automatic nature of most motor responses. Evidently, new experiments are needed to corroborate our proposal, but the relevance of kinematic information seems to be clearly demonstrated.

A final discussion concerns the magnitude of the neural signals. As we can observe in figure 6.7, the neural signal increases from biological to less biological stimuli, a constant pattern in our experiment. This apparently contradictory result can be explained by a well-documented phenomenon in fMRI studies: the repetition suppression. Simply put, repetition suppression refers to a reduction in neural response in a specific brain area when a prior exposure stimulus is presented to an observer (Horner & Henson, 2008; Noppeney & Penny, 2006). That means that familiar stimuli have a lower neural signal than a new one. Here, the results conformed well to the argument. Biological motion stimuli presented almost always the lowest neural signal and the neural response for other stimuli increased for stimuli farthest from biological. For instance, recently Valyear and collegues (2012) demonstrated repetition suppression in areas involved in action, specifically in the premotor and sensory motor brain areas. According to the authors, this could be explained by the resonance concept (Gibson, 1979), i.e., the potential uses of an object that can be directly perceived and are fundamental to action. In their opinion, affordances are represented in sensorimotor areas and, from an evolutionary perspective, this facilitates the transformation of visual information in an action plane. Considering again the relevance of kinematic properties, a repetition suppression effect is a secondary evidence of our experiments. Note that we just manipulated the temporal component of stimuli, changing the signal properties, and that we only presented one dot representing one foot. Nevertheless, this was sufficient to activate areas part of the "where" pathway and part of the perception action system, but also to elicit a repetition suppression response. From that, we can suggest not only that we have sensibility to perceive motion signal properties, but also that these properties can be central to an action planning mechanism. Moreover, it can explain why the STS, the area commonly referred to as being selective to biological motion, did not have a specific response, as shown by the significance level, in our experiments. There are some evidence that the STS "learns to see" biological motion (Carter & Pelphrey, 2006; Grossman, Blake, Kim, 2004). This means that a natural suppression repetition response, and consequently an ecological explanation supported by the affordance concept, was not expected. So, the perception of signal properties seems to be supported by perception-action areas, such as the MT and premotor areas, and occurs not by signal category (biological or non-biological), but mainly by familiarity or prior experience. It appears to be more in consonance to an ecological signal processing that integrates a signal-processing paradigm with Gibsonian ecological concepts, than to a categorization of stimuli. We will return to Gibson's concepts in the next chapter, where we will discuss the arguments in a perception-action perspective, using the same stimuli procedure adopted in this chapter and chapter 5.

7. Perceiving acceleration, acting accelerated

7.1 Introduction

“We know what it is to get out of bed on a freezing morning in a room without a fire, and how the very vital principle within us protests against the idea... We think how late we shall be, how the duties of the day will suffer; we say, “I must get up, this is ignominious.” (...) Now how do we ever get up under such circumstances? If I may generalize from my own experience, we more often than not get up without any struggle or decision at all. We suddenly find that we have got up” (James, 1890/1950, vol. 2, p.524). In the Principles of Psychology, William James reflected about free will and the current idea that our actions always result from our conscious intentions. Taking the physiologist William Benjamim Carpenter’s idea about the automatic function of the perceptual system (1874/1984), James ran with it and developed a theory about the relation between perception and action. As James (1890/1950) said in the cited work, "whenever a movement unhesitatingly and immediately follows upon the idea of it, we have ideomotor action. This is not a curiosity, but simply the normal process...and we may lay it down for certain that every mental representation of a movement awakens to some degree the actual movement which is its object; and awakens it in a maximum degree whenever it is not kept from so doing by an antagonistic representation present simultaneously to the mind”. This initial argument that perception and action could be related and actually interact with each other has been gaining empirical support over time. As has been shown in numerous studies, observing or imagining an action excites the motor programs used to execute that same action (Ernst, Banks, & Bülthoff, 2000; Hommel et al., 2001; Jeannerod 1994; Knoblich & Flach, 2001; Prinz, 1997).

This interdependence appears to be definitively upheld by the existence of mirror neurons, that fire not only when someone performs a specific task but also when he/she observes that same action being performed (Gallese et al.,1996; Rizzolatti et al., 1996a; Rizzolatti et al., 2001). In the previous chapter we have discussed and shown evidence on this. The results of experiment 1 of chapter 6 clearly demonstrated that the observed movement of a foot during one step activated the mirror neuron system. In our experiment, the smoothness level of the stimuli had a different neuronal response, showing that we can recognize different patterns of velocity and acceleration, but mainly distinguish actions that we can perform. In spite of this neuronal linkage between perceiving an event and activating not only visual areas but also motor areas, this does not necessarily mean that action is influenced by perception. In other words, can we expect that the same visual task elicits different responses if subjects are performing a specific action? Or, put differently, can we expect that motor performance changes according to the visual stimuli available? Several results appear to support this argument.

Even though the interest on perception-action interaction increased after the discovery of the mirror neuron system, previous work had already shown evidence about this relation. One of the first studies that tested this idea proposed that perception and production of phonetic information share the same representations, i.e., the same representational codes (Liberman & Mattingly, 1985). This first result allowed for the later development of a *common-coding theory* (Prinz, 1997) that explains how perceptional and motor representations are related. In other words, the neurophysiologist and Nobel Prize Roger Sperry (1952) defended the notion that perception is a variety of actions, and that actions are a form of perception. According to the author brain processes are prepared to transform sensory patterns into motor patterns: "the evolutionary increase in man's capacity for perception (...) may be regarded, not so much as an end itself, as something that has enabled us to behave, to act, more wisely and efficiently" (Sperry, 1952, p.299; see Trevarthen (1990) for an exhaustive review).

Thus, perception and action processes are functionally intertwined, not only by sharing some brain areas, but also by the observed behavioural response. Brass, Bekkering and Prinz (2001) give us a clear evidence of the influence of perception on action. In their study, participants executed pre-instructed finger movements in response to compatible and incompatible finger movements, presented visually. The authors analysed two conditions: the dynamic spatial component, by manipulating the direction of movements, and the ideomotor component, by manipulating the *type* of movement (hand upright or upside-down). They concluded that both components influence the participants' response and found that reaction time in the initiation of motor response decreases when similar movements were presented, suggesting that perception excites a specific neuronal motor network.

The findings discussed in chapter 6 support this conclusion. The different activation patterns of the mirror neuron system demonstrate that we can distinguish in terms of action how biological the movement is. If on the one hand we know that motor response is influenced by visual perception, and on the other hand that mirror neurons have different responses depending on how biological the movement is, we can thereby hypothesize that changing the temporal component of biological motion, as suggested in the experiments of previous chapters, will affect the motor response.

However, in contrast to classical visual perception tasks, acting presupposes a multimodal perception that involves, at the very least, vestibular and visual systems. As affirmed by Bingham, Schmidt and Rosenblum (1995, p.1484), the perception of gravitational direction occurs through the vestibular system as well as by the visual. Probably, the interaction between systems is possible because of the internal gravity model that coordinates perception and action. McIntyre and colleagues (2001) tested this hypothesis by analyzing how subjects coordinate movements to catch a falling object at different levels of gravity. Participants performed the same action on Earth and space conditions, during the 17-day Neurolab space shuttle mission. The results show that a second-order internal model was used, that is, a model that uses velocity and acceleration information. They concluded that this model makes sense in Earth conditions, where we combine visual and vestibular cues. Nevertheless, at 0*g*, authors observed the anticipation of motor response, regardless of visual information showing the absence of gravity. These findings, however, according to the authors, are not necessarily in agreement with Gibsonian perspective (Gibson, 1966,1979), in which first order strategies, based on the velocity information available through the sensorial signals alone, conformed better. But Gibson (1966) did not neglect the importance of the vestibular system, stating that the "vestibular organ is suited to detect active locomotion or passive starts and stops but not constant-velocity transportation. For millions of years animals moved by rhythmic transportation pushes, not as Newtonian bodies and not in railroad cars or airplanes. It is therefore reasonable that an individual should be susceptible to vestibular illusion when passively transported in a vehicle" (p.69). In other words, the human system has been specializing in biological motion perception, integrating the information of different biological channels, such as the visual and vestibular system. The capacity to perceive velocity or acceleration differences in biological patterns would be more of an issue of action than of pure perception. Keeping within this argument, the smoothness of the temporal component of biological motion, as proposed and presented in experiments of previous chapters, will be reflected in behavioural responses, i.e., in observers' actions. As noted by Carello and Turvey (2002), a theory of perception cannot ignore what animals do, since the main reason for perception to occur is not an issue of brain processes, but rather of animal-environment systems.

In fact, Gibson organized all of these arguments (1950) in a theory towards a visual guidance of locomotion. Gibson proposed that the visual system needs to know what it is approaching but also how it is approaching it, i.e., how it is moving. The motor response, such as avoiding collisions, starts or stops moves, or changing trajectory are a consequence of that. Therefore, the possibility to integrate the stimuli's motion patterns represents a relevant question. That possibility could be interpreted as the ability to understand small differences between stimuli and could be expressed as an *invariant*, i.e., the reliable patterns of optical structure derived from the optical flow, which is comprised of vectorial patterns of light available to a point of observation, resulting of animal-environment settings. If that capacity is explained by the invariants, we can thereby expect that manipulations of motion will decrease these invariants' reliability, and consequently their recognition.

Therefore, if we take biological signals as *invariants*, as we do with other different biological components (Aaen-Stockdale et al., 2008), such as structure for instance, we are considering that the relation between space and time, and the particular patterns of velocity and acceleration, need to be preserved. If they are not preserved, we can recognize something that mimes the biological patterns but not an invariant. Then, the motor response will be influenced differently by the non-invariant pattern. Considering the motion signal as an invariant, the discussion around first or second order variables can be discarded. To recognize the *invariant* both orders need to be preserved, that is, they need to be biological.

We can conceive the invariant concept as an internal model or a natural visual algorithm, a biological mechanism that uses and evaluates sensorial and sensory-motor parameters to originate a specific motor response. In a review about visual perception and the interception of falling objects, Zago and Lacquaniti (2005) reinforce the existence of an internal model that extrapolates time-to-contact from the gravitational kinematics properties on Earth. Changes in these properties harm the human being’s performance to correctly calculate the time-to-contact. Presumably, the recognition of kinematic properties of biological motion and their interaction with them uses a similar internal model that improves the interaction in situations with multiple agents. In human locomotion this issue is crucial.

In a study about walking perception by walking observers, Jacobs and Shiffrar (2005) tried to understand how relevant visual perception is to coordinate actions with other people. In their study participants were asked to compare their own speed with the speed of a point-light walker or were asked to compare the speeds of two point-light walkers (slower or faster). Participants could be in a fixed position, similar to a classic psychophysical task, or they could be walking on a treadmill or cycling in a stationary bike. The results demonstrated that walking observers were worse at evaluating the velocity speed than in static or cycling conditions. The results also showed that observers’ own velocity influenced the perception of velocity in self-based evaluation (comparing own velocity with the stimulus’s velocity), but not in other-based (comparing the velocity between stimuli). The authors concluded that the processes implied in perception of biological motion patterns are distinct, and that previous motor experience can explain the results of egocentric (self-based) tasks.

Nevertheless, we can argue that it is not an issue of distinct processes or available cues, but only of the source available to perform optimally. In egocentric tasks both the visual and vestibular systems could provide critical information. Here, it is relevant to know what and how the stimulus is approaching, but also how I am approaching, i.e, how I am moving. The first information is given by the visual system, for instance by optical flow, but the second involves an interaction between the vestibular and visual systems. In sum, we are always talking about biological motion signals, processed and captured by different human systems. The ecological result should be the correct action to perform optimally. Kilner, Hamilton and Blakmore (2007) brought new evidence for these arguments.

From a previous work (Kilner, Pauligman, & Blakmore, 2003), the authors studied the interference effect of observed movement on observers' hand movements. They presented observers with horizontal or vertical movements of a human arm or of a ball moving across the screen. These movements could be biological (minimum jerk model) or non-biological (constant velocity). Participants were asked to look at the screen and perform the same type of movements, in a congruent condition (same direction) and in an incongruent condition (tangential direction). The results showed that the interference was greater when participants observed a human arm moving in a tangential direction, but only for the biological motion condition (minimum jerk model). Moreover, interference occurred for both velocity profiles when participants observed the ball's movements.

The authors argued that most likely biological and non-biological motion are processed differently in the brain when a human being executes them. But the most interesting conclusion is that the interference appears to be explained by the nature of the human movement and not by the form of the human body. Two issues need to be considered, one of them related to the executor and the other to the motion properties. On the one hand, human arms moving at constant velocity do not exist. Unless the structure features represent in themselves a critical cue to perceive the movement, as the authors tried to clarify, they could be extraneous variables. The visual system processes all information available: structure and motion. Processed in the same brain areas or not, both are combined in a coherent percept. However, if one of them is ambiguous or does not make sense, the system can simply neglect one of them or, if not, the integration process of incoherent cues can generate an interference effect. As pointed out by Garcia & Grossman (2008), biological motion perception requires intact motion perception, but secondary mechanisms that may be the integration of form and motion are also involved. So, we can expect that, if they are presented, form cues are involved in the interference effect.

On the other hand, the relevant information that explains the interference effect appears to be the "nature of human motion", in other words, the properties of motion signal defined by its spatiotemporal components. As results demonstrated, only the condition of a human arm moving at constant velocity did not interfere in participant's actions, curiously the most ambiguous stimulus. The other three conditions interfered with participants' arm movements, and all of them were realistic or, at least, possible movements. The human arm moving biologically is easily understandable, the ball moving at constant velocity is the typical motion of an object according to Newton's laws, and the ball moving with a biological profile is possible when a hand moves it. Conceptually, this last condition is equivalent to Bingham, Schmidt, and Rosenblum's (1995) hand-moved pendulum stimulus, better described in chapter 5, page 63. As the authors pointed out, despite the fact that participants were looking at a pendulum, they perceived it as if being moved by a hand, i.e., the signal properties were the strong cue.

The motion signal process appears to be crucial in action coordination. In this sense, the signal properties need to be preserved because they carry out relevant cues to perception and action. If not sufficient, they are at least necessary, as suggested by Garcia & Grossman (2008). All natural or realistic movements, biological or not, are characterized by specific relations of space and time, with correspondent velocity and acceleration profiles. If motion perception is nothing but a signal process interpretation, the internal models need to know the underlying parameters in order to react accordingly. Changes in these parameters can affect both perception and action. Although these parameters do not need to be necessarily biological, they must be realistic, that is, they must preserve the natural relationship between space and time. The study of McLeod and Dienes (1996) showed evidence of this. In their work, participants were asked to predict where balls launched into the air would fall. The balls were projected towards them, but because of the air resistance, they could fall in front or behind their initial launching position. Participants were filmed running backwards or forwards to catch the ball and, as the results showed, they were always running when they caught it. The authors concluded that the internal model used to intercept an object ensures that subjects arrive at the right place at the right time but it does not tell them where or when that is. They also defended that subjects ran to try to maintain the optical velocity of the ball constant, i.e., the space-time relation given by a specific realistic motion signal. So, the motion signal cues appear to be the critical source of information and, in this sense, need to be the central variable studied.

The present chapter tries to study the perception of biological motion signals, as proposed in previous chapters, but now within a perception-action paradigm. If kinematic properties are central in biological perception, if we are sensible to small variations of biological profiles, if motor responses are affect by perception, then small changes in biological kinematic properties can interfere in subjects' motor response. If this is true, then these kinematic properties are critical not only for perception but also for action. Adapting Kilner, Pauligman and Blakmore's (2003) experimental design and using the same rationale to stimuli construction as used in chapters 5 and 6, we will analyse the interference of kinematic properties on subjects' motor responses, hypothesizing that participants are able to recognize and react to temporal changes of biological motion patterns. We will present the methodology, describing in detail the more complex issues: stimuli construction and procedure. Then we will show the results, discussing afterwards their implications.

7.2 Experiment 1: interference on simple arm movement

In experiment 1 we presented participants with their own arm movement captured previously or the same movement with changes in the velocity pattern. The main goal was to understand the interference of biological velocity patterns on action and, consequently, understand the importance of motion signal properties. Participants executed horizontal arm movements and, simultaneously, visually tracked the motion stimuli computed from their own movement previously captured. Differences in the participants' motor responses should show the sensibility to velocity patterns and the minimum physical changes needed to affect their own action. The results show that biological motion signals interfere on participants' actions, meaning that the processing of signal information is relevant on the motor response's preparation.

7.2.1 Method

7.2.1.1 Participants. Five volunteers took part in the study, all of them naïve as to the purpose of the experiment. Participants were students or researchers in the Laboratory of Visualization and Perception with an average of 24 years old, ranging from 20 to 27 years old. All had normal or corrected-to-normal vision based on the automatic screening test and tests of kinetic (dynamic visual acuity with moving stimuli varying direction, speed and spatial frequency) of the equipment for visual screening (Essilor, Ergovision). All had no physical problems or clinical orthopaedic history.

7.2.1.2 Apparatus and Stimuli. A 3-chip DLP projector Christie Mirage S+4K, with a spatial resolution of 1400x1050 pixels and a refresh rate of 101Hz, presented the stimuli. Images were displayed with OpenGL running over a Vr/Net Juggler software on a computer with a graphic board NVIDIA Quadro FX 4500. The stimuli were projected on a surface 2.10m high and 2.80m wide. This apparatus was possible in the Laboratory of Visualization and Perception of the University of Minho, in an immersive virtual environment (see figure 4.6 in chapter 4).

The stimulus was a white dot against a black background, representing the movement of a human arm moving either horizontally or vertically, as showed in figure 7.1. The movements were captured using a motion capture system (VICON; Oxford Metrics, Oxford, UK), with six near-infrared cameras (VICON MX F20 of 2 megapixels with a frame rate of 240 Hz). A retro-reflexive marker was attached to the hand of the participant's dominant arm, as showed in figure 7.2. We captured each movement for 25 seconds, asking participants to move the arm comfortably and imagine that they were drawing a straight horizontal or vertical line. The procedure was repeated twice, resulting in a set of six captures, three horizontal and three vertical. The stimuli construction was based on the procedure developed and detailed in experiment 1 and resumed in table 5.4 of chapter 5, briefly described below.

Figure 7.1 Arm movement captured for stimuli construction.

Horizontal Movement

Vertical Movement

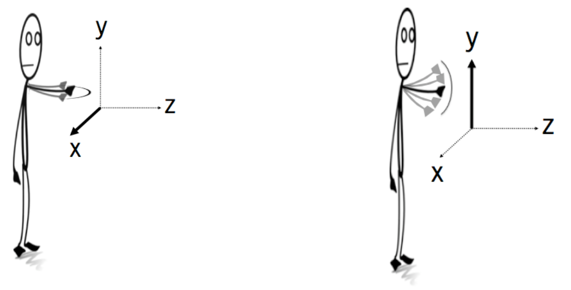
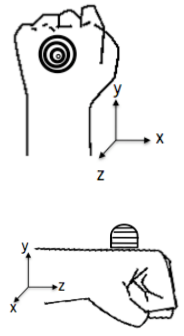


Figure 7.2 Fixation of the retro-reflexive marker on the hand.



Firstly we chose, for each type of movement, the most regular of the three captures, or the motion sequence where the arm appeared to move in the most perfect straight line, i.e., the movement with lower standard deviation in the y-axis for horizontal movement and x-axis for vertical movement. Secondly, we selected 20 seconds of the capture sequence of 25, deleting the first and last seconds corresponding to the typical initial acceleration and final deceleration movements. The first frame of motion corresponded to the maximum value of *z*, i.e., the position where the hand was furthest from the body, corresponding in both type of movements to the moment where the arm is parallel to the ground and makes an angle of 90° with the body. Considering the arc of the motion curve, as shown in figure 7.1, the start position corresponds to the moment where the tangent on the z-axis assumes a value of 0.

From the biological sequences of 20 seconds, we computed four stimuli with different temporal components but the same spatial component. We smoothed the biological velocity profile using a simple moving average, obtaining four stimuli with 0%, 25%, 50% and 75% of the standard deviation of the biological velocity pattern. The result was a set of five stimuli ranging from biological motion (100% of velocity standard deviation) to constant velocity (0% of velocity standard deviation). The procedure was applied to the horizontal and vertical movements. For the stimulus at constant velocity the moving average order was equal to the total number of frames. However, the moving average order of other stimuli was distinct from subject to subject and stimulus to stimulus, as a consequence of individual patterns of motion.

After calculating the new velocity pattern, we computed the new 3D coordinates (translation, elevation and sagittal). Considering a frame rate of 240Hz, we firstly computed the translational component, assuming that

$$v = \frac{d}{t} \Leftrightarrow d = vt$$

and that v is the velocity frame by frame calculated with the moving average process and that t is the same for each frame (240Hz/1000ms). Assuming an initial value for the trajectory, we computed the formula for each frame, taking into account each frame's instant velocity and keeping in mind that the time difference between frames remains constant. With the new translational pattern known, we were able to calculate the new elevation pattern (y). For that, we used the linear interpolation method because the differences between two consecutive values are small and the elevation values do not change rapidly (Billo, 2001). Assuming the general formula,

$$y_1 = y_0 + \frac{x_i - x_0}{x_1 - x_0}\left(y_1 - y_0\right),$$

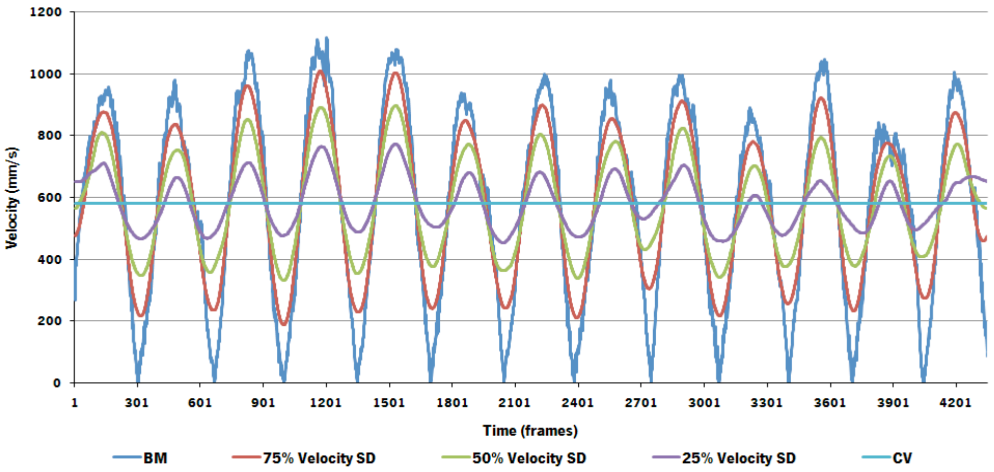
and knowing that x_0 and y_0 are the biological values and x_i is the value of the new translational pattern calculated previously, we obtain the new elevation value for each frame, y_1, and consequently the new elevation pattern. The same process was applied to the sagittal (z-axis).

It is important to note that all procedures were computed for each cycle of movement. A cycle corresponds to the frame in which the velocity function returns to zero. For vertical stimuli a cycle corresponds to the descendent or ascendant arm movement, i.e., to the maxima and minima of the translation function on the y-axis. For horizontal stimuli a cycle corresponds to the right-to-left or left-to-right movements, i.e., to the maxima and minima of the translation function on the x-axis. Because there are not equal cycles, we need to calculate the smoothed velocity pattern and the new 3D coordinates for each of them, a very long but unique process that preserves the spatial component of natural movement. The result was a set of ten stimuli per participant, five with vertical motion and five with horizontal motion, with the same spatial component and the same average velocity. Only the instant velocity differs between cycles for each stimulus.

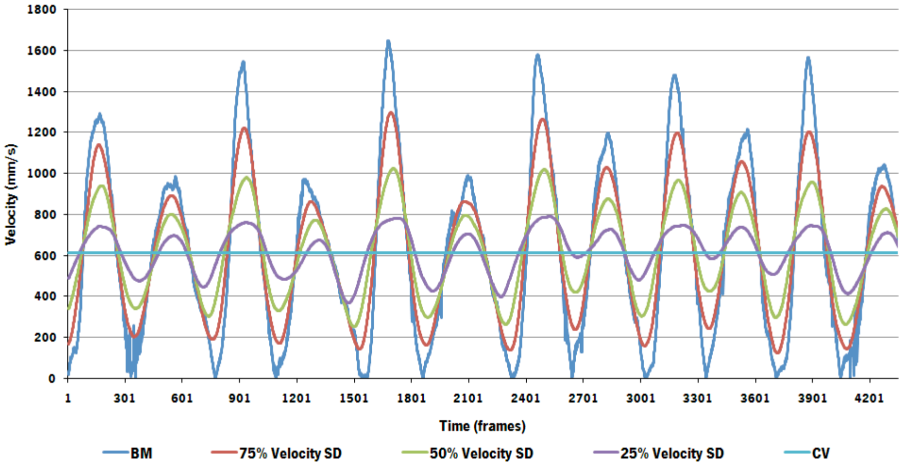
Figure 7.3 illustrates the velocity patterns for all stimuli, while graph A represents the horizontal movements and graph B the vertical ones, for one participant. For the same average velocity, the lower the standard deviation of the velocity, the lower the maxima and minima of the function. In graph B, the differences between cycles correspond to the ascendant (higher maxima) and descendent (lower maxima) movements. The impulse in ascendant movements causes higher values of velocity, in contrast with the controlled falling process of descendent movements. This difference does not happen in horizontal movements because gravity affects right-left and left-right movements alike.

Figure 7.3 Procedure of experiment 1.

A) Horizontal arm movement



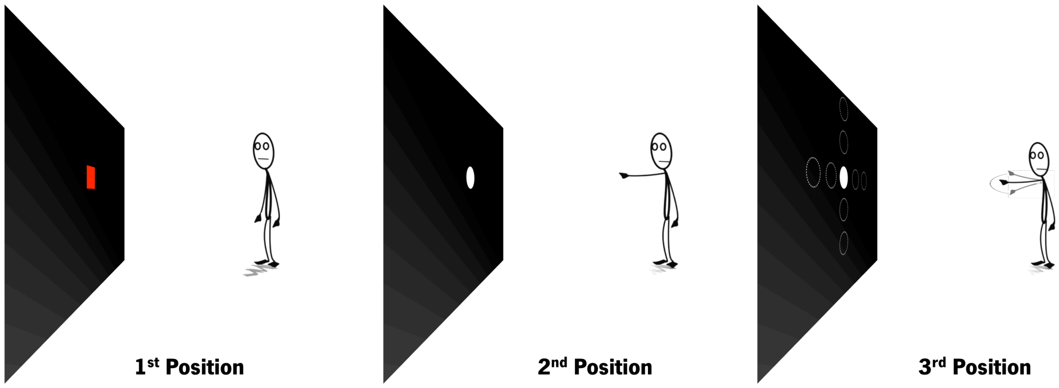
B) Vertical arm movement



The stimuli had a temporal resolution of 101Hz. Although the projector had been prepared to frame rates up to 120Hz, we could actually only ensure frame rates up to 101Hz, with the best spatial resolution (1400X1050 pixels). In spite of this, all calculations for the stimuli construction were made at 240Hz.

7.2.1.3 Procedure. Participants were standing on a platform (1.25m high, 0.9m wide, 0.15m long) in a dark room, 3 meters away from the display. The platform served as a reference, ensuring that participants were in the same position during both the capture trials and the experiment.

Figure 7.4 Procedure of experiment 1.



1st Position
Break
10s

2nd Position
Preparing
5s

3rd Position
Execution
20s

Firstly, a black frame with a red square was presented for 10s, corresponding to a break between movements. Participants were instructed to relax when the red square was presented. Secondly, we displayed a black frame with a white dot in a fixed position for 5s, the visual signal for preparing the arm. The white dot was the first frame of the movements, equal for all stimuli, and presented in the direction of the arm (parallel to the ground and making an angle of 90° with the body). In a third moment the stimuli were presented for 20s and participants were asked to perform a horizontal arm movement while simultaneously visually tracking the moving white dot on the screen. Nothing was said about aligning the movement with the visual stimulus. Participants performed 10 trials for each of the ten conditions, a 2 x 5 experimental design: two types of movements (horizontal or vertical) and five velocity profiles (from biological motion to constant velocity). Participants took part individually in five sessions, each lasting for about 12 minutes and with 20 trials. No feedback was provided for correct responses. The stimuli were presented randomly and participants' arm movements were captured as described for the stimulus construction: a retro-reflexive marker on the hand as showed in figure 7.2. Figure 7.4 illustrates the procedure described.

Before presenting the stimuli in the first session, the procedure was executed 5 times for participants to get used to the sequence. In this training we presented the horizontal biological motion stimulus.

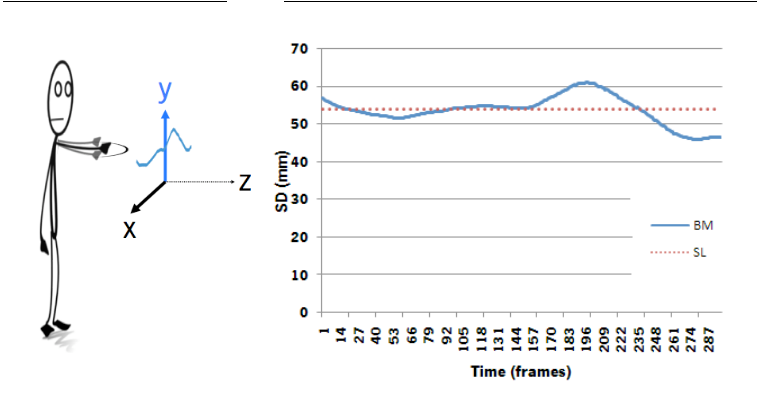
7.2.2 Results

An exploratory analysis allowed the assumption of normality, demonstrating that all data fall in the normal range, according to the Kolmogorov-Smirnov normality test. Having confirmed this assumption, we performed statistical analyses to confirm the existence of a significant action interference effect in the perception of biological motion velocity patterns.

For analysis purposes, we considered only 16s of the 20s captured. The initial and final 2.5s were eliminated, corresponding to the typical initial acceleration and final deceleration movements. This avoids the surprising effect caused by the presentation of incongruent movement (vertical motion stimuli), but also fatigue effects towards the end of the movement.

To investigate the interference effect of different velocity profiles on motor response, we analysed the standard deviation of movement tangential to the axis of motion, i.e., the standard deviation on the y-axis. Figure 7.5 illustrates the movement on y-axis for one cycle (movement left-right). The blue line represents a human arm moving naturally from left to right (BM) and the red line a hypothetical condition where the human arm moves in a straight line (SL). We measured this swing up and down to analyse the interference of visual stimulus on action.

Figure 7.5 Data analyses measure.



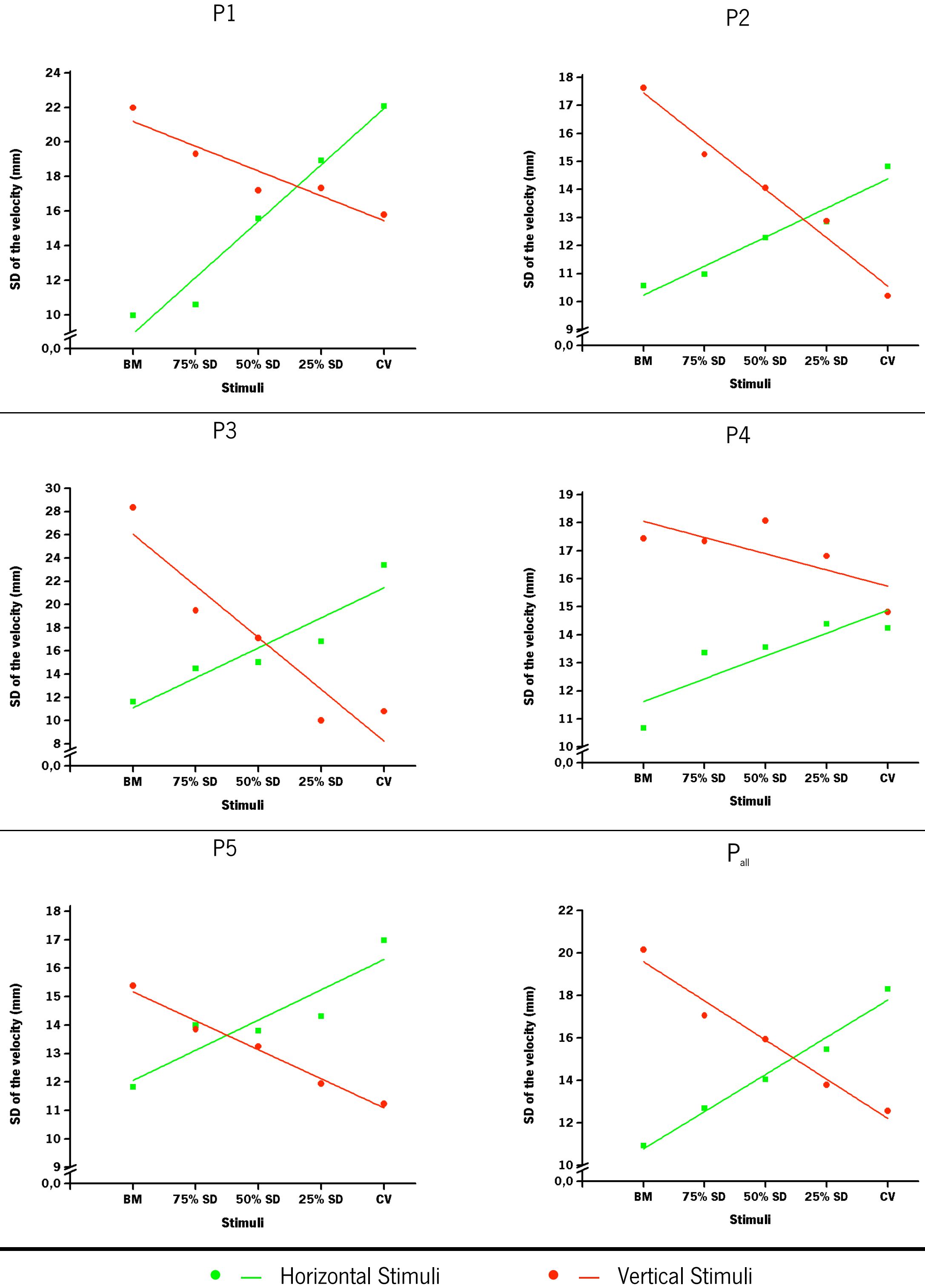
Movement

Graph

The results clearly show an interference effect of visual stimulus on motor action. The graphs of figure 7.6 show the mean standard deviation in millimetres tangential to the axis of movement for individual (P1-P5) and aggregated (P_{all}) data. The mean of standard deviation increases with the smoothness of velocity patterns when participants were executing congruent movement, i.e., executing horizontal movements when the horizontal stimulus was being presented. A repeated measures ANOVA ($F(4,4)=9.79$, p <

0.01) revealed a significant main effect. The inverse effect was found when an incongruent condition was performed, i.e., executing horizontal movements when vertical movements were being displayed. Here, the mean standard deviation decreases with the smoothness of velocity patterns. A repeated

Figure 7.6 Results of experiment 1.



measures ANOVA (F(4,4)=5.96, p < 0.01) also revealed a significant main effect. Excluding participant 4, individual and aggregated data fit well to a linear function, as demonstrated by high values of adjusted R-squared, as discriminated in table 7.1.

There was no effect of type of motion, i.e., congruent or incongruent. The mean standard deviation is similar when incongruent (vertical) or congruent (horizontal) movements were displayed, as revealed by the t-test for dependent measures (t(24)= 0.3, p > 0.05).

The results show a significant interaction between type of motion and the smoothness of the velocity pattern. Computing the differences between the mean standard deviation of horizontal and vertical movements for each visual stimuli, a linear relation was found. For that we considered the equation $y_s = h_s - v_s$, where s represents the level of smoothness, h the horizontal movement and v the vertical movement. The difference of the mean of standard deviation tangential to the axis of movement increases from biological motion to constant velocity. A repeated measures ANOVA revealed a significant effect (F(4,4)=11.48, p < 0.01). Graphs of figure 7.7 illustrate this interaction and the linear adjustment for individual and aggregated data. The individual data are detailed in table 7.2.

Table 7.1 Mean, standard deviation and fitting of SD tangential to the axis of movement (values in millimetres).

Participant	Type of movement	Stimuli					Linear Fit
		BM	75% SD	50% SD	25% SD	CV	
P1	Horizontal	9.98 (2.60)	10.59 (2.47)	15.57 (1.71)	18.93 (7.97)	22.07 (5.45)	y=5.67 + 3.25x (adj. R^2= 0.95)
	Vertical	21.98 (6.04)	19.32 (4.54)	17.2 (3.88)	17.34 (6.73)	15.79 (4.48)	y=22.63 - 1.43x (adj. R^2= 0.86)
P2	Horizontal	10.57 (1.65)	10.98 (1.11)	12.28 (3.14)	12.86 (3.58)	14.82 (3.97)	y=9.19 + 1.04x (adj. R^2= 0.93)
	Vertical	17.63 (4.97)	15.26 (4.62)	14.05 (2.07)	12.87 (2.11)	10.2 (2.40)	y=19.18 – 1.72x (adj. R^2= 0.97)
P3	Horizontal	11.64 (3.71)	14.49 (5.69)	15.02 (5.71)	16.88 (3.35)	23.38 (5.80)	y=8.52 + 2.58x (adj. R^2= 0.82)
	Vertical	28.33 (5.41)	19.49 (6.66)	17.11 (2.60)	10.01 (3.11)	10.8 (5.02)	y=30.52 – 4.46x (adj. R^2= 0.86)
P4	Horizontal	10.68 (5.93)	13.37 (4.64)	13.55 (4.12)	14.39 (3.42)	14.24 (2.55)	y=10.8 – 0.81x (adj. R^2= 0.65)
	Vertical	17.44 (2.65)	17.34 (5.19)	18.08 (3.05)	16.81 (4.85)	14.81 (4.84)	y=18.63 – 0.58x (adj. R^2= 0.38)
P5	Horizontal	11.82 (5.04)	13.99 (4.61)	13.79 (5.35)	14.31 (4.26)	16.98 (7.95)	y=10.99 + 1.06x (adj. R^2= 0.78)
	Vertical	15.38 (2.75)	13.85 (4.38)	13.25 (4.41)	11.94 (3.86)	11.23 (1.68)	y=16.19 – 1.02x (adj. R^2= 0.98)
All	Horizontal	10.94 (3.79)	12.68 (3.70)	14.04 (4.01)	15.46 (4.52)	18.29 (5.15)	y=9.03 + 1.75x (adj. R^2= 0.97)
	Vertical	20.15 (4.37)	17.05 (5.09)	15.93 (3.20)	13.79 (4.13)	12.56 (3.68)	y=21.43 + 1.84x (adj. R^2= 0.96)

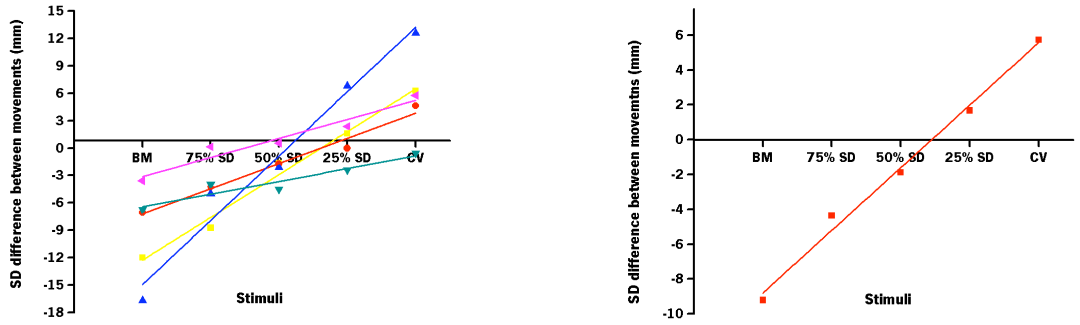
Table 7.2 Mean, standard deviation and fitting of the difference of SD between types of movements (values in mm).

Participant		Stimuli					Linear fit
		BM	75% SD	50% SD	25% SD	CV	
■	P1	-12	-8.72	-1.63	1.59	6.28	y= - 16.96 + 4.69x (adj. R^2= 0.98)
●	P2	-7.06	-4.27	-1.77	-0.02	4.62	y= - 9.98 + 2.76x (adj. R^2= 0.97)
▲	P3	-16.4	-5.01	-2.08	6.82	12.58	y= - 21.99 + 7.04x (adj. R^2= 0.96)
▼	P4	-6.76	-3.98	-4.52	-2.41	-0.57	y= - 7.83 + 1.39x (adj. R^2= 0.87)
◀	P5	-3.56	-0.14	0.55	2.37	5.75	y= - 5.21 + 2.08x (adj. R^2= 0.92)
All		-9.22	-4.36	-1.89	1.67	5.73	y= - 12.4 + 3.59x (adj. R^2= 0.99)

Figure 7.7 Graphs of the differences between types of movements for each smoothness velocity pattern.

Individual data

Aggregated data



7.2.3 Discussion

The results clearly show a significant influence of perception on action. On the one hand, the motor response is affected by the stimuli's velocity profile, and on the other hand, this influence also reflected the type of movement presented. Decreasing the velocity's standard deviation to 0% (constant velocity) elicited two distinct patterns. When participants executed arm movements congruent with the visual stimuli the interference effect was greater for biological movement. On the other hand, when an incongruent movement was present the opposite pattern was found, with greater interference in less biological movement.

These findings replicate the results of Kilner and colleagues (2007) in the study we based our construction of this experiment in. However, the authors presented only two distinct velocity profiles: biological motion and constant velocity, both animating a human arm (natural stimulus) or a ball (abstract stimulus). They found an interference effect when biological movements executed by the human arm were presented, but not for non-biological movements. Nevertheless, when the stimuli were abstract the interference occurred for both patterns. In our experiment participants visually tracked a moving white dot on the screen, a condition close to the abstract condition of Kilner and collaborators. If we understand that it is an abstract stimulus, our results are in agreement with Kilner and colleagues, because we also found an interference effect for both types of velocity profiles in both types of movements. The authors defended that the human system processes biological and non-biological stimuli differently when a human arm executes them, as we discussed in the introduction. Because this interference happened only for incongruent stimuli they also concluded that it is explained better by biological properties of motion than by structure cues. One of the explanations proposed was the existence of brain areas exclusive to process biological motion, such as the STS (Allison, Puce, & McCarthy, 2000). Still, different explanations can be proposed that are related with our previous experiments.

Firstly, the interference occurs gradually from biological to constant velocity. As occurred on the psychophysics experiments described in chapter 5, participants perceived the smoothness of the velocity pattern. If in those experiments the response was mediated by a forced choice paradigm, here, the response is directly observed on the participant's action. Without structure cues and presenting only motion signal variations, we have a clear motor response pattern. If we act only on an average velocity basis we would expect a similar response for all stimuli, at least within each condition. We would eventually have two different responses explained by congruency. Note that during 20 seconds many cycles were presented (the number varied from participant to participant) and that we just manipulated the temporal component inside cycles. This presupposes that the white dot returns to the correct spatial position after each cycle, the same 3D coordinates to all stimuli. Even if we can perceive different temporal properties of the motion signal, biomechanically our motor schemes could not reflect this information. Visibly, it is not true. Perhaps this explains the related phenomenon of movement's synchronization that happens when two subjects are walking together (Schmidt, Carello, & Turvey, 1990). Probably the current arguments of phase and frequency of movements can be better understood thinking just in terms of motion signal properties. Note that all visual stimuli had the same frequency and the same phase. If participants were trying to align their movements, and if we found different interference effects for each velocity profile, then it means that they were perceiving the signal differences. Moreover, if participants kept the movement constant, they initiated and finished the cycles at the same time. So, the perception of temporal differences appears to justify the effect. However, more evidence are needed to corroborate this idea.

Another possible explanation could be the theory of internal oscillators, i.e., a network of neurons that produces a correlated syncopated output (Strogatz & Stewart, 1993; West & Scafetta, 2003). According to West and Scafetta (2003), the locomotion model governs the stride interval time series for human gait. The internal time series would be generated by two types of stress processes. “One stress mechanism, which has an *internal* origin, increases the correlation of the time series due to the change in the velocity of the gait from normal to the slower or faster regimes. The second stress mechanism has an *external* origin and decreases the long-range time correlation of sequences as under the frequency constraint of a metronome” (Scafetta, Marchi, & West, 2009). In future experiments it could be interesting to adapt our experiment to test this theory, but for now the smoothness of the motion signal could be understood as an external stress that affects the internal time series.

Secondly, the interference effect produces an opposite pattern, with the interference increasing from biological to constant velocity for congruent movements and decreasing for incongruent movements. If we just processed the variations in motion signal we could expect that the interference takes place in the same way for both conditions. Considering the idea of stress mechanisms, the higher the difference on velocity profiles, the higher the stress effect on internal time series. But, although this conformed well to the congruent movement results, it does not explain the incongruent condition. The mirror neuron system could be an alternative. When we are observing an identical pattern, we easily synchronize the movements. When we have another pattern, however, the synchronization efforts appear to be higher for biological patterns but not for a stimulus that not only neglects the biological properties but also is not related to our actions. In other others, it appears to be the biological signal properties that explain an apparently contradictory result. In congruent situations the signal influences a similar action and the degradation of biological properties affects the performance negatively. However, in incongruent motion it is not only the biological signal properties that influence the performance, but also if the stimulus is biological or not. Returning to the arguments presented in the introduction, it appears to be an issue of *invariants*. Brain networks can be prepared simultaneously to process signal properties, as shown in chapter 6 by the MT area and mirror neuron systems, but also to respond to a motion *invariant* with higher survival value. So, in congruent stimuli the processing could be an issue of *resonant* (the mechanism to pick up the invariant information available) and in an incongruent situation it could be an issue of invariant.

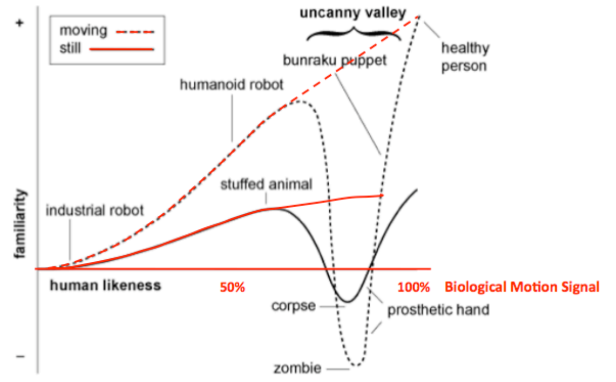
Although these arguments can be plausible explanations, more evidence need to be collected. In spite of all, the experimental design is sufficiently non-ecological but is appears to be a good starting point towards an ecological theory of signal processing. For that, not only the visual system should be tested but also other human systems such as, in case of motion patterns, the vestibular system. Effectively, we could have asked participants to perform the task sitting down, but we opted for a standing position. The vestibular system, a mechanic system of acceleration perception, would be more excited in a standing than in a sitting position. However, is this insufficient to explore its contribution and to understand its real relevance? Future experiments should try to explain the vestibular system's contribution to motion signal processing simultaneously to the development of the concepts discussed above.

8. Afterwards

We are now able to return to the uncanny valley, the valley where the familiarity sensation falls when the appearance of a robot becomes closer to that of a human being. We were clear when we refused the recurrent explanations, supported by religious and cultural interpretations, as well as categorization processes about what a human being should be, suggesting instead that this problematic could be better explained by an issue of congruency between structure and motion features (Saygin et al., 2011; Seyama and Nagayama, 2007). We stated, at the time, that it is therefore necessary to go further – even if we could avoid falling into the valley, why do we have a strong sense of unfamiliarity in the presence of robots acting as humans? Why does this feeling happen only when the similarity is closer to that of a healthy person? And why does motion have a strong contribute to the uncanny valley? Why is this effect so pronounced in motion conditions?

We suggested, in chapter 1, that the explanation for these questions can be found in some motion properties that are likely to have a critical role on perception and, consequently, on the sense of familiarity or, in other words, on the comfortable human-machine relation. Considering the argument, we proposed that only by investigating the biological motion's properties could we understand their importance for perception and action. We proposed that we needed to demonstrate that biological motion carries with it some crucial motion properties that, more than biological, are spatiotemporally defined and, in this sense, temporally processed and integrated. These properties could be extremely relevant in the perception of biological motion, while simultaneously being responsible for the uncanny valley phenomenon. We hypothesized that it could be an issue not of appearance, but of biological signal properties, i.e., the feeling of familiarity would not fall into the valley if biological motion properties were respected. Here, the results could be expressed as a relation between the sense of familiarity and biological properties, as shown in figure 8.1 - the more respected the biological properties are, the higher the feeling of familiarity.

Figure 8.1 The Uncanny Valley Revisited.



Credits: Adaptation of the simplified version of the figure shown in the English translation of Mori's original article by MacDorman and Minato.

Hypothesizing that the spatiotemporal characteristics of the signal would be fundamental to the visual perception of biological motion, we proposed a set of experiments that could answer the issues presented above. These experiments showed that the visual system is highly sensitive to biological motion's properties, as is corroborated by the brain areas involved. They showed also that not only visual perception, but also the observer's actions are influenced by small changes in the signal's temporal properties.

In this final chapter, we will bring forward an overview of the findings presented in each chapter and that clearly show the importance of motion signal properties on the perception of biological motion. Then we present some implications of those results in the research on biological motion, trying to demonstrate how they can be relevant not only in fundamental areas, but also in applied research. After that we will present future proposals that, with the findings discussed here and other results in the literature about biological motion, can drive us towards a new ecological theory of signal processing. We will finish with a concluding note about all the work so far.

8.1 Experimental results overview

Using the uncanny valley metaphor, we hypothesized that kinematic properties of biological motion are central information in its perception. These kinematic properties, as defined in chapter 2, were described as simple translational patterns in a period of time from which we can compute the differential equations associated, such as velocity and acceleration for example. However, this spatiotemporal relation is restricted by the biomechanical properties of the human body, making these patterns of movements distinctive from others. In this sense, it is reasonable to talk in terms of biological motion, not motion *per se*, and consequently study its intrinsic properties and its influence on visual perception.

With this assumption, it is crucial to ensure that the stimuli used in perception experiments really contain or represent those properties. In chapter 3 we presented a new approach to capture the biological motion's patterns and, after that, to construct the biological motion stimuli. As we asked at the time, why a new approach to create and develop point-light walkers? Precisely because the distinctive properties of biological motion are neglected or non-considered in numerous experiments and stimuli. If it can be defensible that in many experiments of categorization or simple recognition the motion signal's properties are not critical, in experiments about signal properties they most definitely are. Therefore, two main issues were considered in the process of point-light stimuli construction.

One of them was related to the biological motion signal's acquisition. Data accuracy depends, at first, on the options taken with the motion capture procedures. For that, we proposed an acquisition protocol that considered the best technical options in a motion capture system based on 3D data and the best methodological option available. Here, the selection of participants is a basic step to avoid signal noise associated with physical problems, as well as asymmetric postures that will be revealed later in data treatment. Our protocol described the physical characteristics of subjects that served as models in the capture process, the procedure to attach the retro-reflective markers, the instructions to improve the naturalness of the participants' gait during motion capture, the options in terms of capture system preferences and the procedures to take the main anthropometric measures. Together, all these components allowed for the construction of a database of biological motion that permits, at any time, to relate motion signal and body structure and to use one or both in numerous experiments. The experimental possibilities are immeasurable, mainly because of the preservation of the translational component. As we discussed, numerous studies investigate biological motion properties neglecting the translational component, mostly because stimuli with translation patterns are not easily accessible. Nevertheless, the acquisition of one type of action – subjects walking at different velocities – is a limitation here. Still, all relevant questions to capture different actions are now already discussed and considered in the methodology proposed in chapter 3 of this work (Aragão, 2010).

The second main issue concerned the stimuli construction. Until now all procedures were taken to ensure the best sequence of motion, i.e., the sequence with less difference between the subject's real motion pattern and the data captured. Therefore, it is important that the manipulations done during the stimuli's construction preserve all kinematic properties captured. We discussed in detail the smoothness processes and their implications in the preservation of real kinematic properties. As we argued, some kinematic characteristics are currently considered signal noise and, after smoothing the data, they are absent in point-light stimuli. If smoothness in other kinds of signals does not mean loss of relevant information, in biological motion it does. Thus, we proposed a set of methodologies that preserve the kinematic properties of biological motion when we transpose the data from motion capture to stimuli construction. The methodologies describe the procedures to compute the dots of point-light figures, discussing the most appropriated solutions in case of missing data and the cost, in terms of accuracy, of interpolation processes. We described also the issues related to the translation component of motion. If the construction of stimuli that preserve this feature is one of the main advantages of our database, it is also true that in many experiments we were forced to remove the translational component. We developed a set of routines that remove the translational component without loss of information and without neglecting the kinematic properties. (Aragão et al., 2009a).

Note that the manipulation of data, in spite of all concerns, presupposes either minor or major changes on the original data, increasing the signal's noise or creating virtual signals. In this sense, rather than just being concerned with the fact itself, we should concern ourselves with the difference they produce at the end of the process. In other words, it is critical that we know the real properties that will be displayed when we present point-light stimuli. The discussion about visualization settings provides here a good example. We presented and discussed in chapter 3 a set of procedures to ensure that frame rate and resampling processes or reorientation of the stimuli on the display preserved realistic properties of biological motion.

Thus, we now have a complete protocol, from motion capture to stimuli construction, which can be easily executed if we need any human action that is absent from our biological motion database. The main results were a set of human motion patterns available and numerous point-light stimuli that all researchers can easily use. All stimuli used in the present work are available in this database. Nevertheless, if the methodological options are not consensual they are, at least, explained and thoroughly documented.

After creating biological motion stimuli, and before beginning the study of their kinematic properties, we investigated if the frame rate used in visual perception research could be an extraneous variable. We tried to dismiss the argument that the larger temporal summation in the perception of biological motion might be just a consequence of an insufficient temporal sampling of the stimuli. In other words, could we accept that something in motion patterns explains the complexity of motion and that this complexity justifies the large temporal summation? If resampling processes influence the signal displayed to observers, this could perfectly explain this phenomenon. So, in chapter 4 we tried to understand the effect of different frame rates on the perception of biological motion. The same motion stimulus was presented at two possible frame rates and participants had to discriminate the direction of motion. The results showed no differences between conditions (30 Hz versus 120 Hz), which probably means that this factor cannot explain the large temporal summation of biological motion perception (Aragão et al., 2009b).

However, when we analyse the motion signal at different frame rates, we found significant differences. Although frame rate changes the motion signal properties, experiment 1 does not reflect these differences. However, in experiment 1, we only manipulated the displayed frame rate, not the frame rate of the motion signal. So, in experiment 2, we hypothesized that it could be an issue not of the displayed frame rate, but mainly an issue of sampling. Therefore, we presented participants with a set of stimuli that had been smoothed, ranging from a biological motion pattern to 72 moving averages of the velocity pattern. Each set was presented with a specific frame rate (30 Hz and 120Hz). The results showed significant differences in reaction time, but not in recognition. The differences in kinematic properties between stimuli can explain the differences between conditions. If changes in biological motion signal influence the observers' response, what signal characteristics could explain it? This question was answered in the following chapters (5, 6 and 7).

Firstly, we investigated the perception of biological motion signals by changing their temporal characteristics. For that, we manipulated in both experiments of chapter 5 the velocity patterns of motion. In experiment 1 we presented observers with the feet of a point-light walker and they were asked to choose the most natural of two stimuli presented. The results showed the capacity of the visual system to perceive small physical changes and to recognize different biological motion velocity patterns. Using the same procedure, in experiment 2 we presented a more impoverished stimulus: one foot walking a single step. We eliminated the structural cue maintained by the feet's relation and reduced the duration of the stimuli, thereby trying to demonstrate that the perception of biological patterns is signal dependent and is a sufficiently robust percept. Results also showed the capacity of the visual system to perceive small physical changes and to recognize different biological motion velocity patterns. Both psychophysical experiments demonstrated that minimum physical changes are needed to perceive signal differences (Aragão & Santos, 2010; Aragão, Santos, & Castelo-Branco, 2010).

Secondly, in chapter 6, we demonstrated the brain processes involved in the perception of motion signals. More than corroborating the literature that describes the areas typically involved, we showed specifically how temporal properties are processed and what is their contribution to perception and action. The results clearly showed the importance of the MT area, the area that primarily processes motion. We demonstrated that MT not only recognizes motion, but it also processes its signal properties. Furthermore, the activation of STS demonstrates that kinematic properties are critical in the perception of biological motion, but mostly demonstrates the higher capacity to perceive biological motion in the most impoverished stimuli possible: one foot during one step only. Nevertheless, the most curious result in chapter 6 was the activation of the mirror neuron system, in the premotor cortex. These findings can explain the relation between perception and action and how observers perform better when acting simultaneously.

Precisely, the final experimental issue was concerned with perception and action. In chapter 7, we presented participants with their own arm movement captured previously or the same movement with changes in the velocity pattern. The main goal was to understand the interference of biological velocity patterns on action and, consequently, to understand the importance of motion signal properties. Participants executed horizontal arm movements and, simultaneously, visually tracked the motion stimuli computed from their own movement previously captured. The results showed that biological motion signal interferes on participants' actions, meaning that the processing of signal information is relevant on the motor response's preparation (Aragão, Santos, & Castelo-Branco, 2011).

In conclusion, we started capturing biological motion patterns and creating biological motion stimuli. This initial task ensured that the stimuli used in experiments preserved intact the kinematic properties of this specific kind of motion. Then we were able to study the relevance of motion signals in the visual perception of biological motion. Firstly, we discarded some methodological explanations related to frame rate and sampling processes, showing that the kinematic properties had a critical influence on biological motion perception. By manipulating the temporal characteristics of the stimuli we showed how the visual system is sensitive to small physical changes, but also how it seems to integrate the temporal properties of motion. These findings were also supported with the perception-action task, showing that it is not only an issue of perception, but also of signal properties influencing the observers' action.

8.2 Implications for research

The results and evidence found in our work bring methodological, technical and theoretical contributions to the research on biological motion. From the new approach to stimuli construction to the relevance of kinematic properties on visual perception, we can bring up two main implications where we can distinguish some particular points.

The first of them concerns the stimuli used in research on the visual perception of biological motion. Point-light figures are the most used stimuli in biological motion research, in spite of the recurrent criticism on the absence of real spatio-temporal characteristics of point-light walkers and the limitation of their ecological value. The protocol used to capture human body movements, the available database of anthropometric measures, and the procedures developed to construct biological motion stimuli respond to both criticisms. Firstly, the biological motion data captured preserves the kinematic properties of human gait. If it is defensible that other kinds of stimuli represent human biological motion better, it is not true that all biological motion data available in our database neglect the real kinematic properties. The spatial and temporal components have accuracy close to 2mm and translational patterns are integrally preserved. This allows for all stimuli properties to be known in detail in any experiment on visual perception. Moreover, our methodological proposal responds to the second criticism on biological motion stimuli – the absence of biological features and the impoverishment caused by the representation of the human body as a stick figure. Recently, some authors began defending that the efficiency of the human visual system to extract information from point-light stimuli is low, in spite of the fact that they carry with them relevant information (Gold et al, 2008). Full-figures, natural films or contrast figures will be mostly used in future studies. Citing Thornton (2006, p.288), “it seems likely that filming natural scenes will become a more standard initial step in acquiring biological motion stimuli”. With this assumption, we considered it crucial to use a larger number of markers, in motion capture procedures, than the number of markers needed to construct a point-light stimuli. These markers and the anthropometric measures taken allow the construction of a full body figure, i.e., a body that preserves volume properties. Here, the range of possibilities in stimuli construction increases significantly, even more when we have 3D-data, because we have a detailed description of their properties. Moreover, even though the research shows contradictory results (van Boxtel & Lu, 2011), both options are acceptable. In essence, it is fundamental that in any case all stimuli properties can be specified, one of the best advantages of our proposal.

Still, other methodological implications could be mentioned. In a point-light stimulus paradigm the translational motion and the range of the average velocity of our stimuli represent, probably, the most important advantage. Effectively, as we discussed in chapter 3, the translational component is frequently absent. When long sequences of movements are required, the solution is to generate loop cycles. To avoid that, the motion patterns captured have up to ten gait cycles at different average velocities. In experiments about time-to-passage or time-to-contact, so relevant in human factors, traffic or human-machine interaction, stimuli now available have an enormous potential (see Mouta, 2009, for a review). Also in a perception-action paradigm, perhaps one of most promising areas on future research on biological motion, the possibility to present observers with long sequences of movements with which they can interact justifies the efforts applied in the database construction.

In sum, the range of possibilities to construct interesting experimental designs is vast, using point-light figures or full body stimuli, studying local or global motion components, opting by different perspective-views, using the patterns of one subject only or trying a mix of patterns, exploring the contribution of different body parts or simply manipulating the point-light figure itself. Some of these possibilities can be demonstrated by their effective contribution in some works, such as Mendonça, Santos, and López-Moliner (2011), Mouta, Santos and Lopez-Moliner (2012) or Silva (2011).

The second main implication concerns the role of kinematic properties of biological motion on visual perception. Not preserving spatio-temporal components can generate less accurate results and, consequently, erroneous interpretations. The sensibility of observers to small physical changes in motion signals can imply a worse performance when they are absent. If we think that many tasks in everyday life involve reaction times, we can assume that it is crucial to study the influence of signal properties, as we did, but first we must ensure that biological stimuli preserve intact all of kinematic properties. As a time-varying function, biological motion presupposes the integration of temporal components, expressed in terms of velocity and acceleration for a given space-time condition (Orgs et al., 2011). The option for high temporal samplings and high frame rate displays are a direct consequence of our work, and demonstrates the relevance of kinematic and temporal motion characteristics. Also, the option for synthesized motion patterns and their consequences on stimuli quality and visual perception are now more visible. The naturalness of motion is a critical feature to visual perception, but to perception-action also. The brain areas involved, specially the mirror neuron system, represent a powerful argument.

In an applied perspective, the recognition of the significance of motion signal properties can influence the human-machine interaction and developments in robotics' area. The uncanny valley provides an interesting example. It is remarkable that research has developed machines that mimic almost perfectly cognitive high-level functions, such as memory, speech production, and capacity of solving complex or abstract problems or, for example, software programs that mimic clinical psychologists. In most of these cases, human beings cannot distinguish if they are in presence of a machine or a human being. Curiously, this does not happen with motion. Put simply, why does a low-level process characterized by biomechanical rules appear to be impossible to mimic? Probably because the spatio-temporal relation of motion is neglected, in spite of spatial and temporal components being preserved independently. Our results appear to corroborate this hypothesis.

A final question is concerned with computational principles for biological motion recognition. As pointed out by Giese (2006, p.325), "in contrast to human brain, none of the existing technical algorithms and theoretical models for motion recognition is suitable for solving all of [computational problems] in a satisfactory way" (square brackets added). The author gives the example of recognition of a walking human being in a natural scene and the problems associated, such as discrimination of figure-background, determination of space and time of movements, the reconstruction of the 3D structure, prediction of movements of future frames and action classification. Assuming biological motion as a temporal integrated signal, an algorithm will always need to contain parameters that can process spatio-temporal variables.

8.3 Future proposals

The results presented along the work demonstrated the importance of motion signal properties for biological motion's visual perception. Kinematic properties are perceived accurately and the subjects' motor behaviour reacts to them. Also, brain areas involved showed the system's capacity to integrate those properties. Keeping in mind the survival value of motion perception, and the impressive results of Johansson's (1973) work, nearly forty years ago, we can put forward that the perception of motion signals is central in human perception and has a critical role in action. The integration of kinematic properties can help us explain more than simple recognition of human beings or animals. But is biological motion perception different than other kinds of complex motion? Retrieving the distinction between artificial, biological and realistic motion, can we hypothesize that the visual system simply processes the kinematic properties of realistic motion, where biological motion is a specific case? Can it be just a signal processing mechanism? That is, can we assume the existence of a biological algorithm, whose parameters include spatial and temporal variables that need to respect the physical and biological laws of motion?

In an ecological perspective, it appears to be reasonable that the visual system has highly powerful algorithms, but in a limited number. As in other areas, living beings tend to improve performance efficiently, while reducing the energy involved. Therefore, an algorithm of motion perception can respond to that. Beyond the results that we have been discussing in the present work, many experimental results converge to this argument. For instance, the sensitivity to the gravitation of objects in motion showed in 7-month-old infants (Kim & Spelke, 1992) demonstrates an earlier capacity of extracting information from signals of realistic motion. The results of Chang, Harris, and Troje (2010) showed that, when uninformative egocentric information was displayed, observers used the information provided by gravity as a reference to biological motion perception, instead of using the information provided by the visual environment. We can argue that the signal's motion properties are more available in gravity information that in the visual environment. However, the authors demonstrated that the relevant source of information to perceive biological motion was the egocentric information. As pointed out by Thornton (2006, p.264), in the perception of biological motion we can probably recruit mechanisms and information not available in other kinds of motion perception. Here, our own movements can represent a useful source of information, but the vestibular system appears to play a critical role. Moreover, the vestibular system also has a strong influence on the perception of non-biological motion. In a study about perception of velocity of realistic but non-biological movements, Mallery and collaborators (2010) showed that subjects performed much better in the discrimination of rotational velocities than predicted by Weber's law. In the authors' opinion, this demonstrated that the vestibular system is more sensitive to motion than other sensory systems. If we consider that the vestibular system is one of the most basic systems, processing our rotation and translational movements from changes in our acceleration and deceleration movements, the relevance of the signal's motion information is enhanced (see Highstein, Fay, & Popper (eds.), 2004, for an exhaustive review of the literature on the vestibular system).

Furthermore, signal motion properties appear to be involved not only in motion perception. In their work, Wang and Jiang (2012) showed that the spatio-temporal component of biological motion affects the perceived temporal duration. They suggested that time perception can be related to life motion signals through the temporal encoding of biological motion. As we have repeatedly said, if motion is a time-varying function, it seems reasonable that temporal properties represent a powerful source of information.

However, to propose in the future an ecological theory of signal processing, more evidence need to be collected. At first, it will be useful to review and summarize the evidence and results dispersed through the scientific literature. The evidence can appear unrelated, such as, for example, the time perception experiment cited above, but these efforts can bring up interesting relations. After that, it will be easier to identify unexplored areas or, at least, areas that need more evidence. One of them is the role of the vestibular system. In spite of the studies mentioned, little is know about its real contribution to perception. For instance, in terms of brain functioning, it is known that the cerebellum and the thalamus process vestibular information, but their real implications are not clearly understood.

Furthermore, it can be useful to adopt the methodology proposed in chapters 5, 6 and 7, using other kind of realistic and synthesized motion. The results could be compared with biological motion, and then the influence of kinematic properties could be effectively discussed.

8.4 Summing up

It seems to be pragmatic to say that our experimental work and the arguments that we have been discussing add new evidence on the visual perception of biological motion. Nevertheless, it also appears to be reasonable to say that more issues were opened than those that we effectively answered. The temporal integration in the perception of biological motion was the starting point of our proposal. We hypothesized that the temporal properties expressed in velocity and acceleration patterns could explain phenomena such as the high temporal summation found for this type of motion. We tried to demonstrate that this is explained by their signal properties, and that the complexity of biological motion can be better studied in terms of kinematic properties. The survival value provides an empirical argument that, in theory, makes sense. But as Bacon (1620/1994, cited by Hergenhahn, 2001) wrote: “Empiricists, like ants, merely collect things and use them. The Rationalists, like spiders, spin webs out of themselves. The middle way is that of the bee, which gathers its material from the flowers of the garden and field, but then transforms and digest it by a power of its own. And the true business of philosophy is much the same, for it does not rely only or chiefly on the flowers of the mind, nor does it store the material supplied by natural history and practical experiments untouched in its memory, but lays it up in the understanding changed and refined. Thus from a closer and purer alliance of the two faculties – the experimental and rational, such as has never been made – we have good reason for hope” (p.98).

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Appendix I | Anthropometric measurement procedures

A. Equipment

1.

Designation	Anthropometer
Description	Four hollow graduated tubes that fit into one another to form a rigid rod, each one with 50 centimetres (2 meters total). One of them has two parallel sliding arms that can be moved to contain the part of the body being measured, providing a measurement of the distance between the two body parts.
Function	Used for determining the length of a section of the body such as an arm or leg, not for determining perimeters. Used also for determining the different between two anatomical points, such as the shoulders offset. Measures in millimetres.

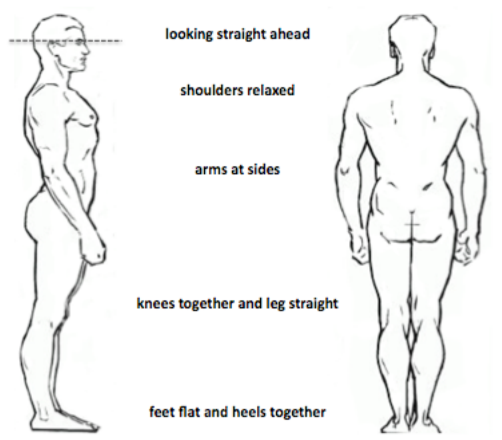
2.

Designation	Digital Bathroom Scale
Description	Portable digital platform where subjects place their feet.
Function	Weight measurement in kilograms.

3.

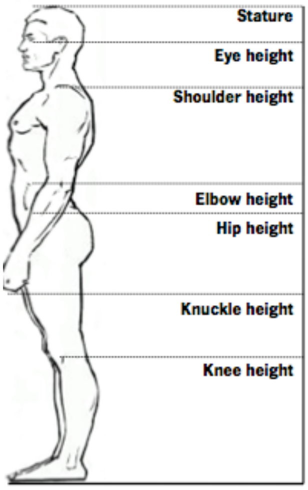
Designation	Tape-measure
Description	Flexible tape measure with 1 meter.
Function	Body perimeter measurement in millimetres.

B. Body posture in anthropometric measurement



Body posture affects the assessment of anthropometric measures. To minimize the error and the differences between subjects, all measures should be taken in the same anatomical posture. The person should be in a standing position, looking straight ahead. The shoulders must be relaxed with the arms at the sides. The knees should be together as well as the heels, with the feet flat and the legs straight. Ideally, the person should be barefoot and with as little clothing as possible.

C. Measures

Measure	**Measurement procedures**
Body mass	The subject should place both feet on the digital bathroom scale. Ideally he/she should be barefoot and wearing only a swimsuit.
BMI	It’s the individual's body weight divided by the square of his height. The index characterizes the relation between height and weight, serving as a body fat indicator. The World Health Organization provides the values adopted to categorize the subjects.
Stature	The body posture described above should be strictly respected in height measurements. Measures taken with incorrect postures could improve the error more than 5 – 10 cm. Uses the anthropometer to measure the different heights, repeating the procedure until two measurements agree within 2 mm. The image on the right illustrates the anatomical points to correctly take the seven main height measures. 
Shoulder height	
Eye height	
Elbow height	
Hip height	
Knuckle height	
Knee height	
Shoulder offset	Distance between the left and right acromioclavicular joints.
Elbow width	Distance between the lateral and medial epicondyle of the elbow.
Wrist width	Distance between the thumb-side and pinkie-side of the wrist.
Waist width	Distance between the two anatomical points on the left and right side of an imaginary horizontal plane that passes in the narrowest part of the torso.
Hip breadth	Distance between the left and right iliac crest.
Hip width	Distance between the two anatomical points in the anterior and posterior side of an imaginary horizontal plane that passes in iliac crest.
Antero-posterior thoracic width	Distance between the two anatomical points in the anterior and posterior side of an imaginary horizontal plane that passes in the xiphoid process, just underneath the breasts.

Transverse thoracic width	Distance between the two anatomical points in the left and right side of an imaginary horizontal plane that passes in the xiphoid process, just underneath the breasts.
Knee width	Distance between the lateral and medial epicondyle of the knee.
Ankle width	Distance between the lateral and medial malleolus of the ankle.
Neck perimeter	The circumference on the imaginary horizontal plane that passes between the thyroid cartilage and the cricoid cartilage.
Thoracic perimeter	The circumference of the imaginary horizontal plane that passes through the xiphoid process, just underneath the breasts.
Arm perimeter	The circumference of the imaginary horizontal plane that passes in the middle of the biceps brachii.
Forearm perimeter	The circumference of the imaginary horizontal plane that passes in the mid-forearm, in the middle distance between elbow and wrist.
Wrist perimeter	The circumference on the imaginary horizontal plane that passes through the thumb-side and pinkie side of the wrist.
Waist perimeter	The circumference of an imaginary horizontal plane that passes in the narrowest part of the torso.
Thigh perimeter	The circumference of an imaginary horizontal plane that passes in the mid-thigh.
Leg perimeter	The maximum circumference of an imaginary horizontal plane that passes in the calf.
Ankle perimeter	The circumference on the imaginary horizontal plane that passes through the lateral and medial malleolus of the ankle.
Hand Thickness	Distance between two imaginary anatomical points located one in the palm and the other in the back of the hand, in the pinkie side

Appendix II | Marker placement protocol

Marker	Full Designation	Placement
LFHD	Left Frontal Head	Placed over the left temple.
RFHD	Right Frontal Head	Placed over the right temple.
LBHD	Left Back Head	Placed on the back of the head, approximately in a horizontal plane of the LFHD marker.
RBHD	Right Back Head	Placed on the back of the head, approximately in a horizontal plane of the RBHD marker.
C7	7th Cervical Vertebra	Placed on the 7th cervical vertebra (known as *vertebra prominens*). It is a palpable long and salient spinious process on the skin.
T10	10th Thoracic Vertebra	Placed on the 10th thoracic vertebra.
CLAV	Clavicle	Placed on the jugular notch. The jugular notch is located on the superior border of the sternum, between the clavicular notches.
STERN	Sternum	Placed on the posterior face of the sternum, on the lower part, precisely on the xiphoid process.
RBAK	Right Back	Placed on the middle of the right scapula. There is not a symmetric marker on the left side, making the recognition of right and back side of subjects in the labelling process easier.
LSHO	Left Shoulder	Placed on the left acromioclavicular joint. The acromiocalvicular joint is the junction between the part of the scapula that forms the highest point of the shoulder (the acromio) and the clavicle.
LUPA	Left Upper Arm	Placed on the left upper arm between the shoulder and elbow markers. Should be placed asymmetrically with RUPA. This makes the identification in case of cross trajectories on the 3D space easier.
LELB	Left Elbow	Placed on the lateral epicondyle of the left elbow.

LFRA	Left Forearm	Placed on the left forearm between the elbow and writs markers. Should be placed asymmetrically with RFRA. This makes the identification in case of cross trajectories on the 3D space easier.
LWRA	Left Wrist A	Placed on the thumb-side of the left wrist. Should be placed symmetrically to the LWRB, in an imaginary axis that passes through the wrist by the centre.
LWRB	Left Wrist B	Placed on the pinkie-side of the left wrist. Should be placed symmetrically to the LWRA, in an imaginary axis that passes through the wrist by the centre.
LFIN	Left Fingers	Placed on the dorsum of the left hand, near the head of the second metacarpal.
RSHO	Right Shoulder	Placed on the right acromioclavicular joint. The acromiocalvicular joint is the junction between the part of the scapula that forms the highest point of the shoulder (the acromio) and the clavicle.
RUPA	Right Upper Arm	Placed on the right upper arm between the shoulder and elbow markers. Should be placed asymmetrically with LUPA. This makes the identification in case of cross trajectories on the 3D space easier.
RELB	Right Elbow	Placed on the lateral epicondyle of the right elbow.
RFRA	Right Forearm	Placed on the right forearm between the elbow and writs markers. Should be placed asymmetrically with LFRA. This makes the identification in case of cross trajectories on the 3D space easier.
RWRA	Right Wrist A	Placed on the thumb-side of the right wrist. Should be placed symmetrically to the RWRB, in an imaginary axis that passes through the wrist by the centre.
RWRB	Right Wrist B	Placed on the pinkie-side of the right wrist. Should be placed symmetrically to the RWRA, in an imaginary axis that passes through the wrist by the centre.
RFIN	Right Fingers	Placed on the dorsum of the left hand, near the head of the second metacarpal.

LASI	Left Anterior Superior Iliac Spine	Placed over the left anterior superior iliac spine. It's the anterior extremity of the left iliac crest of the pelvis.
RASI	Right Anterior Superior Iliac Spine	Placed over the right anterior superior iliac spine. It is the anterior extremity of the iliac crest of the pelvis.
LAPSI	Left Posterior Superior Iliac Spine	Placed over the left posterior superior iliac spine.
RPSI	Right Posterior Superior Iliac Spine	Placed over the right posterior superior iliac spine.
LTHI	Left Thigh	Place over the lateral surface of the left thigh, always below the swing of the left hand, thereby avoiding occlusion caused by the left hand's movements. Should be placed asymmetrically with RTHI. This makes the identification in case of cross trajectories on the 3D space easier.
LKNE	Left Knee	Placed on the lateral epicondyle of the left knee.
LTIB	Left Tibia	Placed over the shank, allowing the alignment of the ankle flexion axis. Should be placed asymmetrically with RTIB. This makes the identification in case of cross trajectories on the 3D space easier.
LANK	Left Ankle	Placed on the left lateral malleolus. Should be placed in an imaginary line that passes through the transmalleolar axis.
LTOE	Left Toe	Placed over the second metatarsal head of the left foot.
LHEE	Left Heel	Placed on the calcaneous above the plantar surface of the foot, at the same height as the LTOE, imagining a line that joins the two markers.
RTHI	Right Thigh	Placed over the lateral surface of the right thigh, always below the swing of the right hand, thereby avoiding occlusion caused by the right hand's movements. Should be placed asymmetrically with LTHI. This makes the identification in case of cross trajectories on the 3D space easier.
RKNE	Right Knee	Placed on the lateral epicondyle of the right knee.

RTIB	Right Tibia	Placed over the shank, allowing the alignment of the ankle flexion axis. Should be placed asymmetrically with LTIB. This makes the identification in case of cross trajectories on the 3D space easier.
RANK	Right Ankle	Placed on the right lateral malleolus. Should be placed in an imaginary line that passes through the transmalleolar axis.
RTOE	Right Toe	Placed over the second metatarsal head of the right foot.
RHEE	Right Heel	Placed on the calcaneous above the plantar surface of the foot, at the same height as the RTOE, imagining a line that joins the two markers.