

Accepted Manuscript

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PII: S0304-3940(15)30313-X
DOI: <http://dx.doi.org/doi:10.1016/j.neulet.2015.12.022>
Reference: NSL 31716

To appear in: *Neuroscience Letters*

Received date: 2-9-2015
Revised date: 28-11-2015
Accepted date: 10-12-2015

Please cite this article as: Etienne Thoret, Mitsuko Aramaki, Lionel Bringoux, Solvi Ystad, Richard Kronland-Martinet, When eyes drive hand: influence of non-biological motion on visuo-motor coupling, *Neuroscience Letters* <http://dx.doi.org/10.1016/j.neulet.2015.12.022>

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When eyes drive hand: influence of non-biological motion on visuo-motor coupling

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Highlights

- Visuo-motor coupling of biological motion is examined in visual open-loop
- 17 subjects reproduced 3 circular visual motion (1 biological – 2 non biological)
- Non biological kinematics significantly distort the motor reproductions
- Motor reproductions significantly amplified the perceptual illusion

Abstract

Many studies stressed that the human movement execution but also the perception of motion are constrained by specific kinematics. For instance, it has been shown that the visuo-manual tracking of a spotlight was optimal when the spotlight motion complies with biological rules such as the so-called $1/3$ power law, establishing the co-variation between the velocity and the trajectory curvature of the movement. The visual or kinesthetic perception of a geometry induced by motion has also been shown to be constrained by such biological rules. In the present study, we investigated whether the geometry induced by the visuo-motor coupling of biological movements was also constrained by the $1/3$ power law under visual *open* loop control, i.e. without visual feedback of arm displacement. We showed that when someone was asked to synchronize a drawing movement with a visual spotlight following a circular shape, the geometry of the reproduced shape was fooled by visual kinematics that did not respect the $1/3$ power law. In particular, elliptical shapes were reproduced when the circle is trailed with a kinematics corresponding to an ellipse. Moreover, the distortions observed here were larger than in the perceptual tasks stressing the role of motor attractors in such a visuo-motor coupling. Finally, by investigating the direct influence of visual kinematics on the motor reproduction, our result conciliates previous knowledge on sensorimotor coupling of biological motions with external stimuli and gives evidence to the amodal encoding of biological motion.

Keywords: Action-perception, Biological movements, Illusion

1. Introduction

Being able to perceive and interact with the surroundings is essential for human beings, not only to properly communicate with their congeners, but above all, to react with appropriate movements regarding external stimuli. Many studies have shown that human (or more generally biological) movements are constrained by specific kinematics. In particular, in the case of two dimensional arms movements, it was shown that motion tangential velocity v_t co-varies with the curvature C of the arm trajectory according to the so-called 1/3 power law: $v_t(t) = KC(t)^{-1/3}$ with K a constant depending on the mean velocity of the movement [1,2]. From a perceptual point of view, it has been demonstrated that the visual perception of the trajectory is altered when the movement kinematics are non-biological, i.e. when the velocity deviates from the 1/3 power law [3,4]. For instance, a spotlight moving along a geometrical circle with a velocity that corresponds to an elliptical trajectory is perceived as moving along an ellipse [3]. Similarly, the kinesthetic perception of the geometry of a movement induced by a mechanical arm trailing a circular motion with a velocity corresponding to an elliptical movement is perceived as elliptical [4]. From the sensorimotor point of view, Viviani, Baud-Bovy, and Redolfi also showed that the kinesthetic tracking of an induced movement [4] and the visuo-manual pursuit tracking of a moving spotlight [5] were constrained by the 1/3 power law. Taken together, all these considerations suggest that humans base their perceptual judgments on the rules of biological motion and in particular, according to the biological plausibility of the perceived motion. Nevertheless, the influence of the biological plausibility of a visual motion on the intrinsic visuo-motor coupling has not been so far investigated and would extend the previous results. Moreover the comparison between the perceptual distortions induced by non-biological kinematics – either visual or kinesthetic – and the distortion induced by the motor reproduction (involving both perception and movement production) would give relevant information about the differences between the

perception of movement across different modalities and its perceptual-motor reproduction.

In the present work, we investigated the visuo-motor coupling between hand movement and a visual motion, and whether the produced geometry induced by this coupling was biased according to visual kinematics complying or not with the $1/3$ power law. In order to explore the direct influence of kinematics, we adapted the experiments conducted by Viviani et al. [3,4] in visual *open loop* configuration in which extrinsic visual feedback is no longer available to adjust the produced movement (subjects do not see their hand movement during the task). Hence, we asked subjects to synchronize their drawing movement on a graphic tablet with a spotlight moving along a circle with a velocity complying or not with the $1/3$ power law. Under such configuration which avoided the visual feedback, we assumed that the motor execution is primarily modified by the kinematics of the visual stimulation. The results were analyzed regarding the perceptual results from Viviani et al. [3,4]. Note that while studies concerning sensorimotor synchronization often focused on the temporal aspect of the synchronization ([6] for a review), we here focused on the geometrical distortions of the motor reproduction as a first step. In particular we compared our results with the distortions observed in the visual [3] and kinesthetic [4] experiments. Finally, results were discussed regarding the assumption of an amodal coding of biological rules constraining both perceptual and motor processes.

2. Methods

2.1. Participants

Seventeen right-handed subjects (2 women) of average age 28.5 years ($SD = 8$) voluntarily took part in the experiment. They had normal or corrected vision. All the subjects were naive to the experiment and gave their informed consent before beginning the experiment in accordance with the standards of the local ethical board of Aix-Marseille

University.

2.2. Stimuli

The visual stimuli were produced by a 6mm diameter white moving spotlight displayed on a black background screen based on a method proposed by Viviani and colleagues [3,4]. The geometrical trajectory of the spotlight was circular, had a radius of $R = 6.36$ cm and a perimeter that equaled 40 cm. The spotlight followed the circle with three different *visual kinematics* so that its motion complied or not with the 1/3 power law. For that purpose, we considered two coupled harmonic oscillators that differed by a relative phase noted RP_{vk} . The system can define an elliptical motion in an appropriate coordinate system $(x_{vk}(t), y_{vk}(t))$ as follows:

$$\begin{cases} x_{vk}(t) = A \cos\left(\frac{2\pi}{T}t\right) \\ y_{vk}(t) = A \cos\left(\frac{2\pi}{T}t + RP_{vk}\right) \end{cases}$$

where A is the amplitude of the motion, x_{vk} and y_{vk} the coordinates of the motion, T the period of the oscillators and t the time. This model has been proposed for planar hand movements such as drawing or handwriting [7,8] and has been shown to derive from biomechanical constraints [9]. Three visual kinematics were thus considered (see Figure 1). Firstly, when the relative phase $RP_{vk} = 90^\circ$ and $A = R$, a circular movement was generated. Since the geometrical visual trajectory used in this experiment was circular, the motion was in this case biological with a constant velocity that equaled 22.2 cm.s^{-1} . In the second and third situations $RP_{vk} = +/-45^\circ$ and $A = 6.92$ cm, the motion kinematics corresponded to a biological elliptical motion along an ellipse of eccentricity .91. These two situations were non-biological since elliptical kinematics was combined with the circular geometrical trajectory. They differed by the sign of the relative phase, meaning that the accelerations of the spotlight either took place in the horizontal parts ($RP_{vk} = 45^\circ$) or in the vertical parts ($RP_{vk} = -45^\circ$) of the circle. The

spotlight velocity of these situations varied between 13.8 cm.s^{-1} and 31.6 cm.s^{-1} . In all situations, the spotlight motion was counterclockwise. Each visual motion contained 19 complete cycles of period $T = 1.8\text{s}$ and therefore lasted for 34.2s .

2.3. Apparatus

The experimental set-up is presented in Figure 2. The experiment was carried out in a quiet room in the dark. Subjects were seated in front of a computer screen of 1280×1024 resolution (DELL 1907fp) and a graphic tablet (Wacom Intuos5). The experimenter was present in the room during the whole experiment to manage the generation of visual stimuli on a separate personal iMac computer (not visible to the subjects). The stimuli were generated in real time on the iMac with the Max software (<http://cycling74.com>). The visual stimuli were displayed on the DELL screen connected to the iMac via a DVI interface. The display rate was set to 60 Hz. The spotlight motion was generated by 108 sequentially displayed pairs of coordinates for smooth motion perception. A wooden board was set above the graphic tablet so that subjects did not see their hand during the task. Hand movements were recorded with the graphic tablet at a sample rate of 129 Hz and with a spatial precision of 5.10^{-3} mm .

2.4. Task

The experiment began by a familiarization with the task. Subjects were instructed to synchronize their gestures with visual motions by using a pen on the graphic tablet for the entire duration of the visual motions (for the 19 complete cycles) without seeing their drawing hand (i.e. in a visual open loop configuration, see Figure 2). The familiarization lasted as long as necessary to ascertain that subjects properly understood the task. They were encouraged to imagine that they were producing the motion themselves and asked to perform hand movements in a counterclockwise direction as the visual stimuli. They were also asked to lock

their right hand wrist, to maintain their elbow lifted above the table and to generate the movement solely with their forearm and shoulder. Finally, they were also asked to lock their upper body in order to avoid postural oscillations that could influence the movement produced.

2.5. Data analysis

Data collected on the graphic tablet were analyzed with respect to the relative phase noted RP_{drawn} of the reproduced shape resulting from the synchronization of the drawing movement with the visual motion. For each trial, we calculated the mean value of RP_{drawn} on the last 10 out of the 19 drawn cycles. To compute RP_{drawn} , we firstly computed the eccentricity e of the reproduced shape (i.e. a variable characterizing the flatness of the shape) of each of the last 10 cycles by using the inertial tensor method proposed by Vivani et al. [4]. The 10 values of e were then transformed into relative phases thanks to the following formula: $RP_{\text{drawn}} = 2 \arctan \sqrt{1 - e^2}$ and were finally averaged for each subject and then between subjects for each situation.

In addition to the analysis of the relative phase, the variability of the motor reproductions was evaluated by considering the normalized standard deviation of the semi-major and semi-minor axes of the reproduced enclosed movements. For each trial, the semi-axes values were calculated as in the previous analyses from the last 10 out of the 19 drawn cycles with the inertial tensor method [4]. The normalized standard deviations $\sigma_{N,\text{major}}$ and $\sigma_{N,\text{minor}}$ in percents were then calculated with the following formulas:

$$\begin{cases} \sigma_{N,\text{major}} = 100 \frac{\sigma(\overline{S_{\text{major}}})}{\overline{S_{\text{major}}}} \\ \sigma_{N,\text{minor}} = 100 \frac{\sigma(\overline{S_{\text{minor}}})}{\overline{S_{\text{minor}}}} \end{cases}$$

where $\overline{S_{\text{major}}}$, $\overline{S_{\text{minor}}}$, and $\sigma(\overline{S_{\text{major}}})$, $\sigma(\overline{S_{\text{minor}}})$ are the semi-axes mean values and standard

deviation respectively. The normalization of the standard deviations by the mean values for each trial enables to compare the variability that may vary in size between subjects' performance.

2.6. Statistical analysis

A repeated measures ANOVA was performed with Statistica© software to evaluate the effects of the three different visual kinematics on the relative phase. The analysis of the distortion between the reproduced shapes and the circular geometry of the visual motion in terms of flatness was performed by means of a one-sample two-tailed t-test between the relative phase of the reproduced shapes RP_{drawn} and the mean $RP = 90^\circ$ in the three visual conditions. A two-way repeated measures ANOVA was also performed on the semi-axes' normalized standard deviations, i.e. (2 semi-axes) x (3 visual conditions), to evaluate whether one semi-axis was drawn with more precision than the other one, and to evaluate the influence of the visual conditions on the semi-axes variability. For the two repeated measures ANOVAs, significant effects were further analyzed with Neuman-Keuls (NK) post-hoc tests. We previously ensured that the requirements for running parametric statistics were satisfied. The significance level of the p-value was set to .05 for the analysis.

3. Results

3.1 Distortion of the reproduced shapes

The geometry of the reproduced shapes is remarkably distorted by non-biological kinematics (main effect of the visual kinematics: $F_{2,32} = 7.65$, $p = .0019$, $\eta^2 = .992$). The elliptical kinematics ($RP_{vk} = \pm 45^\circ$) clearly flatten the drawn shapes towards ellipses (see Figure 3C; NK: $p = .003$ in the two non-biological conditions). Circles trailed with biological kinematics are reproduced with a mean relative phase of 76.55° (CI95% [74.61° 78.49°]),

whereas circles trailed with non-biological kinematics provide a mean relative phase of 69.44° (CI95% [66.54° 72.34°]) and 68.58° (CI95% [63.44° 73.72°]). These results reveal that visual kinematics bias the visuo-motor coupling since the reproduced shape is altered by non-biological kinematics. Moreover, it should be noted that even in the biological condition, the reproduced shape is distorted into an elliptical one (Two-tailed t-tests between RP_{drawn} and 90° : $RP_{vk} = 90^\circ$: $t(16) = -14.56$, $p < .001$; $RP_{vk} = 45^\circ$: $t(16) = -15.16$, $p < .001$; RP_{vk} : $t(16) = -8.70$, $p < .001$).

In addition to the relative phase distortions, the variability of the semi-axes also depends on the visual condition (main effect of the visual kinematics: $F_{2,32} = 9.13$, $p = .001$, $\eta^2 = .363$). For the biological condition ($RP_{vk} = 90^\circ$) the semi-axes vary by 8.1% (CI95% [7.6 8.5]), whereas the non-biological conditions ($RP_{vk} = 45^\circ$ and $RP_{vk} = -45^\circ$) lead to significantly larger normalized standard deviations: 10.6% (CI95% [9.8 11.4]; NK: $p < .001$) and 9.5% (CI95% [8.8 10.1]; NK: $p = .003$) respectively. No significant differences appear between the two non-biological conditions (NK: $p = .13$). It should also be noted that the semi-major axis variability 8.51% (CI95% [8.13 8.86]) is significantly smaller the semi-minor one 10.3% whatever the visual condition (CI95% [9.92 10.67]; main effect of semi-axes: $F_{1,16} = 21.8$, $p < .001$, $\eta^2 = .576$). At last, a significant interaction between the semi-axes and the visual conditions was observed ($F_{2,32} = 5.46$, $p = .009$, $\eta^2 = .255$). This revealed that for the semi-minor axis, the variability was smaller in the biological condition than in the two non biological conditions (NK: 45° : $p < .001$ and -45° $p < .001$). For the semi-major axis, only the 45° non biological condition provided a significantly larger variability than the biological one (NK: 45° : $p = .017$ and NK: -45° : $p = .79$) and the difference between 45° and -45° was marginally significant (NK: $p = .059$). This marginally significant effect between the two non-biological conditions for the semi-major axis would suggest a possible effect of the orientation of the non-biological motion on the precision of the reproduced movement.

3.2 Comparison with the perceptual illusions

The table 1 presents the results of this experiment next to those of Viviani and colleagues in the purely perceptual situations, i.e. visual [3] and kinesthetic [4]. In order to compare them, data from Viviani and colleagues, which were expressed in eccentricity, were converted into relative phase. It is noticeable that the distortions observed in our experiment are clearly larger than the perceptual ones observed by Viviani and colleagues. In particular, the distortions induced by the non-biological situations in the visuo-motor experiment are at least twice larger than those in the visual and kinesthetic ones. Moreover it is noticeable that in the visuo-motor experiment the circles are distorted by 17.57% although the visual stimulus was biological. While in the perceptual judgments, either visual or kinesthetic, the motions are perceived circular with a distortion up to a maximum of 1.01%.

4. Discussion

In this study, we showed that the geometry induced by the visuo-motor coupling in visual *open* loop configuration, i.e. when the hand could not be visually controlled for achieving the task, was biased for visual kinematics that do not comply with the $1/3$ power law. For a circular trajectory, we observed that the subjects tend to reproduce elliptic shape when the visual circle was trailed with elliptical (and consequently non-biological) kinematics. To our knowledge, such a visuo-motor coupling has been studied so far only under closed loop control [5] hence involving a visual feedback on the produced movement. Indeed, Viviani and colleagues conducted a set of experiments revealing that the $1/3$ power law constrains both the visual [3] and kinesthetic [4] perception of the geometry, the kinesthetic tracking [4], and the visuo-manual tracking [3]. They suggested the assumption of an amodal coding of biological movements regarding perceptual and tracking – either visual

or kinesthetic – tasks. Hereby, we extended these previous experiments by considering an open loop configuration (without a visual feedback) and we confirmed that the geometry induced by the visuo-motor coupling with motion was also constrained by the $1/3$ power law. Our results fully complement the proof of such amodal coding assumption.

In addition to the distorted flatness, the semi-axes variability of the reproduced elliptical shapes was larger in the non-biological conditions than in the biological one stressing that non-biological circular motions are harder to reproduce. Moreover less variability was observed in the semi-major axis plan than in the semi-minor one across the three visual conditions. This difference might be interpreted with respect to the velocity profile of the visual trailing motion, which is maximum in the flattest parts of the shape corresponding to the semi-minor axis. It is indeed expectable that the movement is less precise in these parts associated with high velocity than in those with the slowest velocity, i.e. in the semi-major axis plan. At last, the significant interaction between the semi-axes and the visual conditions sheds further light on the effect of non-biological motion orientation on the reproduced motion. Even if the relative phase did not elicit differences between the two non-biological motions, this suggests that the semi-major axis was drawn with more consistency for -45° than for 45° . The effect of verticality on the perceived and/or reproduced movement is in line with previously observed effects by Viviani and colleagues in perceptual [3] and perceptual-motor experiments [4]. Nevertheless, specific experiments are necessary to determine the effect of non-biological motion orientation on the reproduced shape.

In particular, it is interesting to compare our results with those obtained in the purely perceptual – visual or kinesthetic – illusions highlighted by Viviani et al. [3,4]. We found larger distortions in our visuo-motor experiment than in Viviani et al.'s perceptual tasks. Moreover, it is noticeable that whatever the visual condition, and even in the biological condition, the motor reproductions are significantly flatter than the actual circular motions

displayed on the screen. This can be due to the effect of elliptic motor attractors: when we draw quickly an enclosed shape such as a circle, we indeed naturally tend to draw an elliptic motion [10]. In our experiment, we hypothesize that even for the visual biological circular motion, the reproduced circle was distorted as subjects had no visual feedback on their movements and were thus influenced by elliptical motor attractors [8, 10, 11, 12]. In the non-biological situations, the effects were still larger due to the elliptical visual kinematics that induced accelerations in opposite parts of the trajectory that added up with our natural tendency to draw elliptic motion. These observations shed light on the differences between the purely perceptual processes and the visuo-motor ones. In particular this points out the larger influence of biomechanical synergies in the visuo-motor coupling task than in the purely perceptual effects.

5. Conclusions

In this study we showed that visuo-motor coupling of motion was clearly affected by non-biological kinematics in open loop configuration. Our results extend the previous studies of Viviani et al. [3,4] and confirm the amodal encoding of biological motions. The distortion observed here is nevertheless stronger than the perceptual ones and might be due to a motor attractor stressing that enclosed movements are naturally attracted by an elliptic stable state. While we focused here on the produced geometry induced by the visuo-motor coupling, it might be of interest to further study the properties of the temporal sensorimotor synchronization between the performed movements and the trailing one [6,11]. In particular, is the velocity of the synchronized movement affected by the different visual kinematics? The analysis of the coordination could for instance shed light on the influence of non biological kinematics on the stability of motor attractors.

In a broader issue, this study is a preliminary step to explore sensorimotor coupling

under different modalities. In particular, current studies are being conducted to understand how the auditory modality, that is able to evoke biological or non-biological motions independently from geometric information [13], might also influence the produced geometry. Such studies may lead to propose relevant framework to explore perception of biological motions in a multisensory context.

6. Acknowledgments

This work was funded by the French National Research Agency (ANR) under the MetaSon project (ANR-10-CORD-0003) in the CONTINT 2010 framework and the SoniMove Project (ANR-14-CE24-0018).

7. References

1. Lacquaniti, F., Terzuolo, C., Viviani, P., The law relating the kinematic and figural aspects of drawing movements, *Acta Psychol.* 54 (1983) 115-130.
2. Viviani, P., Flash, T. Minimum-jerk, two-thirds power law, and isochrony: converging approaches to movement planning. *J. Exp. Psychol Human*, 21 (1995) 32–53.
3. Viviani, P., Stucchi, N., The effect of movement velocity on form perception: Geometric illusions in dynamic displays, *Atten Percept. Psycho.*, 46 (1989) 266-274.
4. Viviani, P., Baud-Bovy, G., Redolfi, M. Perceiving and tracking kinesthetic stimuli: Further evidence of motor–perceptual interactions. *J. Exp. Psychol Human*, 23 (1997) 1232-1252.
5. Viviani, P., Campadelli, P., Mounoud, P., Visuo-manual pursuit tracking of human two-dimensional movements. *J. Exp. Psychol Human*, 13 (1987) 62-78.
6. Repp, B. H., Su, Y.-H., Sensorimotor synchronization : a review of recent research (2006–2012). *Psychon. B. Rev.*, 20 (2013) 403–452.
7. Hollerbach, J. M., An oscillation theory of handwriting, *Biol. Cybern.*, 39 (1981) 139-156.
8. Athènes, S., Sallagoity, I., Zanone, P.-G., Albaret, J.-M., Evaluating the coordination dynamics of handwriting, *Hum. Mov. Sci.*, 23 (2004) 621–641.
9. Haken, H., Kelso, J. S., Bunz, H., A theoretical model of phase transitions in human hand movements. *Biol. Cybern.*, 51 (1985) 347-356.

10. Dounskaia, N., Van Gemmert, A. W. A., Stelmach, G. E., Interjoint coordination during handwriting-like movements, *Exp. Brain Res.*, 135 (2000) 127-140.
11. Kelso, J. A. S., Multistability and metastability: understanding dynamic coordination in the brain, *Philos. T. Roy. Soc. B*, 367 (2012) 906-918.
12. Danna, J., Athènes, S., Zanone, P. G., Coordination dynamics of elliptic shape drawing: Effects of orientation and eccentricity, *Hum. Mov. Sci.*, 30(4), (2011) 698-710.
13. Thoret, E., Aramaki, M., Kronland-Martinet, R., Velay, J. L., Ystad, S., From sound to shape: auditory perception of drawing movements. *J. Exp. Psychol Human*, 40 (2014) 983-994.

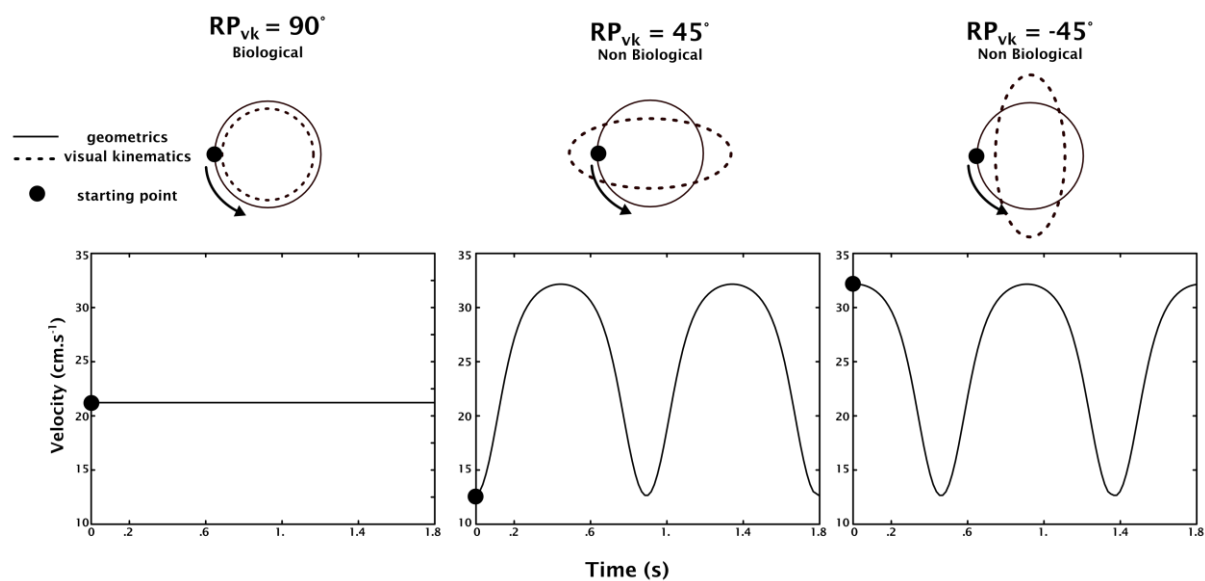


Figure 1. Visual stimuli of the experiment – The first situation ($RP_{vk} = 90^\circ$) is biological and the two others ($RP_{vk} = \pm 45^\circ$) are non biological – Top: the solid line denotes the geometrical trajectory which is always a circle while the dotted line denotes the visual kinematics of the movement. The dot represents the starting point of the spotlight motion on the circle – Bottom: the three associated velocity profiles for one period are presented.

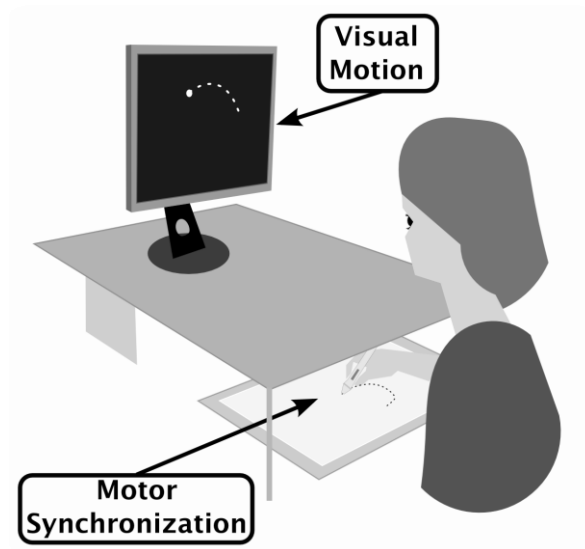


Figure 2. Experimental set-up.

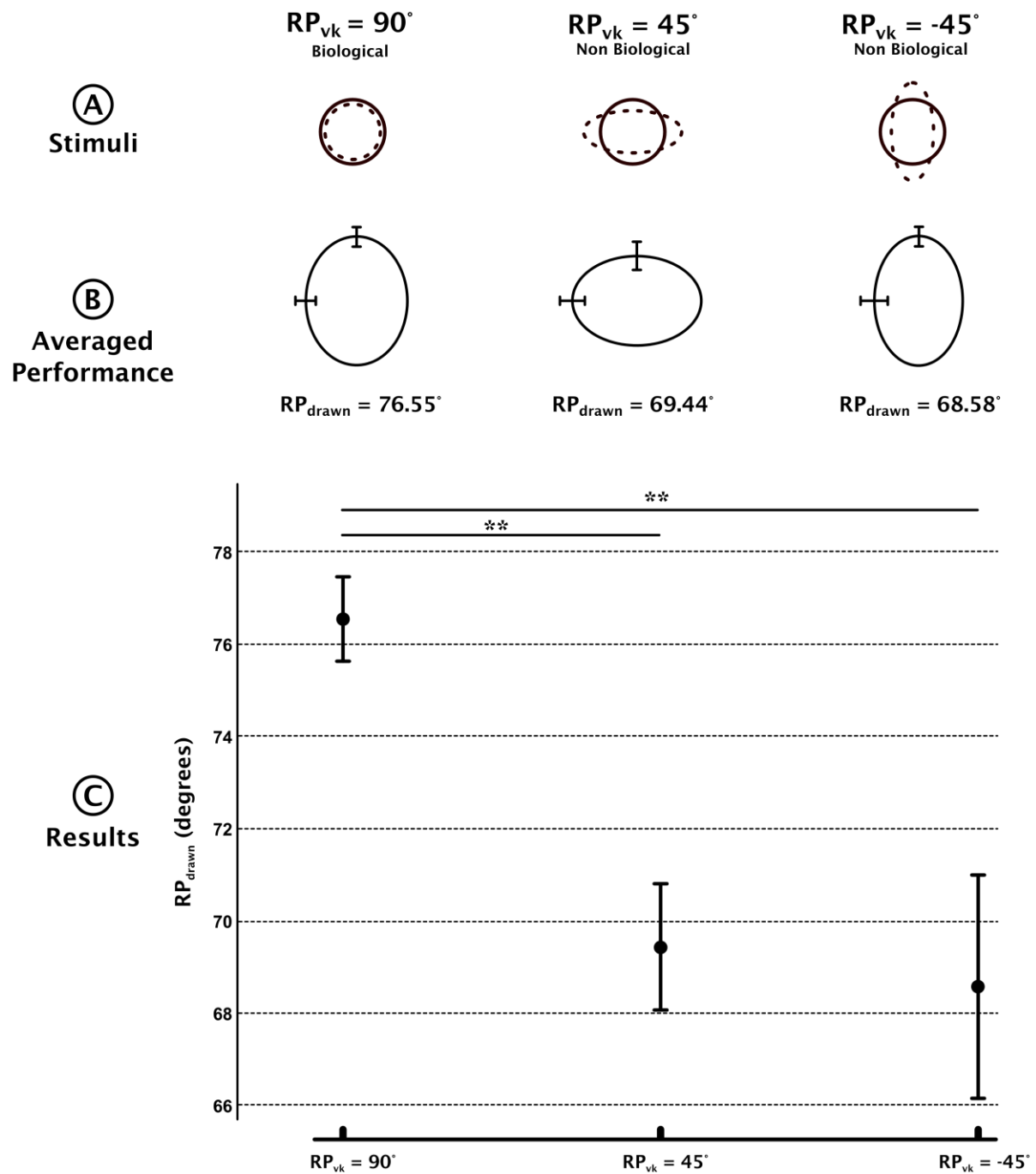


Figure 3 A) Visual Stimuli – B) Averaged performance: Mean (plain line) and semi-axes normalized standard errors (error bars) – C) Results: Mean relative phases and standard errors of the reproduced shapes in the three situations – the significance of the differences between the biological and the two non-biological conditions are denoted by ** $p < .01$.

Table 1. Comparisons with the results obtained in perceptual experiments, i.e. visual [3] and kinesthetic [4]. The averaged relative phase between subjects (RP_{mean}), the distortions Δ_{circle} (in percents) with the circular template, and the distortions $\Delta_{\text{biological}}$ (in percents) in the non-biological situations (NB) with the averaged relative phase in the biological situation are presented.

		90° (B)	45° (NB)	-45° (NB)
Visuo-motor	RP_{mean}	76.55°	68.58°	69.48°
	Δ_{circle}	17.57%	31.23%	29.53%
	$\Delta_{\text{biological}}$		11.62%	10.17%
Visual	RP_{mean}	88.83°	85.73°	87.94°
	Δ_{circle}	1.01%	4.98%	2.34%
	$\Delta_{\text{biological}}$		3.61%	1.01%
Kinesthetic	RP_{mean}	89.72°	87.88°	89.98°
	Δ_{circle}	0.3%	2.40%	0.002%
	$\Delta_{\text{biological}}$		2.0%	-0.01%