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DrawBot: a bio-inspired robotic portraitist

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Abstract

We are developing the control architecture of a portraitist artificial agent called *DrawBot* that reproduces the visuomotor behaviour of a human carrying out a realistic portrait. The visuomotor strategy adopted by *DrawBot* is based on computational models of eye movements in human beings, and on experimental findings on eye-hand coordination in expert draughtsmen. In this paper we present a behavioural model of the visuomotor coordination adopted by a draughtsman, designed in terms of visual routines. Eventually we outline the implementation of the basic routines.

Keywords: computer drawing, creativity, scan-path, visual routines, visuomotor coordination

1 Introduction

Visual creation is a specifically human activity, with a long history and multiple uses. From the perspective of cognitive sciences, the process of carrying out a visual creation can be seen as a goal-directed activity involving several human skills and abilities: visuomotor coordination, evaluation and decision, memory and emotion.

DrawBot is a project that investigates the visuomotor behaviour in realistic drawing, whose practical application is a portraitist artificial agent (*DrawBot*) that carries out realistic drawings from life.

In the field of traditional artificial intelligence, the interest in artificial agents that draw was first witnessed by *AARON* (Cohen 1994); currently there is a growing interest in building robots that exhibit creative behaviour and produce abstract drawings, such as the *Mbots* (Moura and Pereira 2004) and the *Draw-Bots* (Boden, Brown, Husbands and Gere 2006) projects. While those works are not primarily concerned with realistic drawing, recently also two portraitist robots have been implemented (Epiney, Calinon and Billard 2005; Robotlab 2004), but without focussing on the process as carried out by humans; furthermore, painting strategies driven by models of perception are being developed in the field of non-photorealistic rendering (e.g. Collomosse 2006), but without considering the issue of embodiment.

Our motivation for studying realistic drawing is that the behaviour adopted in this case can be considered as a building block of the visual creative behaviour in a broader sense, and it allows us to concentrate on the

physical aspects of the creative process; thus, differently from the above examples, we focus our attention on visuomotor coordination and present a control architecture for *DrawBot* which is based on computational models of eye movements, and on experimental findings on eye-hand coordination in expert draughtsmen.

In this paper we discuss the first stage of the project, which consists in designing a behavioural model of the visuomotor strategy¹ adopted by a draughtsman, and a bio-inspired implementation. This general issue comprises several aspects that should be analysed separately: in particular, our current work aims at modelling the generation of eye movements on the scene and the subsequent generation of hand movements in a biologically plausible way. We leave instead for future work the analysis of the visual activity related to the evaluation of the emerging drawing and to the ensuing feedback on hand movements.

In section 2 we introduce some assumptions that reflect the differences between drawing and other visuomanual tasks. Then in section 3 we present our behavioural model, based on visual routines, which tries to capture the essential features of the draughtsmen's visuomotor strategy. In section 4 we outline the control architecture of the robotic portraitist, and in section 5 we present and briefly discuss some preliminary results.

2 Background and assumptions

A survey of the literature on biological and artificial vision, visual attention and visuomotor coordination, provides us with useful indications for modelling the behaviour of a draughtsman. Indeed, a model of the process of realistic drawing as carried out by a human being should take into account at least the general observations that are discussed in the following.

2.1 Task specificity and visuomotor coordination constraints

Realistic drawing is not considered a 'common' visuomanual activity like driving (Land and Lee 1994), washing one's hands (Pelz and Canosa 2001), or making a sandwich (Hayhoe et al. 2003), neither is it considered a 'common' visual task such as the recognition of a face or a specific object in the scene; in fact, drawing requires a better precision of hand movements and a higher degree of voluntary attentional control of fixations².

Making a realistic portrait of a visual scene is a very specific task, and it imposes rigid constraints on eye-hand coordination. A visuomotor strategy can be clearly observed on subjects involved with this task, even if the strategy can vary significantly among different subjects.

As a starting point to characterize such strategy, we will make a number of hypotheses that try to capture the essential features that distinguish drawing from other tasks, both with respect to the a priori requirements and the observed behaviour.

For what concerns fixations on the scene to be portrayed, our first hypothesis is that the whole scene is to be scanned by the gaze centre, in contrast to the behaviour observed in most natural visual and visuomanual tasks: usually, in these cases saccades (see endnote 2) directed towards few key points can be sufficient to identify or manipulate the object of interest (Yarbus 1967).

On the other hand, in situations where subjects passively view pictures, it appears that fixations are distributed over the whole scene; nevertheless, the scanpath (see endnote 2) seems to be guided mainly by the properties of the image, and it can be modelled e.g. by a pre-attentive strategy (Itti and Koch 2001) or as a constrained random walk (Boccignone and Ferraro 2004) upon the saliency map of the image. Contrarily to this, we make the hypothesis that when the task is realistic drawing, the sequence of fixations on the scene is

determined in such a way that tracing hand movements are continuous: for instance, one possible realization of such a scanpath would be a coarse-grained edge following, with the centre of gaze moving in successive discrete steps, along the contour of the object that is to be portrayed.

Thus, any visuomotor strategy adopted for realistic drawing should satisfy these constraints: the whole scene must be scanned by the centre of gaze, and the scanning should follow a regular sequence. Similar strategies were actually observed in recent experiments (Findlay and Brown 2006) on a spatial search task, and described as direction based and based on local perceptual information.

This kind of behaviour, while functional to realistic drawing, seems rather counter-functional to recognition or other perceptual operations. Furthermore, drawing experiments on subjects affected by visual agnosia showed that patients were able to draw objects that they could neither recognize nor describe verbally (Pylyshyn 1999). These facts can be understood considering that most recent research in neurobiology witnesses that the visual system is tailored to accomplish two major functions: the first one is the creation of an internal model—or ‘percept’—of the external world (vision for perception); the second one is to keep the control of an object-directed action (vision for action) (Goodale and Humphrey 1998).

Therefore, if one refers to the vision for perception vs. vision for action schematization, one could state that mainly the action stream of the visual system seems to guide the visual activity that precede hand movements in realistic drawing.

For sure, the perception stream too is involved while drawing, especially when fixations are made to identify objects in the scene or to evaluate the emerging result.

These are purely perceptual operations, and the manual execution is interrupted several times during the making of a portrait

(Miall and Tschalenko 2001) in order to accomplish them.

As a third hypothesis we propose that, when more than one object can be identified in the scene, a preliminary segmentation of the scene is made, in such a way that each single object can be portrayed separately in sequential order.

This hypothesis too reflects a specificity of drawing with respect to common visual (Pylyshyn 2000) and visuomanual (Hayhoe et al. 2003) tasks, since in those cases gaze is shifted back and forth among different objects of interest.

Thus, the comparison of the drawing task with different activities, and the hypotheses we introduced, both highlight the requirement of a tight strategy for controlling fixation locations and the sequence of saccades; a high degree of voluntary control is involved, or, in other words, a deep level of cognitive penetration (Pylyshyn 1999) of the visual system seems to be achieved when making a realistic drawing.

3 Behavioural model

The above considerations lead us in a natural way to think that a visuomotor strategy for drawing can be learned and refined with the experience. Support to this idea comes from experimental evidence both at the ‘low level’, i.e. the level of motor control of single eye and hand movements, where the fixation duration and frequency are found to be quantitatively different in expert and non-expert draughtsmen (Tschalenko et al. 2003); and at the ‘high level’ of management of concurrent ‘low level’ operations, in which case the evidence is provided mainly by the observation of a regular execution cycle in a professional portraitist at work.

3.1 ‘High level’ visuomotor coordination

Almost any complex visuomanual task can be described as composed by concurrent subtasks

which require specific processing of the visual input; the centre of gaze, the control of which is needed to accomplish each subtask, must then be considered as a resource which is not easily shared and instead must be sequentially allocated (Hayhoe and Ballard 2005).

While drawing, the control of eye movements is required to accomplish at least the following purposes:

- 1 scene segmentation and feature extraction (acquire information on the scene in order to plan hand movements);
- 2 feedback control (acquire information about hand movements in order to control them);
- 3 evaluation (acquire information to decide if the emerging result is satisfactory).

It is reasonable to think that a great deal of drawing strategies exist, due to different teaching methods and personal skills; nevertheless, we hypothesize that the strategies learned by professional portraitists, independently from the differences among the individuals, should be functional to decompose the drawing task into simpler subtasks.

As a matter of fact, behavioural observations on a professional portraitist (Miall and Tchalenko 2001) indicate a possible implementation of a 'high level' strategy, as a more or less regular oscillation between the two visual behaviours that in section 2.1 we associated to the perception and the action pathway respectively:

- 1 global look at the scene, for segmentation or evaluation;
- 2 localized eye movements on the scene and on the canvas for hand motion planning and control.

We interpret this oscillation as functional to keeping separate two visual behaviours that are significantly different, since the first is global in nature and perceptual in purpose, while the second is local and aimed at producing a precise hand movement.

Notice that the second visual behaviour can be further decomposed, and the way this

is done by the portraitist observed in (Miall and Tchalenko 2001) is by adopting an execution cycle which is schematically divided as follows:

- 1 fixation on the scene;
- 2 fixation on the canvas;
- 3 hand movement;
- 4 fixation on the canvas.

Not only such a cycle indicates a clear separation of the low level operations related to motion planning (i.e. feature extraction and subsequent generation of motor commands) and motion control (i.e. generation of corrective motor commands when necessary), but it also provides the portraitist with a precise temporal sequence of operations to carry out.

3.2 'Low level' operations

In interpreting the cycle discussed above, we make the hypothesis that, the low level strategies are combined so as to obtain quite specific information; this situation is well described by the concept of visual routines (Ullman 1984), i.e. specialized procedures that direct eye movements and guide visual activity to extract task-specific information.

At least two routines can be identified in the above cycle.

The first routine includes fixations of point 1. The oculomotor strategy (see endnote 1) produces fixations that proceed along the contours of the object of interest; then, the visual input is processed to extract just the kind of geometrical information (e.g. the orientation and curvature radius of a segment) that is needed to plan the subsequent hand movement.

The second routine manages the fixations of points 2 and 4, providing a feedback on hand movements. The most frequently observed visuomotor strategy consists in the gaze centre following the pencil tip in a stepwise fashion; this can be called close pursuit (Tchalenko 2006) to differentiate it from smooth pursuit where the gaze centre follows continuously something moving in the visual field.

3.3 The model at a glance

Here we present a simple behavioural model (see Figure 1) that takes into account most of the above considerations.

The model adopts the concept of visual routines, and reproduces just one possible ‘high level’ strategy for their management. The visual routines we consider can be classified in two pairs: two perceptual routines that require global information on the scene:

- * ‘Segmentation’
- * ‘Evaluation’

and two action-related routines that require mainly local information:

- * ‘Feature extraction’ for motion planning
- * ‘Hand feedback’ for motion control.

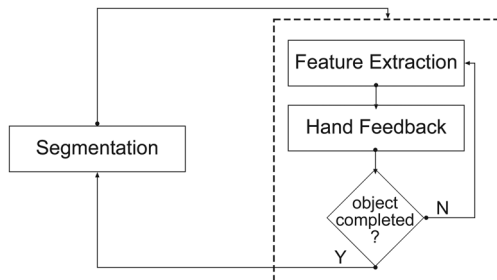


Figure 1. Schematic view of the behavioural model based on visual routines.

The ‘Segmentation’ routine is called first; it parses its input image—the whole scene—into a list of separate objects. Then the first object in the list is passed on as the output, and the corresponding portion of the image is flagged in order to exclude it in subsequent calls to this routine.

The object is then passed as the input to the ‘Feature extraction’ routine: a portion of the object, corresponding to the current location of fixation, is chosen, processed into motion parameters, and flagged.

Next, control is passed to the ‘Hand feedback’ routine: now the input is the image of the hand moving across the canvas, and the elaboration produces corrective motor commands whenever the hand trajectory is found

to be different from the planned one.

When the hand movement terminates, either ‘Segmentation’ or ‘Feature extraction’ can be called, depending on if the current object has been completely reproduced or not.

Note that we have not included the ‘Evaluation’ routine, since there is still a complete lack of experimental studies regarding this part of the drawing task (but see Kozbelt in press for the dynamic evaluation of non-realistic paintings).

Far from being predictive, nonetheless this model provides us with a framework for implementing some of the visual routines presented, allowing for a comparison of the outputs against data obtained from suitably designed experiments.

4 Visual routines implementation

The system we present here implements the ‘Segmentation’ and ‘Feature extraction’ routines; nevertheless these are sufficient to produce the motor plans to control a robotic arm, and constitute the first step towards the robotic implementation of the behavioural model. In this section we first explain the implementation criteria for the ‘Segmentation’ and ‘Feature extraction’ routines, and then outline the whole architecture which includes the generation of motor commands. The model strives to be biologically accurate and therefore the design reflects the modular architecture of the visual system.

4.1 The implementation criteria

With respect to the ‘Segmentation’ routine, we assume that this perceptual operation is accomplished through two modules for ‘Early vision’ and ‘Perception’ (see Figure 3), which are sufficient to transform an image into a list of regions (objects) that are evaluated as significantly different from the background. Standard computer vision techniques are available to implement this function (Boccignone, Ferraro and Napoletano 2004).

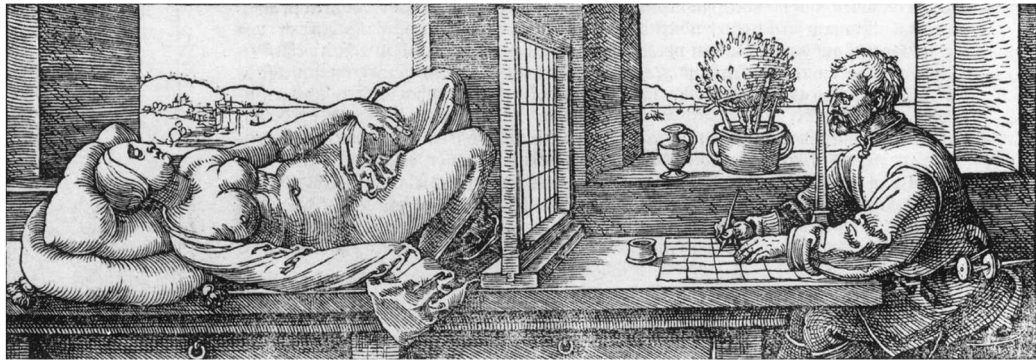


Figure 2. Albrecht Dürer, *The Goddess and the Craftsman*, 1525.

The ‘Feature extraction’ routine is distributed across different modules, mainly because we combine different criteria to generate the gaze locations.

In fact, an old idea in psychology (James 1981) suggests that subjects selectively direct attention to objects in a scene by using both bottom-up, image-based saliency cues and top-down, task-dependent cues.

Recently, a computational model that accounts for bottom-up gaze allocation has been proposed (Itti and Koch 2001), based on the concept of saliency map, namely an explicit two-dimensional map which encodes the saliency of objects in the visual environment.

In this model, competition among neurons gives rise to a single winning location (Focus Of Attention—FOA), which corresponds to the next attended target. Inhibition of the currently focused location automatically allows the system to attend to the next most salient one.

In order to automatically determine the FOAs, we propose an approach that, differently from (Itti and Koch 2001) and more similarly to (Boccignone et al. 2005), does not rely on purely bottom-up mechanism, but attempts to account for the cooperation/competition between bottom-up and top-down mechanisms; in Figures 4 and 5 the scanpaths obtained in the two cases are shown.

The expertise of a draughtsman is the top-

down contribution, provided here in the form of a fixed visuomotor strategy. Such strategy, encoded by a visual grid which is reminiscent of the renaissance technique illustrated in Dürer’s perspective machines (see Figure 2), directs the gaze from a FOA to the subsequent one along the contours of the objects.

Finally, each time a FOA has been computed, the core of the ‘Feature extraction’ routine is performed, i.e. the extraction of the image parameters which are relevant for hand-trajectory planning. We implement this part of the routine using specialized classifiers sensitive to orientation, curvature and corner features (Forsyth and Ponce 2003).

4.2 The functional architecture

Now we move to the modular architecture (see Figure 3) whose function is to provide us with a sequence of fixation points on the input image (see Figures 4 and 5) and the corresponding motion parameters that will be used to control a robotic arm.

Two modules, namely ‘Early visual analysis’ and ‘Sensorimotor prior knowledge’, are responsible for providing pure bottom-up and top-down task dependent information, respectively. The other modules are engaged in active and joint exploitation of both kinds of information so as to generate the final drawing act.

4.2.1 'Early visual analysis'

From an input image, early visual features such as colour opponents, intensity and orientation are computed in a set of feature maps based on retinal input and represented using pyramids. Then, surround-surround operations are implemented as differences between a fine and a coarse scale for a given feature (Itti and Koch 2001). One feature type encodes for on/off image intensity contrast, two encode for red/green and blue/yellow double opponent channels and four encode for local orientation contrast.

The contrast pyramids for intensity, colour and orientation are summed across scales into three conspicuity maps and, finally, are sent to the 'Fusion' module.

4.2.2 'Sensorimotor prior knowledge'

The module implements the drawing strategy by exploiting prior knowledge on drawing. In the proposed *DrawBot* prototype such prior knowledge, as shown in Dürer's woodcut, is shaped as a drawing frame or 'grid aid'.

Such knowledge is forwarded to and conditions both the perceptual and FOA scheduling modules, which in turn constrain the generation of movement parameters. In this sense, the drawing strategy is determined on a joint visual and motor planning of the draughtsman's sensorimotor behaviour.

Interestingly enough, such a sensorimotor map could eventually be learned in time as suitable dynamic network (e.g. via a Dynamic Bayesian Network).

4.3.3 'Perception'

In the perceptual pathway, after a preliminary edge linking/grouping leading to image segmentation, the first part of a coarse-grained edge following is performed according to the grid template set by the draughtsman's experience.

The result is a topographic grid-map that encodes which cells are to be foveated and how they are linked to each other.

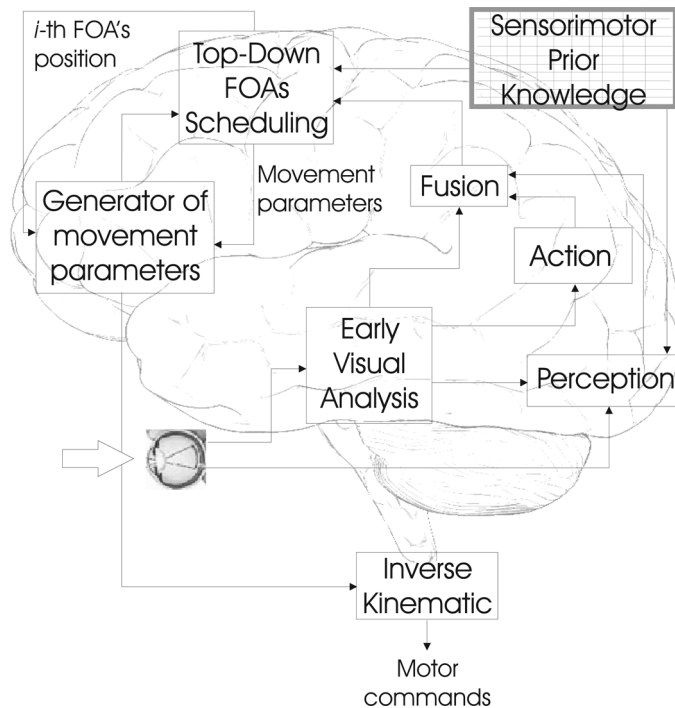


Figure 3. Functional view of the model.

Note that when the 'Evaluation' routine is to be included, also perceptual operations like geometrical features classification should be performed by this module.

4.2.4 'Action'

The 'Action' pathway deals with the extraction of curvature and corner features for hand motion planning, according to the grid template. The feature extraction step produces a set of parameters associated to a given cell in the grid. Such a set represents the trajectory that the arm will follow to reproduce the observed portion of the portrait. The result is a topographic map that encodes the shape of each arbitrary line in the cells' grid.

4.2.5 'Fusion'

Once the visual input is processed, a fusion map is derived in order to select the candidate FOA locations and store the parameters.

For instance, a fusion map could be

obtained by associating, to each cell of the grid, the maximum saliency value in the cell, the shape parameters and the list of linked surrounding cells.

4.2.6 'Top-down FOAs scheduling'

In this module, using the generated 'Fusion map', an ordered sequence of FOAs is derived thus completing the implementation of the edge following. One FOA per time step is forwarded to the next module, and the next FOA is computed upon generator module request.

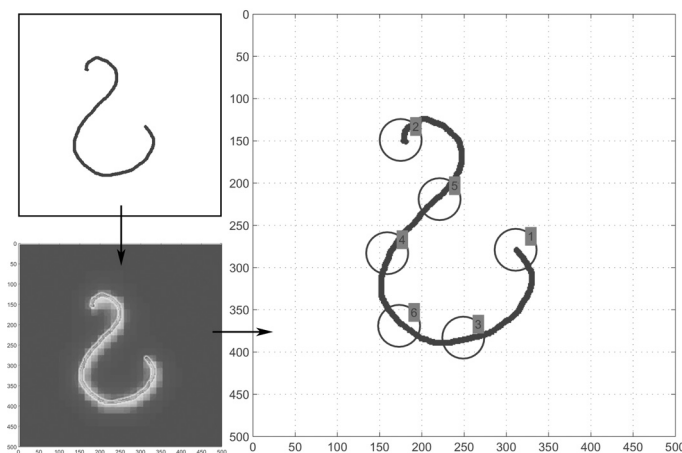


Figure 4. The scanpath produced by a pre-attentive strategy.

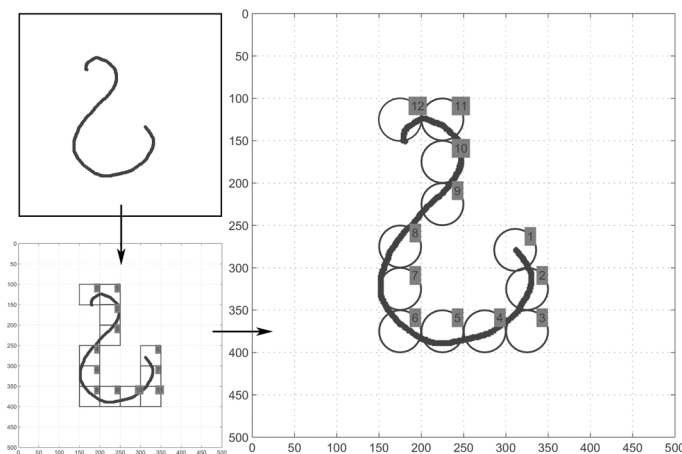


Figure 5. The scanpath obtained introducing the top-down grid aid.

4.2.7 'Generator of elementary movements sequence'

The FOA input provides the location in the grid, namely the cell and the set of parameters needed to reproduce the cell features. Therefore, the module generates a sequence of elementary trajectories that are sequentially sent to the next module.

4.2.8 'Inverse kinematics'

Given the parameters describing a trajectory, this module transforms them into a motor command, on the basis of standard robotic methods (Sciavicco and Siciliano 1996; De Santis et al. 2005).

5 Conclusions and future work

In this paper we presented the first stage of a research project aimed at realizing a robotic portraitist: we proposed a behavioural model of the visuomotor coordination in a drawing task.

We adopted the schematization of visual routines, and outlined the implementation of two routines that are the core of the model. Our preliminary results show that, accounting for the specificity of the drawing task by means of a top-down module influencing eye movements, we are able to generate a scanpath (see Figure 5) that is more suited to produce continuous drawing movements than a scanpath generated following a purely bottom-up approach (see Figure 4).

While we plan to complete our implementation with the routines for 'Hand feedback' and 'Evaluation', the system can already manage motion planning in a robotic portraitist. Furthermore our current implementation generates data that could be confronted with data obtained from suitable eye-tracking experiments.

DrawBot aims at being not only a research project or an artwork, nor just a detournement of the robotic systems technology, but a point of true intersection of science, art and technology.

In its final robotic implementation, *Draw-Bot* will propose an aesthetic experience of the creative process itself, yet presenting at the same time a physical occurrence of it and a permanent creation in the form of a drawing. From the theoretical standpoint, the project aims at furthering current understanding of creativity; although the concept of creativity is hard to capture, and the products of creativity are far more than just handcrafted objects, nonetheless we agree with the philosophical position which states that ultimately the creative behaviour is embodied.

Indeed, we hope that our analysis of visuomotor coordination in a basic visual creative activity such as drawing from life, will provide a contribution to a grounded understanding of visual creativity.

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Notes

¹ The expression ‘visuomotor strategy’ refers to the control of two kind of movements, that can be analysed separately: in the first case ‘visuomotor’ is used equivalently to ‘oculomotor’, as it refers to the generation and control of eye movements; in the second case, ‘visuomotor coordination’ relates to the spatio-temporal coordination of eye and hand movements.

² We follow the standard terminology: a “fixation” is made when the gaze centre does not move

significantly for at least a hundred milliseconds; the eye movement is referred to as ‘saccade’; the sequence of fixations and saccades is called ‘scanpath’.

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