Drawing skill is related to the efficiency of encoding object structure

Florian Perdreau*

Laboratoire Psychologie de la Perception, Université Paris Descartes, Sorbonne Paris Cité, CNRS UMR 8242, Paris, France; e-mail: florian.perdreau@parisdescartes.fr

Patrick Cavanagh

Laboratoire Psychologie de la Perception, Université Paris Descartes, Sorbonne Paris Cité, CNRS UMR 8242, Paris, France; e-mail: patrick.cavanagh@parisdescartes.fr

Abstract. Accurate drawing calls on many skills beyond simple motor coordination. A good internal representation of the target object's structure is necessary to capture its proportion and shape in the drawing. Here, we assess two aspects of the perception of object structure and relate them to participants' drawing accuracy. First, we assessed drawing accuracy by computing the geometrical dissimilarity of their drawing to the target object. We then used two tasks to evaluate the efficiency of encoding object structure. First, to examine the rate of temporal encoding, we varied presentation duration of a possible versus impossible test object in the fovea using two different test sizes (8° and 28°). More skilled participants were faster at encoding an object's structure, but this difference was not affected by image size. A control experiment showed that participants skilled in drawing did not have a general advantage that might have explained their faster processing for object structure. Second, to measure the critical image size for accurate classification in the periphery, we varied image size with possible versus impossible object tests centered at two different eccentricities (3° and 8°). More skilled participants were able to categorise object structure at smaller sizes, and this advantage did not change with eccentricity. A control experiment showed that the result could not be attributed to differences in visual acuity, leaving attentional resolution as a possible explanation. Overall, we conclude that drawing accuracy is related to faster encoding of object structure and better access to crowded details.

Keywords: artists, drawing accuracy, expertise, object structure, object perception, impossible objects.

1 Introduction

Drawing skills vary enormously across individuals, particularly when participants are asked to simply draw an object present in front of them. Here, we will examine if this skill is related to the ability to process object structure when tested in a non-drawing context. The common excuse many of us give for our poor drawing performance is a lack of the motor coordination required to draw the object outlines. However, Tchalenko (2007) showed that novices were as accurate as experts in tracing simple straight and curved lines and experts were only more accurate when copying more complex arrays of lines (Tchalenko, 2009). If it is not simply an advantage in motor control, perhaps experts are able to perceive the target patterns more accurately (Cohen & Bennett, 1997). For example, studies using Navon stimuli (Chamberlain, McManus, Riley, Rankin, & Brunswick, 2013; Drake & Winner, 2011), have shown that observers who are skilled in drawing are better able to disregard the global shape of the stimulus when required to report local shape. In line with this perceptual advantage, Mitchell, Ropar, Ackroyd, and Rajendran (2005) reported that the magnitude of perceptual errors made in a Shepard illusion task was inversely correlated with the participants' drawing skills. Several studies extended this result to perceptual tasks involving shape (Cohen & Jones, 2008) and size constancy (Ostrofsky, Kozbelt, & Seidel, 2012). However, these findings have been challenged by several failures to replicate (McManus, Loo, Chamberlain, Riley, & Brunswick, 2011; Ostrofsky et al., 2012 in their shape constancy task; Perdreau & Cavanagh, 2011, 2013a) calling into question the idea that skill in drawing is related to more accurate (veridical) perception. If accuracy in drawing is not a result of better perception (i.e. more veridical) or motor coordination, where does it come from? In a previous study (Perdreau & Cavanagh, 2013b), we suggested that drawing skill relies on the ability to construct

*Corresponding author.

and maintain a robust internal representation of object structure in visual memory (i.e. the relative spatial position of the object's segments).

This robust internal representation is critical because observational drawing is characterised by many sequential eye-movements between the original object and the drawing, both to encode the to-be-drawn information and to visually control the hand position on the drawing (Coen-Cagli et al., 2009; Land, 2006; Locher, 2010; Tchalenko & Miall, 2009; Tchalenko, 2007, 2009). In particular, Tchalenko (2009) showed that experts in drawing used a segmentation process, encoding and copying the object line by line, while novices tended to process larger areas of the object. This is consistent with previous findings (Cohen, 2005) showing that artists shift their gaze more often between the original object and the drawing than beginners. According to these studies, a segmentation process selects salient portions of the object, reducing the amount of information to be encoded as well as the load on visual memory. Consistent with this hypothesis, Glazek (2012) found that experts in drawing drew more information than novices even when both groups saw the same extent of the target for the same duration. This suggests that more skilled participants may be able to encode more information (bigger chunks, e.g. Gobet & Simon, 1996) at each fixation. It remains unclear, though, how the various segments and chunks can be successfully integrated despite the many changes in retinal inputs and reference frames (Cai, Pouget, Schlag-Rey, & Schlag, 1997; Crawford, Medendorp, & Marotta, 2004).

In a previous study (Perdreau & Cavanagh, 2013b) relating drawing skill to object encoding, we examined the ability to discriminate possible from impossible objects (Schacter, Cooper, Delaney, Peterson, & Tharan, 1991; Schacter, Cooper, & Delaney, 1990) while viewing only a portion of the object viewed through a window, centred on the fovea, that moved with the gaze. We found that more skilled and experienced participants could discriminate an object's structure based on a smaller visible portion of the object. These results suggested that the more skilled and trained participants had a more robust mental representation of the object's global organisation that allowed them to add new portions from small samples acquired across several eye-movements. Many of the requirements of this contingent window task are shared with those of a drawing task—for example, sampling small segments of the object over many fixations and building an internal representation of its global structure.

However, our previous study could not rule out the possibility that the advantage of skilled participants was due to more efficient coding of the object's structure "at a single glance" in addition to a more robust internal representation sequentially built across eye movements. Our present study will address this question of perceptual encoding (how much can be encoded at a glance) versus construction across eye movements. We compared how quickly object processing can operate in a single fixation and related it to participants' drawing skills. We presented possible and impossible objects and varied the stimulus-mask SOA (from 8 ms to 1500 ms) as well as the extent of space covered by the object around the central fixation dot (8° or 28° of width, fixation controlled with an eye-tracker). This allowed us to measure the time required by our participants to encode object structure for a single fixation.

A second question that we addressed was the importance of peripheral information. Tchalenko (2007) has suggested that during drawing, even with gaze locked within a 5° range either around the pencil tip or the currently selected target segment, peripheral information may help to locate the current region of interest within the object's global organisation (e.g. using the paper's edge that is visible in the periphery to check the line's orientation). We assessed the role of peripheral information in a separate experiment in a previous study (Perdreau & Cavanagh, 2013b) where central vision was masked and participants could only see the periphery as they explored the test object. We found no advantage for the skilled participants but in that task participants could see *only* the periphery (masked central vision). In contrast, during a drawing task, the entire structure of the target object is visible so it is possible that peripheral information might help build the representation if central information is also present. Therefore, in addition to varying the stimulus duration in this first experiment, we also varied the size of the object, centred at fixation point (8° or 28°) to see how large an expanse of spatial information could be analysed at a single glance (visual span, Rayner, 1998). If drawing accuracy is related to larger visual spans, then the more skilled participants may be better able to make use of peripheral information (i.e. beyond about 3° of eccentricity) giving them more of an advantage at the larger image size than the smaller.

Finally, classifying an object as possible or impossible requires access to the individual features of the object's structure, its lines and junctions, in order to construct its global representation. During free viewing, the different local features can be scanned with eye movements to access them, but in our experiments, participants had to fixate a central dot throughout the trial (monitored by an eye-tracker)

so that stimuli were inspected without eye movements. This means that when adjacent features are closely spaced and presented in the periphery, they may be hard to access or individuate as they may be crowded. In a second experiment, we examined the role of crowding by varying object size (1° to 12°) at two locations in the periphery (3° or 8°. crowding experiments are typically run at 3° or more in the periphery) to see if participants with better drawing skills were also better able to access closely spaced details in the periphery. It is well known that the presence of flankers surrounding a target can impair the identification, recognition and position encoding of a target (Greenwood, Bex, & Dakin, 2009; Martelli, Majaj, & Pelli, 2005; Toet & Levi, 1992; Whitney & Levi, 2011; Intriligator & Cavanagh, 2001). This phenomenon is commonly referred to as visual crowding and it has been described as a limit of the spatial resolution of visual attention (He, Cavanagh, & Intriligator, 1996, 1997). This effect is dependent on the spacing between items and the critical spacing to produce crowding is a constant proportion of the target's eccentricity (Bouma, 1970). The crowding effect is seen not only for discrete items—targets and flankers—but also for inner features of complex stimuli like faces, where the resulting difficulty in recognising the whole stimulus has been called self-crowding (Martelli et al., 2005). This self-crowding will impose a limitation on the access to local features required to build the object structure in our possible versus impossible task and this limitation should be particularly critical for peripheral presentation where crowding is stronger. Interestingly, it has been shown that attentional resolution, and the ability to individuate features within a cluttered visual environment in periphery, can be enhanced by intensive training (e.g. in video game players; Green & Bavelier, 2007). For this reason, we suggest that one consequence of the years of drawing experience of participants with better drawing skills is to reduce the effects of crowding. They should be able to access individual features of the objects at smaller image sizes in our impossible versus possible object task, when their close spacing will produce significant crowding and performance loss for the less skilled participants.

Although object size was manipulated in both experiments, we expected that size would have different effects in the two tasks. In the first experiment, the size was manipulated with the test object always centred at the fovea (Experiment 1a). This should not affect the degree of crowding because foveally centred scaling maintains the critical ratios of feature spacing to eccentricity (Bouma, 1970). However, the larger size will increase the absolute inter-feature distance, which may require extra time to covertly scan the figure (Chakravarthi & VanRullen, 2011; Donnelly, Found, & Müller, 1999; Kosslyn, Ball, & Reiser, 1978; Posner, Petersen, Fox, & Raichle, 1988) especially if the image size exceeds the participant's perceptual span (Rayner, 1998). In contrast, varying the size of an object that is centred in the periphery (Experiment 2a) will interact with crowding. Increasing its size in this case will increase feature spacing relative to eccentricity for the more peripheral features, diminishing the effect of crowding. We expected that increasing the size, and therefore the spacing between the object's features, leads to better classification performances in this second experiment and that the critical size needed for accurate performance also increases with eccentricity (we tested 3° vs. 8°). However, we hypothesised that more skilled participants have better attentional resolution—they can individuate features with closer spacing—and so they should be able to accurately classify the stimuli at smaller sizes. Again, if the skilled participants use peripheral information more efficiently (have larger visual spans), their performance may not decrease as much at larger eccentricities as that of the novices.

2 General method

2.1 Participants
Novice participants were all recruited from a pool of voluntary participants (RISC), whereas professional artists and art students were recruited in art schools and workshops (n = 10; age = 27.3 ± 1.9, 6 females). Although the present study focused on drawing skill and not artistic ability, however that might be defined, we included artists and artists in training to increase the range of tested drawing skills. All the participants were naïve about the purpose of this study and our hypotheses. They all had a normal or corrected-to-normal vision. Before taking part in the experiments, they all gave their explicit written consent according to the principles defined by the University Paris Descartes ethics committee.

2.2 Material
All the experiments, except for experiment 2B, used the same apparatus. The participant's head was held by a chinrest so that his or her eyes were approximately 55 cm from the screen's centre. The stimuli were projected on a 22″ CRT screen, with a resolution of 1024 × 768 pixels and with a frame

rate of 120 Hz. The experiments were programmed in MATLAB using the Psychophysics and Eyelink Toolbox extensions (Brainard, 1997; Cornelissen, Peters, & Palmer, 2002; Pelli, 1997), and were run on an Apple computer.

Participants' eye movements were recorded with an eye-tracking system (SR research Eyelink 1000 monocular, 35 mm lens) at 1000 Hz sampling rate. The eye-tracker was always calibrated for the participant's dominant eye (9-point calibration. Eye dominance was assessed with an aiming task). Finally, eye-movements events and saccades were parsed using the Eyelink 1000 algorithm (saccade acceleration threshold = 9500°/s², saccade velocity threshold = 35°/s).

2.3 Object selection

The object selection procedure we used in this study was similar to that presented in Perdreau and Cavanagh, (2013b). Part of the set of possible and impossible objects used in the present study was taken from previous collections (Schacter et al., 1991; Soldan, Hilton, & Stern, 2009; used with authors' permission). The other objects were outlined versions of impossible objects provided by an Internet database ("Impossible world" website), and one of the authors (PF) designed corresponding possible versions using Adobe Illustrator CS4. At the end, our collection included a possible and an impossible version of 260 objects (total: 520) with an original size of 1667 × 1667 pixels.

In order to reduce the ambiguity about the structural possibility or the impossibility of the objects used in our experiments, we asked 20 independent observers, not participating in this study, to judge all our line-drawn objects as being structurally possible or not. They were particularly instructed that: objects were drawn with lines, every line represented a visible edge of the object, every visible edge was necessarily represented, an object's surfaces could only face one direction and were opaque and objects were volumes standing in a 3D space. All objects were seen in a random order. Only objects that had an inter-observers agreement equal to or larger than 95% were kept and used in the experiments presented in this paper (a total of 317 objects of which 170 were possible objects).

In addition, a previous study reported that perceived impossibility may be related to the object's complexity (Carrasco & Seamon, 1996). Thus, we computed complexity of every object according to the number of line segments and junctions. Objects complexity was normalised and objects were categorised as below ("Low complexity") or above ("High complexity") the median object complexity. Next, for each main experiment, we randomly selected 160 objects to create Low- and High-complexity levels for both possible and impossible object categories (40 objects in each category) such that the average complexity of Low-possible versus Low-Impossible and High-possible versus High-Impossible were not statistically different ($p > .05$). These categories were subsequently used to match object complexity across our experimental conditions.

2.4 Drawing accuracy

To assess our participants' drawing accuracy, we asked them to perform a drawing task where they had 15 min to copy a greyscale picture of an inverted house (Figure 1A) as accurately as possible, that
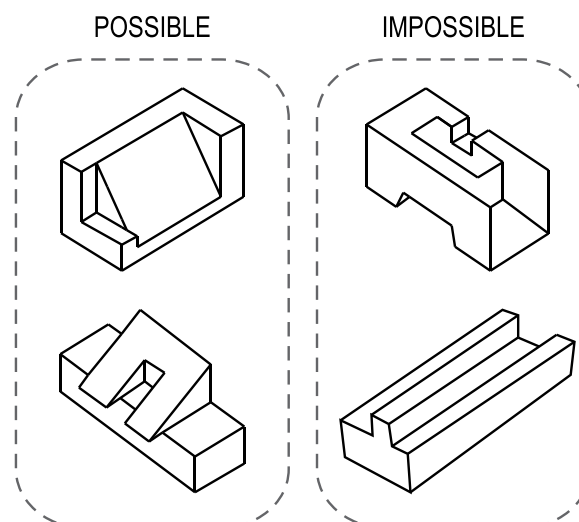
Figure 1. Examples of structurally possible and impossible line-drawn objects used in the present study.

is, without emphasising aestheticism or style. The use of an inverted house may avoid any canonical perception of the stimulus that could decrease drawing accuracy, even if the existence of such effect has not been demonstrated (Cohen & Earls, 2010). Moreover, without well-practiced elements to represent (e.g. an ordinary house), the artists, like the non-artists, would be showing their basic copying skills. The original picture was displayed on a computer screen and our participants had to copy it on a white A4 sheet of paper using a pencil. They were allowed to erase and correct their drawing as many times as they wished. Because the picture had many elements to draw, we asked participants to start by tracing the house's structure, then to depict its details and if they had enough time, to copy the house's environment (trees, etc.). This made sure that all of our participants went through the same stages and had completed at least the first of them (house's structure, which we used in our subsequent measurements).

Drawing accuracy is usually measured by asking independent observers to subjectively rate the drawings made by participants on a scale according to specific instructions (Cohen & Bennett, 1997; Cohen & Jones, 2008; Ostrofsky et al., 2012). Although this procedure can result in high inter-observers agreement, it does not allow the experimenter to know what criteria have been used by the observers, nor if these criteria vary across observers and across studies (Perdreau & Cavanagh, 2013a). Several recent studies have presented novel geometrically based methods to measure drawing accuracy, either using angles and proportion (Carson, Millard, Quehl, & Danckert, 2012; Chamberlain & McManus, 2013) or more sophisticated shape-matching algorithms (Hayes & Milne, 2011). In this study, we present a simple procedure based on the object's structure (i.e. the relative spatial position of the object's junctions). This single measure can account for angle accuracy, proportion and shape. First, we manually selected 16 junctions present in all drawings that defined the house's shape (Figure 2A). Next, we centred both the original picture and the drawings on their leftmost selected junction. Moreover, because we hypothesised that object's structure might be independent from the object's overall size, as it is defined as the relative spatial position of the object's parts, we normalised the junctions coordinates to the maximum horizontal and vertical coordinates in order to match the house size (Figure 2B). Finally, we computed the drawing's accuracy as the mean of the percentage root-mean-square error (%RMSE) computed on each axis (x and y) between the 16 points in the original and in the drawing:

$$\%\text{RMSE} = \sqrt{\frac{\sum(C_d - C_o)^2}{n} \times \frac{100n}{\Sigma C_o}}, \tag{1}$$

where $\mathbf{C}d$ are the transformed coordinates of the copied house, $\mathbf{C}o$ the transformed coordinates of the original house and n the number of selected points ($n = 16$). Smaller root-mean-square errors mean better drawing accuracy.

We next evaluated this geometrical measure by comparing it to human observers' subjective judgments of accuracy. To do so, we designed an online experiment where randomly selected pairs of drawings were presented to participants ($n = 245$) as well as the original picture. Online experiments are known to yield to a similar data quality compared to experiments run in laboratories (Germine et al., 2012). The task was to choose, by clicking on it with the mouse, which of the two drawings more precisely matched the original house. Participants were instructed to make their judgment on the basis of the house's proportion and structure, and not on the amount of detail, the size, style or aestheticism of the drawing. Each participant saw a maximum of 200 pairs of drawings and each possible pair was compared by at least 40 independent participants. To rank each drawing, we used the ELO ranking algorithm developed to rank players in two-competitor games like chess (Elo, 1978). The algorithm computes a probability of win for each compared item (a vs. b) according to its past results and to the score of the other item in the comparison:

$$p_a(\text{win}) = \frac{1}{1 - 10^{-\frac{\text{diff}}{400}}}, \tag{2}$$

where diff is the difference between item a and b's previous ELO scores:

$$\text{diff} = \text{Score}_{b,\text{prev}} - \text{Score}_{a,\text{prev}}. \tag{3}$$
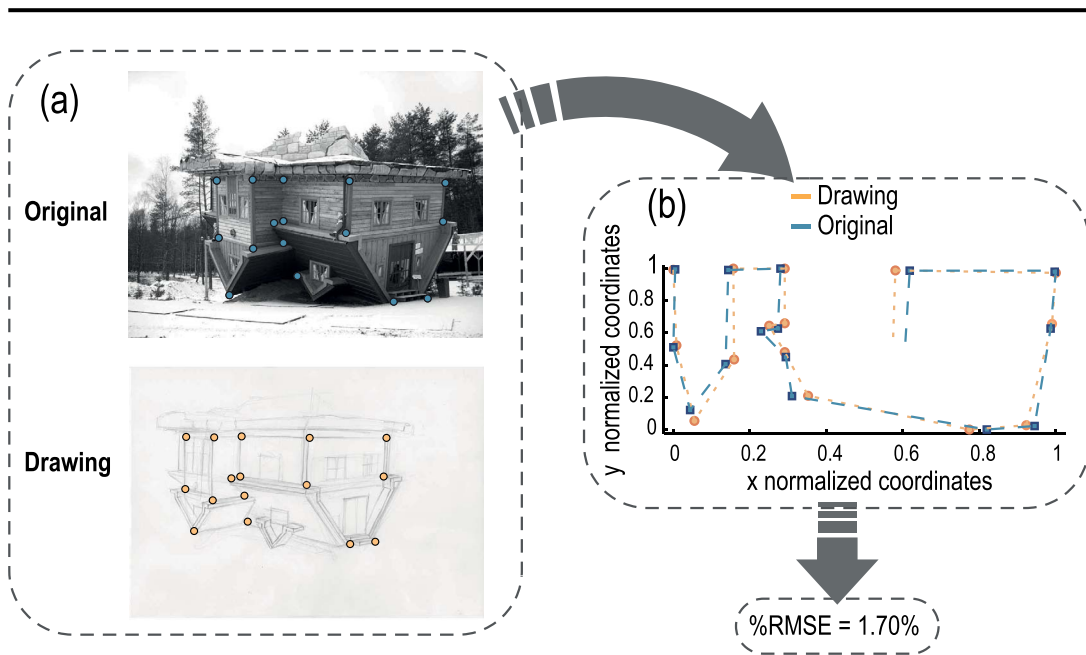
Figure 2. Geometrically measured drawing error. (a) First, we manually selected 16 junctions present in all the drawings (coloured dots) and the original picture, which defined the house's shape and structure. (b) Next, we normalised their coordinates to the maximum horizontal and vertical coordinates, and computed the mean RMS error of each drawing on the basis on these transformed coordinates.

This probability is then used to compute the item a's new score:

$$\text{Score}_{a,\text{new}} = \text{Score}_{a,\text{prev}} + \frac{800}{2n}(W_a - p_a(\text{win})), \tag{4}$$

where W is the item's outcome for the current comparison, a versus b, ($W = 1$ for a win, 0.5 for a draw and 0 for a loss) and n is the number of previous comparisons for the item. These scores for each item reach a final value across all the comparisons made for that item across all the participants.

These subjective rankings were highly consistent with the original geometrical measures [$r(35) = -0.68$ (CI: $-0.82, -0.49$), $p < .0001$]. Because of the objective nature of the geometrical scores, we used them in our evaluations of the participants' performance in the experiments that follow.

3   Experiment 1a: Visual masking
The purpose of this experiment was to test two hypotheses: 1) whether drawing accuracy is related to the efficiency of encoding object structure as measured by the threshold presentation duration of the stimulus prior a mask, and 2) whether drawing accuracy is related to the extent of space that can be encoded at a single glance.

3.1 Participants
Thirty participants took part in this experiment [average age 24.4 ± 0.8, 15 females, 10 artists, of which 6 were female]. Three of these participants were dropped from the analysis as their performance in the main experiment never reached threshold in the tested range and no psychometric function could be fit to their results.

3.2 Stimuli
We generated a list of 160 randomly selected objects from our original collection (40 objects per category and complexity level) that was identical for every participant. All objects were repeated three times during the experiment and they were randomly distributed so that they could not appear within the same experimental condition and with the same orientation ($\theta = 0°$, 90° or 180°).

3.3 Procedure
Prior to the main experiments, participants performed in a practice session to familiarise themselves with the task and the difference between structurally possible and impossible objects. We first

instructed our participants, like those participating in the object selection procedure, that: objects are drawn with lines, every line represents an edge of the object, every edge is necessarily represented and object's surfaces can only face one direction and are opaque, and objects are volumes standing in a 3D space. All objects used in this practice session were different from those presented in the other experiments. Next, we showed some examples of possible and impossible objects and asked the participants whether this categorisation made sense to her or to him. Finally, participants ran in 80 practice trials. On each trial, a $21° \times 21°$ line-drawn object was displayed centred on the screen. Participants had to answer, as fast and accurately as possible, whether this object was structurally possible or not. They had a maximum of 5 s to give their answer. Otherwise, the screen was blanked out and the participant was told to give a response.

In the main experiment, eye-movements were monitored using an eye-tracking system. Each trial started with a central fixation dot that the participant had to fixate for 200 ms to start the trial (Figure 3). After a random delay of 600–900 ms, a line-drawn object was displayed centred on the screen. We varied the object's presentation duration from 8 to 1,500 ms (eight SOAs: 8, 25, 67, 183, 525, 1,500 ms), as well as its size (8° or 28° of visual angle). After this duration, the object was immediately replaced by a dynamic mask with a duration of 16 frames (Bacon-Macé, Macé, Fabre-Thorpe, & Thorpe, 2005). Finally, a red central dot was displayed, indicating to the participants that he or she had a maximum of 2 s to respond. Participants had to fixate the central dot during the entire trial. If a participant's gaze deviated by more than 1° from this dot, the trial was ended and was replayed later in the experiment. Specifically, participants were told to report whether the object was structurally possible or impossible, as fast and accurately as possible, by pressing the appropriate key ("left control" or "right control," respectively). Feedback was shown to participants every 20 trials to indicate their overall performance as well as their progression. This was designed to keep the participants motivated.

We manipulated the object's presentation duration (six from 8 to 1,500 ms) as well as its size (8° or 28°) and its complexity level (low or high) as within-subject factors, although the latter factor was only treated as a control variable for an effect of complexity on perceived impossibility.

The experiment started with a practice block of 24 trials where we presented every possible condition to the participants. This was followed by 480 trials divided into six blocks of 80 trials each. We calibrated the eye-tracking system and made a drift correction at the beginning of each block.

3.4 Results

We first compared the participants' pretest performance (percent correct categorisation of the 80 possible and impossible objects without eye movement constraints) to their drawing accuracy. The two measures showed a correlation of 0.45 [$p < .005$], suggesting that more skilled participants could better discriminate possible from impossible objects in a free viewing condition. This preliminary correlation should be viewed with some caution as a similar baseline condition in our previous study
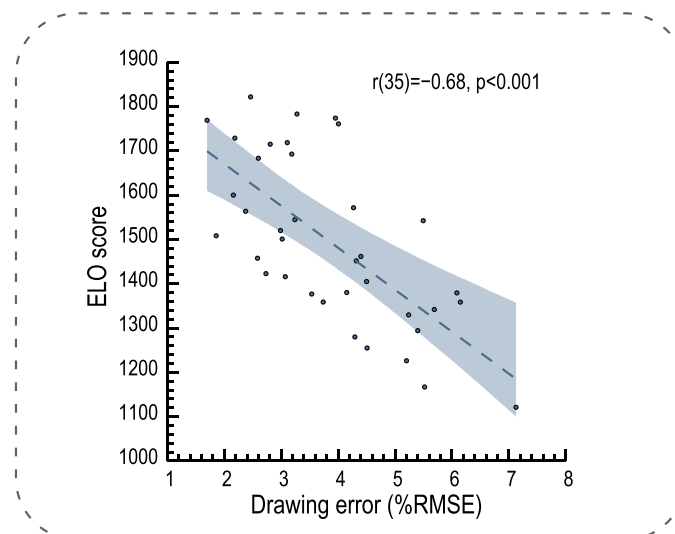
Figure 3. Correlation between objectively (*x* axis) and subjectively (*y* axis) measured drawing accuracy. Each dot represents a participant's drawing. The filled area is the 95% bootstrapped confidence interval of the regression line.
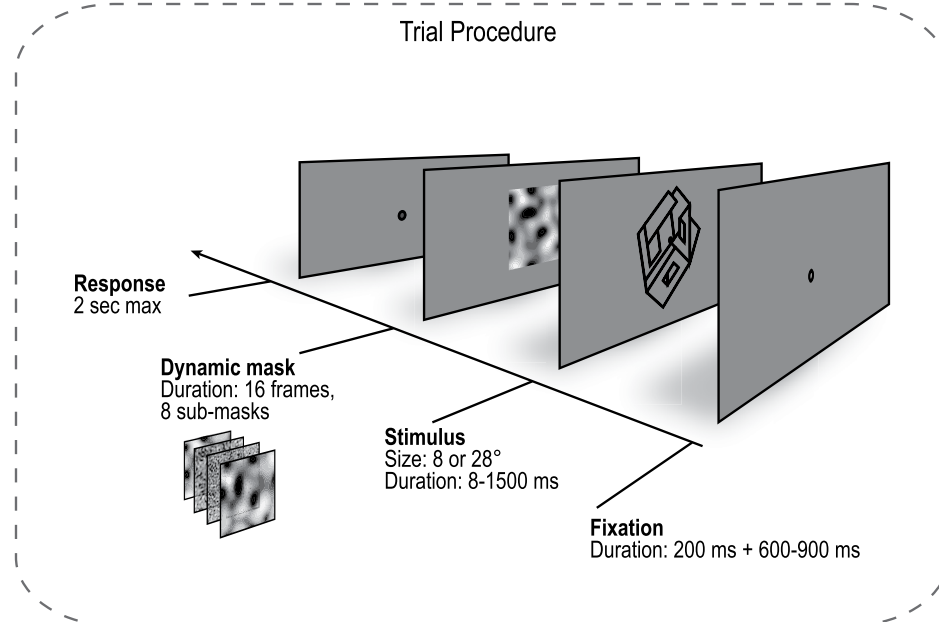
Figure 4. Experiment 1's procedure. Participants had to fixate a central dot for 200 ms to start the trial. After a random delay (600–900 ms), the stimulus was displayed, centred on the screen. We manipulated stimulus presentation duration (from 8 ms to 1500 ms) and size (8° or 28°). Participants had to maintain their fixation on the central dot throughout the trial (within ±1°).

(Perdreau & Cavanagh, 2013b) did not show a significant correlation, again between drawing accuracy and performance. One difference between the two studies was that the time available for the response was shorter (5 s) here than in the previous study (10 s). It is possible that this extra time in the previous experiment was sufficient to allow the less skilled participants to catch up to the performance of the skilled participants.

In the analysis of the main experiment, we first fitted a logistic function on proportions of correct responses plotted against SOAs (Figure 5A) for each participant and object size (8 and 28°), using a maximum likelihood procedure with a fixed gamma parameter of 50% (2-AFC, Prins, 2012). The overall quality of individual fits was good and reliable [mean deviance: 3.12(SE: 0.29), $Ps >> .05$]. Next, we computed the critical SOA for each participant and object size, defined as the SOA value leading to 75% correct responses. However, three of our participants had very poor performance in this experiment despite good performance in the pretest, which led to undefined (infinite) thresholds. We excluded these three participants from the following analyses.

To measure whether better accuracy in drawing is related to faster encoding of object structure, and to an ability to make such encoding over a larger extent of space, we computed the regression between participants' drawing error score and their critical SOA using a linear mixed-effects[1] model on log-transformed[2] SOA and error values with drawing error and object size as fixed factors and with participants as a random factor to account for our repeated-measures design (Figure 5B). We found a significant linear relation between log-error and log-critical SOA [$\beta = 1.39$ (SE: 0.44), $\chi^2(1) = 8.59$, p<.004] and a significant main effect of object size [$\beta = 1.08$ (SE: 0.51), $\chi^2(1) = 14.26$, p < .0002]. However, we found no significant interaction between object size and drawing accuracy [$\beta = -0.44$ (SE: 0.37), $\chi^2(1) = 1.38$, $p = .24$]. These results show that more skilled participants needed overall

---

[1] Linear mixed-effects models are extensions of linear regression models, including both fixed effects (linear regression part) and random effects that allow random individual variations across a grouping factor's levels (as in repeated-measures ANOVA). Linear mixed-effects models presented in this study were computed using the *lme4 R* package with an ML procedure (Bates, Maechler, & Bolker, 2012). Main effects and interaction effects were tested by using a likelihood ratio-test, which compares the residual deviance of both the full model and the reduced model (full model without the factor of interest) and approaches a χ^2 distribution. In addition, we report the log–log regression slope (β) to characterize the effect direction.

[2] A diagnostic of the linear model's residuals showed an heavy heteroscedasticity when we used raw values. This can be explained by the presence of a lower bound in both participant's critical SOAs and drawing accuracy (theoretical minimum at 0). Using log-transformed values solved this issue. We applied this data transformation in all of the following analysis.
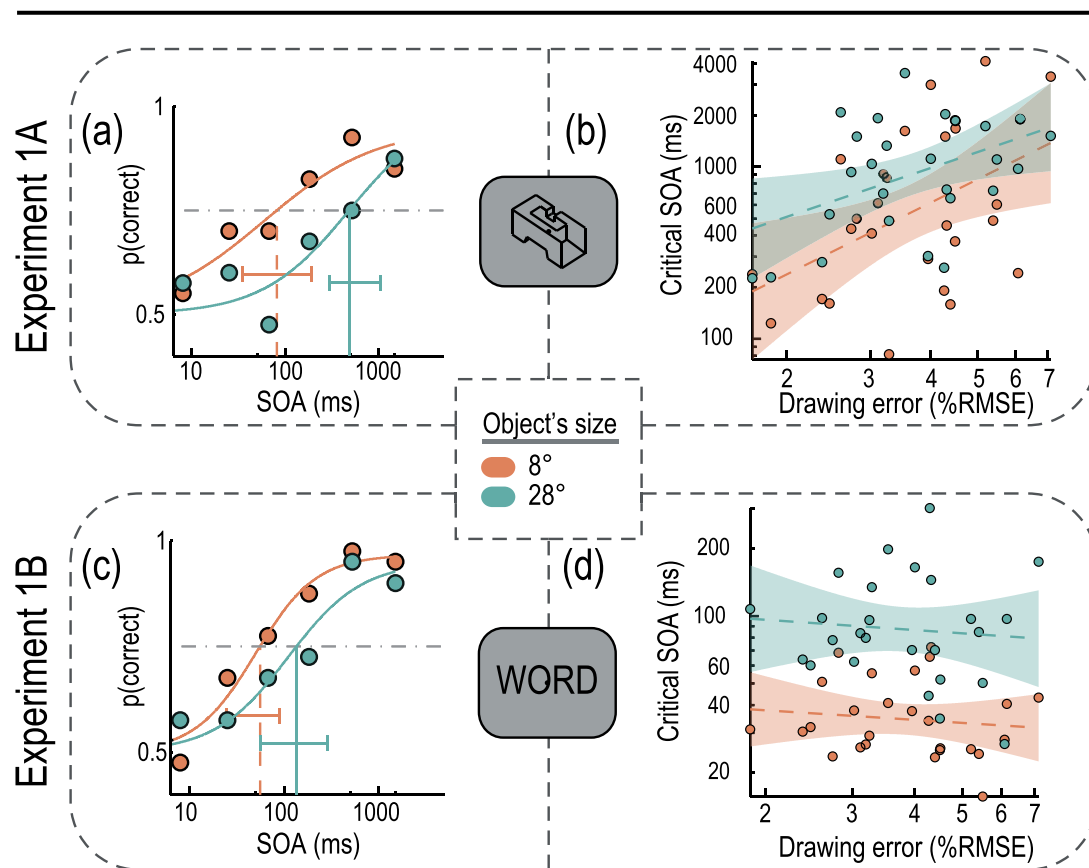
Figure 5. Experiment 1A and 1B results. (a, c) Examples of individual fits for the object and word tasks. We fitted logistic functions on participant's proportion of correct responses plotted against SOA and we measured a critical SOA for each object size (8° and 28°) as the SOA leading to 75% correct response. Horizontal error bars are the 95% bootstrapped confidence intervals of the estimated critical SOA. (b, d) Next, we computed regressions between drawing error and critical SOA using a linear-mixed effects model for both tasks. Filled areas are the 95% bootstrapped confidence intervals of the regression lines.

shorter presentation durations to make accurate decision about the object's structure. Although noisy, the effect was quite large with the regression showing a three to five-fold increase in the critical duration required to classify the objects for least skilled versus most skilled participants. This relation was not affected by object size.

## 4 Experiment 1b: Lexical-decision

The more skilled participants needed less time to make accurate judgments of possible versus impossible objects. However, this might reflect some general advantage of the skilled participants for any task. As a control for a general processing advantage, we ran a lexical-decision task that required integration of letters across space to determine if the letters made a possible or impossible word. Other than the nature of the stimuli, the experiment had the exact same conditions as the possible–impossible object task. If participants with better drawing skills had a general advantage, it should also be apparently better in this lexical decision task.

4.1 Participants

Participants were identical to those of the previously described experiment, with the exception that only the 28 French native-speakers of the original 30 participants ran in this control experiment. Moreover, to allow a more straightforward comparison between this experiment's results and the previous findings, we also excluded the two outliers excluded from Experiment 1a because of indeterminate thresholds (leaving $n = 26$) although this did not affect the results.

4.2 Stimuli

Experimental conditions were identical to the visual masking task with possible/impossible objects. However, instead of using these line-drawn objects we used French words and non-words. These words
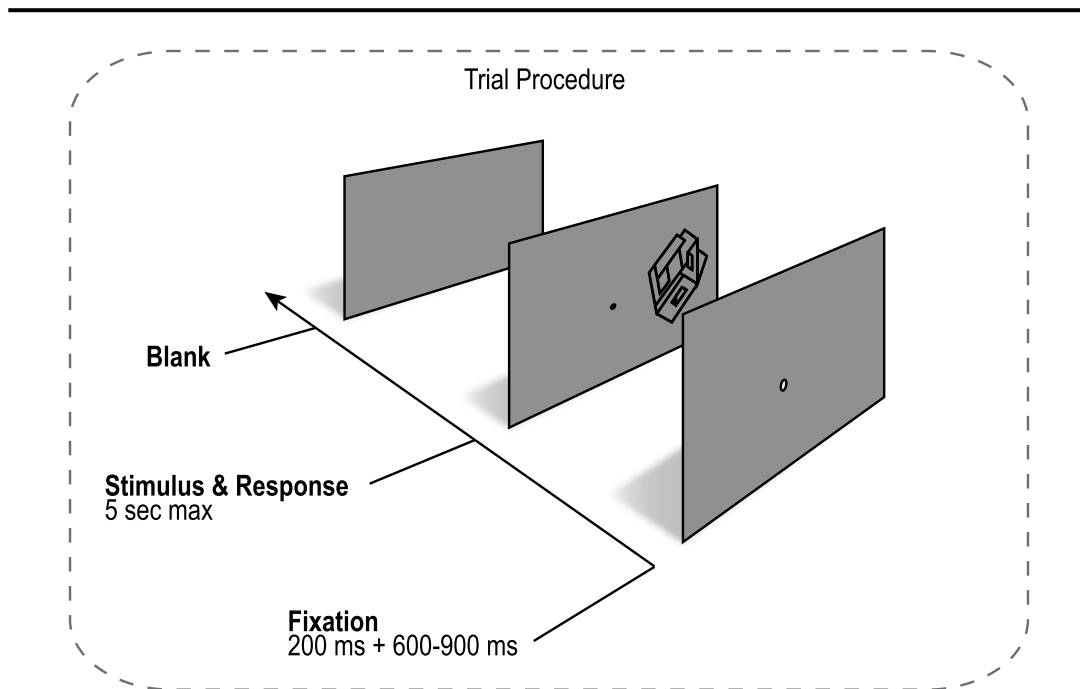
Figure 6. Experiment 2A's procedure. Participants had to fixate a central dot for 200 ms to start the trial. After a random delay of 600–900 ms, a line-drawn object was displayed in the participant's right visual periphery. It remained on the screen until the participant gave his or her response. They were asked to categorise the object as structurally possible or impossible, and they had 5 s maximum to respond. If no response was given within this time, the screen was blanked out and the participant was asked to answer. In this experiment, we particularly varied the object's size (from 1° to 12°) and its eccentricity (3° or 8°).

and non-words were collected from a French database (LEXIQUE 3.55; New, Pallier, Brysbaert, & Ferrand, 2004). More particularly and to avoid any ambiguities of an effect of words frequency, and possibly of participants' education, on participants' performances, we selected words with a frequency greater than 100 times per million words, based on appearances in books, subtitles, webpages, etc. Likewise, for non-words we selected actual French trigrams (sequences of letters making a pronounceable non-word) that had the same mean frequency of occurrence in French as that of the words we used in this task. Finally, to match the first experiment's conditions, we manipulated the number of letters of words and non-words (4 or 8) to simulate words visual complexity as well as their horizontal size (8° or 28°). As in the previous experiment, words complexity was matched across presentation durations. We had a total of 90 words and 90 non-words, each of them having been seen three times during the experiment.

4.3 Procedure

The procedure was identical to that used in the first experiment, with the exception that now participants were asked to categorise the briefly displayed word as a word present in French language or not.

4.4 Results

As previously, we fitted logistic functions on participants' proportions of correct responses, plotted against words presentation duration, and we computed a critical SOA for each participant and each stimulus size (Figure 4C). The overall quality of fit was very high [mean deviance: 2.45(SE: 0.29), $Ps >> .05$].

Next, we computed the regression between drawing accuracy and critical SOA using a linear mixed-effects model on participants' critical SOAs with participants' drawing error and word size as fixed factors, participants as random factor. We found a significant main effect of word size on participants' critical SOAs [$\beta = 0.99$ (SE: 0.33), $\chi^2(1) = 132.62$, $p < .00001$], suggesting that participants overall need longer presentation duration to encode larger words accurately. In contrast to the first main experiment, we found no main effect of drawing error [$\beta = -0.11$ (SE: 0.29), $\chi^2(1) = 0.28$], as well as no interaction between drawing error and word size [$\beta = -0.06$ (SE: 0.24), $\chi^2(1) = 0.07$].
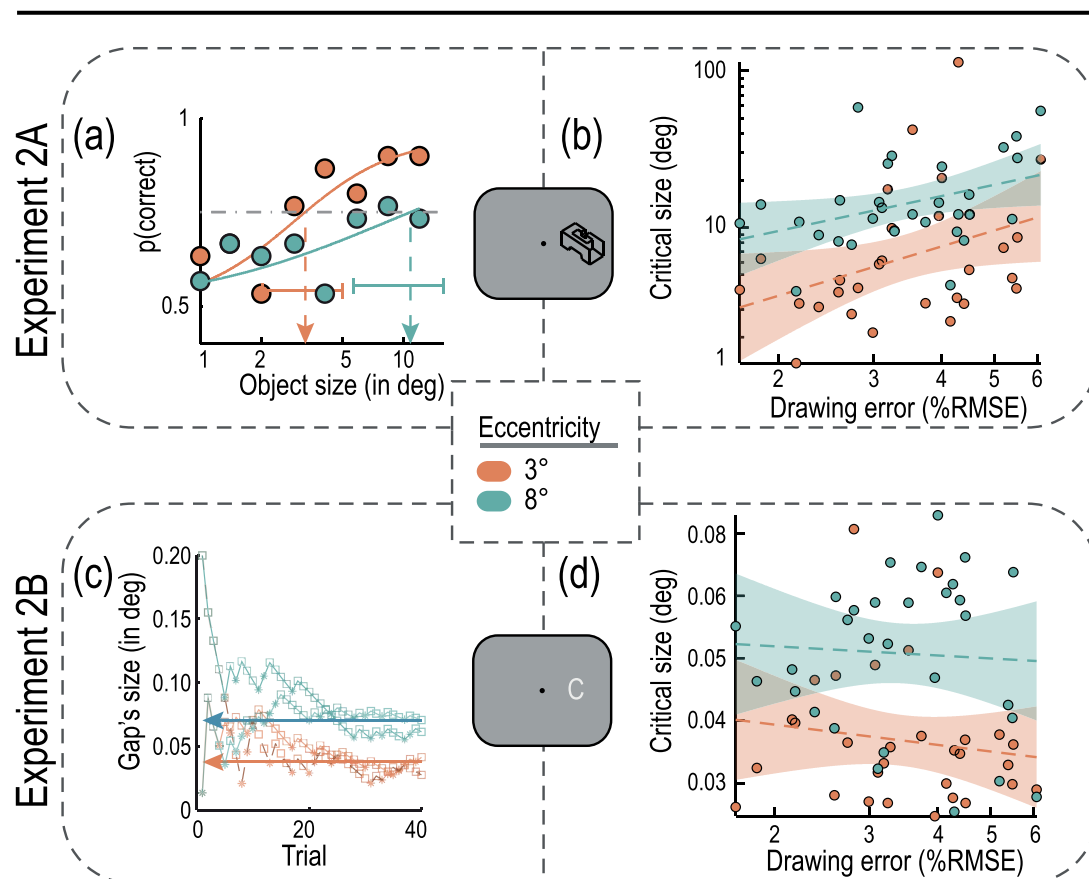
Figure 7. Experiment 2A's and 2B's results. (a) Example of individual fits. As in the first experiments, we fitted logistic functions on participant's proportion of correct responses plotted against SOA and we measured a critical size for each eccentricity (3° and 8°) as the object size leading to 75% correct response. Horizontal error bars are the 95% bootstrapped confidence intervals of the estimated critical SOA. (b) Next, we computed the regressions between drawing error and critical size. Filled areas are the non-parametric 95% bootstrapped confidence intervals of the regression slopes (10,000 runs). (c) To measure participants' visual acuity, we used a Landolt's C test and we measured the critical gap size for each eccentricity with an adaptive staircase procedure. (d) The regressions between drawing error and critical size for the Landolt's C task. Filled areas are the non-parametric 95% bootstrapped confidence intervals of the regression slopes (10,000 runs).

Taken together, these results show that the more efficient processing of object structure by skilled participants that we found in the first main experiment could not be attributed to a more efficient encoding of visual stimuli in general.

5 Experiment 2a

The first experiment's results suggest that drawing accuracy might be related to a more efficient encoding of object structure seen in a single fixation but not to the ability to encode this structural information over larger visual spans without eye movements. This latter finding might not be surprising, for drawing is characterised as a sequential, segmentation process (Tchalenko, [2009]). For instance, an artist might need to encode the segment's position only in the context of elements located in a particular area of the segment's immediate surroundings. The present experiment aims at testing whether drawing accuracy would be related to a more efficient encoding of structural information located in participants' visual periphery.

5.1 Participants

A total of 34 participants ran in this experiment [average age 25.9 ± 1.1, 12 females, 10 artists of which 6 were female]. Four of these participants were dropped from the analysis (leaving 30) as their performance in one of the two main conditions never reached the threshold in the tested range and no psychometric function could be fit to their results.
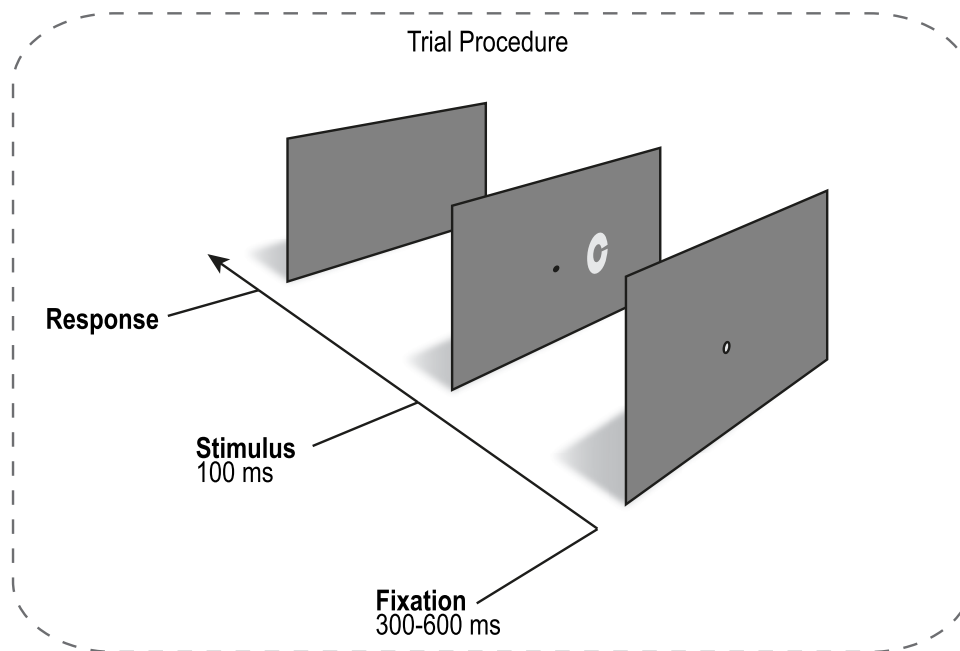
Figure 8. Experiment 2B's procedure. Each trial starts with a fixation dot displayed for a randomly chosen interval between 300 and 600 ms. Then, a Landolt's C was briefly flashed for a duration of 100 ms. Once it disappeared, participants could give their response. We manipulated the position of the gap in the C (top, right, bottom or left) and participants had to report this position by pressing the corresponding arrow key. We varied the C's eccentricity as well as its gap size (proportional to the overall size). For each tested eccentricity, two independent and intermixed staircases were used to measure the gap size leading to 62.5% correct responses (4-AFC).

5.2 Stimuli

In this experiment, we only used the subset of "low-complexity" line-drawn objects from our collection, as a pilot experiment revealed that the task was nearly impossible to perform in the periphery with the most complex objects. We used a total of 60 objects per category (possible and impossible) that were repeated four times during the experiment, but never within the same condition or with the same orientation.

5.3 Procedure

Participants had to fixate a central dot for 200 ms to automatically start the trial. After a random delay varying between 600 and 900 ms, a line-drawn object was displayed in the right visual periphery of the observer (Figure 6). Participants were told to fixate a central dot all along the trial. Eye movements were continuously recorded with an eye-tracker, and every time participants' gaze deviated by more than 1° from this central dot, the object disappeared. Participants were asked to categorise the object as structurally possible or impossible, and they had 5 s maximum to give their response. They were asked to respond as fast and accurately as possible by pressing the appropriate key ("left control" or "right control"). If no response was given within this time, the screen was blanked out and the participant was told to give a response. We varied the object size (eight sizes from 1° to 12°) as well as its eccentricity from the central dot (3° or 8°).

Each participant started the experiment with a training block of 32 trials, which crossed all experimental conditions. Then, participants ran in 480 trials (8 sizes × 2 eccentricity, with 30 trials per condition), which were divided into four blocks. As in the first experiment, participants received feedback about their overall performance and progression every 20 trials. They were free to take a break during these feedback pauses and between every block of trials.

5.4 Results

Logistic functions were fitted on participants' proportion of correct responses plotted against object's size for each tested eccentricity [mean deviance: 6.24(SE: 0.49), Ps>.05]. We then measured the critical size as the object size leading to 75% correct responses (Figure 7A).

To measure how the efficiency of discriminating possible from impossible figures varies with eccentricity and drawing accuracy, we computed regressions between drawing error and critical object

size using a linear mixed-effects model on the log-transformed participants' critical size, with log drawing error and object eccentricity as fixed factors, participants as random factor (Figure 7B) Not surprisingly, we found a significant main effect of eccentricity on participants' critical object size [β = 1.16 (SE: 0.62), $\chi^2(1)$ = 23.97, $p < .0001$], suggesting that participants needed in average larger object sizes to accurately discriminate between possible/impossible figures at farther eccentricities. As in the first experiment, there was a significant linear relation between drawing error and critical object size [β = 1.04 (SE: 0.40), $\chi^2(1)$ = 7.43, $p < .007$], suggesting that more skilled participants needed on average smaller sizes to categorise an object as structurally possible or impossible when presented in visual periphery. Again, although noisy, the effect of drawing skill was large, with the regression showing a two to three-fold increase in the required object size required for accurate classification between the least skilled and most skilled participants. Finally, we found no significant interaction between object eccentricity and the relation between drawing error and participants' critical sizes [β = -0.30 (SE: 0.49), $\chi^2(1)$ = 0.39, $p = .53$].

One explanation for the ability of more skilled participants to accurately process smaller objects is that they have smaller critical zone for crowding—they can access local features when they are more closely spaced. However, this effect of drawing skill did not vary with eccentricity. This advantage for skilled participants in processing smaller stimuli is surprising at a first glance, since we found no difference in the effect of object size for skilled versus unskilled participants in our first experiment. However, as we stated in our introduction, object size has different effects for an object centred at the fovea, as was the case in Experiment 1, compared to one centred in periphery, as here in Experiment 2. In the first case, size changes should not affect the strength of inter-feature crowding because the ratios of feature spacing to eccentricity that determine crowding are maintained when size changes are centred at the fovea. In contrast, with objects centred in the periphery, size changes do affect the feature-spacing to eccentricity ratios. Therefore, in line with our hypothesis of a better attentional resolution for skilled participants, one explanation of their advantage is that they were better with smaller stimuli at finding and individuating features required to construct the object's structure and detect violations.

6 Experiment 2b

The relationship we found between drawing accuracy and the participants' critical object size could easily be due to better peripheral visual acuity in more skilled participants. To evaluate this alternative explanation, we ran a Landolt's C test at the same eccentricities.

6.1 Participants

Participants were identical to those who participated in the previous experiment (2a), and we again excluded the four who had been removed from the analysis in that experiment ($n = 30$).

6.2 Material

The participant's chin was held by a chinrest so that his or her eyes were centered on the screen at a distance of 105 cm. In this experiment, we used a 30-inch flat screen (30-inch Apple Cinema HD Display), with a spatial resolution of 2560×1600 pixels and a refresh rate of 60 Hz. This setting allowed us to display the very small visual angles required by our task.

6.3 Procedure

Each trial started with a fixation dot centred on the screen for a random time of 300–600 ms. Next, a Landolt's C was briefly flashed for 100 ms in the right visual periphery (Figure 8). Once the central dot disappeared, the participants could give his or her response. Participants were asked to report the position of the gap in the C (left, right, top, or bottom) by pressing the corresponding arrow key. In this experiment, we manipulated the C's eccentricity (3° or 8°) as well as the C's gap size. The latter was determined by using two interleaved and independent adaptive staircases (adaptive stochastic approximation procedure; Kesten, 1958) for each eccentricity, one starting at 0.013° and the other at 0.20°. The aim of these staircases was to determine the threshold C's gap size for which participants' performance on this 4-AFC task was 62.5% correct (chance level: 25%).

6.4 Results

In order to assess the relationship between our participant's drawing accuracy and their visual acuity, we computed the regression between drawing error and threshold gap size using a linear mixed-effects model on log-transformed thresholds, with eccentricity and drawing error as fixed factors, participants

as random factors ([Figure 7D](#)). As expected, we found a significant main effect of eccentricity on participants' thresholds [$\beta = 0.25$ (SE: 0.22), $\chi^2(1) = 32.51$, $p < .00001$]. However, we found no significant effect of drawing error [$\beta = -0.11$ (SE: 0.15), $\chi^2(1) = 0.43$] and no interaction between drawing error and eccentricity [$\beta = 0.06$ (SE: 0.17), $\chi^2(1) = 0.12$].

These results show no evidence of a relationship between drawing error score and participants' visual acuity in visual periphery. Therefore, it is unlikely that the advantage of more skilled participants in discriminating possible from impossible objects in the periphery could be due to a more accurate perception of these objects.

7   General discussion

Do artists and others skilled at drawing have any general advantages in processing visual information? Several previous experiments have suggested that they do (e.g. Glazek, [2012](#); Perdreau & Cavanagh, [2013b](#); Tchalenko, [2009](#)). In many of these experiments, however, participants were allowed to scan a test image and we cannot know if the performance differences arose from advantages in integrating information across eye movements or from advantages in encoding information from individual fixations. In our experiments here, we asked whether participants with better drawing skills would have any advantages when their access to the stimulus was limited to a single glance (no scanning eye movements allowed). Participants of varying levels of drawing skill classified line drawings as possible or impossible objects: in the first experiment, presentation time was varied to measure the speed of processing object structure as well as the spatial extent over which this processing could be accomplished at a single glance; in the second experiment, object size was varied at different locations in the visual periphery to see whether participants with better drawing skills could correctly classify stimuli at smaller sizes or further eccentricity.

First, we measured our participants' drawing errors both objectively and subjectively. We extended an objective method that geometrically compared the participants' drawings to the original picture and quantified the drawing's matching error (e.g. Carson et al., [2012](#); Chamberlain & McManus, [2013](#); Hayes & Milne, [2011](#)). In addition, we conducted a large-scale, on-line experiment where drawings were pair-wise compared by participants and then ranked using an ELO ranking algorithm (Elo, [1978](#)). Both measurements were consistent and in the main experiments we used the objective measure where the criteria for accuracy are explicit.

In the first experiment (Experiment 1a), we found a significant relationship between objectively measured drawing error and the presentation duration needed by our participants to accurately categorise an object as structurally possible or impossible. Specifically, the regression result indicated that the most skilled participants reached threshold performance with presentation durations three to five times shorter than the threshold durations for the least skilled. However, the size of the stimulus (8° vs. 28°) did not affect this difference between skilled and unskilled participants. We also ran an additional control experiment using the exact same experimental conditions but using a lexical decision task instead of an object decision task. This control assessed whether the performance advantage of the more skilled participants was specific to the object structure discrimination or whether they were related to more general cognitive abilities that affected all tasks including drawing and the object structure task. However, no significant relationships between drawing skill and performance were found in the lexical-decision task (Experiment 1b). So, drawing accuracy appears be related to a more efficient processing of object structure on a single glance. In contrast, more skilled participants were not any better at processing larger stimuli than those who were less skilled suggesting that they had no advantage in terms of visual span (Rayner, [1998](#)).

In the second experiment, we found a significant relationship between drawing error and the object size needed to correctly identify its structure as possible or impossible. The regression results showed that the most skilled participants reached threshold performance for stimuli that were two to three times smaller than the threshold size for the least skilled. The test objects were presented at different locations in the near periphery (3° and 8°) so one explanation of the advantage for the participants with better drawing skills was that they had better visual acuity—they might simply be able to see the stimuli more clearly. To test this, we conducted a Landolt's C task at the same tested eccentricities and found no differences related to drawing skill, ruling out acuity as an explanation. In the absence of differences in visual acuity, a possible explanation of the better performances of our skilled participants with smaller images may be that they were able to individuate features present within small local structures. This finding suggests a relationship between drawing skill and attentional resolution (He et al., [1996](#), [1997](#)).

In summary, our results showed that the more skilled participants were notably faster at processing object structure at a single glance and were able to accurately classify test stimuli at much smaller sizes. The advantage in speed was independent of the size of the object and the advantage in size was independent of the eccentricity. This strongly suggests that drawing accuracy may be related to a more efficient encoding and representation of structural information that can be captured during a single fixation, regardless of the viewing condition (either in central or peripheral vision).

7.1 Drawing accuracy and possible/impossible object discrimination

Before considering how the processing of object structure differs between participants who are skilled at drawing and those who are not, we first consider what the possible versus impossible task tells us about the processing of object structure. Most of the studies using the impossible/possible object-decision test investigated object representation in long-term memory (e.g. Schacter et al., 1990; Schacter et al., 1991; Soldan et al., 2009), and only a few of them have considered the perceptual aspects underlying this discrimination (Carrasco & Seamon, 1996; Donnelly et al., 1999; Freud, Avidan, & Ganel, 2013; Freud, Ganel, & Avidan, 2013; Seamon & Carrasco, 1999; Williams & Tarr, 1997). Impossible objects have valid object properties (e.g. closed contours, volume and edges) despite their inherent structural violations. This may explain why possible and impossible objects share the same early perceptual processes with possible objects (Freud, Ganel, et al., 2013), as well as why impossible objects can be processed holistically to the same extent as structurally valid objects (Freud, Avidan, et al., 2013), and can be perceived as valid objects (Cowie & Perrott, 1993; Williams & Tarr, 1997). However, discriminating possible from impossible structures takes much more time than discriminating object categories (e.g., animal vs. vehicle) or identities (e.g., spoon vs. fork). For example, our participants needed almost 1,000 ms on average to accurately discriminate an impossible from a possible object, whereas objects or scenes can sometimes be classified in less than 100 ms (Bacon-Macé et al., 2005; Greene & Oliva, 2009; Thorpe, Fize, & Marlot, 1996). Such a difference may mean that possible/impossible object discrimination is not based on the entry-level object "gist," but rather on a scrutiny of its parts and on a serial verification of the consistency between these parts and the object's global structure (Donnelly et al., 1999; Soldan et al., 2009). These verification processes undoubtedly require more extensive and higher level processing (Hochstein & Ahissar, 2002). There are undoubtedly several factors that would contribute to the duration of these serial verifications: for example, the number of locations covertly sampled, the time spent to analyze the features at each location and the time needed to move from one location to the next.

In line with this hypothesis of serial inspection and verification and consistent with previous findings (Donnelly et al., 1999), we found that all participants needed longer durations for an object that covered a larger extent of space (Experiment 1a). Since fixation was maintained throughout, we might expect that object size would not affect the number of locations visited and scrutinised by attention (e.g. Treisman & Gelade, 1980) nor the analysis of the features at each location. The effect of size might arise from the longer time required to move attention from one location in the object to the next in a larger object (Chakravarthi & VanRullen, 2011; Donnelly et al., 1999; Kosslyn et al., 1978; Posner et al., 1988). The speed advantage of the participants who are skilled at drawing (Experiment 1a) may arise from better performance on any or all of the three factors we mentioned: they may be able to construct the object structure based on covertly sampling fewer locations; they may spend less time processing the information from each location and they may be able to move attention more quickly from one location to the next. However, our experiment was not designed to distinguish the separate effects of these three factors and further research will be needed to address this issue. Nevertheless, we were able to show in the second experiment, that more skilled participants could access and analyze more closely spaced details than could the less skilled participants.

7.2 Relating drawing accuracy to the observed performances

Our results here are specific to object analyses performed at a single glance, so we must ask, among the visual processes that would become more developed in artists and those skilled at drawing, which of these would be specific to analysis completed without eye movements.

Let us start by roughly outlining the stages of making a drawing. First, an internal representation of the original object must be constructed, shifting back and forth between local and global levels, to select and analyze local features in the context of their location within the object (Chamberlain et al., 2013; Kozbelt, Seidel, ElBassiouny, Mark, & Owen, 2010). On first glance, it is this stage that appears

most relevant to our possible versus impossible objects task although typically, this stage would involve many eye movements across the original image to build its representation. The drawing then requires a selection of local elements to draw (Kozbelt et al., 2010; Tchalenko, 2009), adding them to the already drawn depiction, maintaining spatial relations. This selection and verification of local elements depends on understanding of the global structure and the relation of the selected element to that structure. If the original is in view, frequent eye movements are made back and forth between the original and the drawing in progress (Tchalenko & Miall, 2009; Tchalenko, 2009) to check details in the original and guide the new additions. If the original is not in view, then the back and forth inspection and drawing is based on the memory representation of the original. In either case, there is again a dependence on a robust internal representation of the object's structure and a requirement to access individual local elements to see if they correspond properly to the expected spatial relations.

Much of this effort involves back and forth eye movements with sampling of information from local regions and integration and comparison of this information with the internal model of the object's global structure. Several previous articles have looked at the link between drawing and visual tasks where eye movements are allowed (e.g. Glazek, 2012; Mitchell et al., 2005; Perdreau & Cavanagh, 2013b) and integration across fixations plays a role. For example, our previous study (Perdreau & Cavanagh, 2013b) focused on the same possible versus impossible visual task with free eye movements but restricting the amount of the test object that could be seen around fixation. The results showed that participants who were skilled in drawing could perform accurately with smaller samples of foveal information. This suggests that drawing accuracy may relate to a more robust internal representation with local features better integrated into more complex chunks.

What is different when eye movements are not allowed, when the analysis must take place in a single fixation? Clearly, rather than integrating samples acquired foveally from one fixation to the next, participants must integrate the information encoded at different eccentricities by moving attention over different locations of interest. We again find that participants skilled in drawing are better at this. The same factors should contribute to good performance here: more robust internal representation, more efficient coding and better integration of local features. The continued superiority of skilled participants with or without eye movements suggests that the management of eye movements and retention of information across fixations is not the critical factor in their advantage. Nor is the difference between foveally acquired local features and peripherally acquired features. The skilled participants appear to be better wherever they acquire object features. They also have an additional advantage for closely spaced features, possibly based on better attentional resolution (He et al., 1996, 1997) that allows them to access closely spaced details that are crowded for less skilled.

We conclude that those skilled at drawing are able to construct better internal representations of objects in less time and are better able to access details despite local clutter from adjacent features. These processes are critical in the rapid analysis of images when producing drawings and the long experience of relying on these processes for making drawings may have altered these core visual and memory processes. Of course, it is also possible that those who are skilled at drawing have those skills because these processes were already more developed. We cannot resolve this question of causality without a longitudinal study following, say, art students across their years of training. Our previous study of the impossible versus possible objects task did find a relation between years of drawing experience and performance that suggested that experience was a causal factor, but it was not a longitudinal study of the same participants across their training so it was not conclusive.

In contrast to these factors that do seem to link drawing to performance in this possible versus impossible object task, we found no evidence for additional advantages for skilled participants in processing more peripheral information. Drawing accuracy was not related to any increase in performance over larger visual spans (8° vs. 28°, Experiment 1a) nor to improved processing at larger eccentricities (3° vs. 8°, Experiment 2a). This result is consistent with the absence of a relationship between drawing accuracy and the ability to make structural discrimination based only on peripheral information in our previous study (Perdreau & Cavanagh, 2013b). It appears that whatever the relation between drawing skill and visual processes, it does not include advantages in processing information from the periphery (the advantage that we saw in dealing with crowded details was similar over the two eccentricities tested). However, it is possible that a difference would have emerged if we had tested a larger range of eccentricities.

To conclude, our present results suggest that drawing skill is related to improved visual processes active in a single glance, including a combination of more robust internal representation, more

efficient coding, better integration of local features and better access to closely spaced details. These results indicate that the advantages seen previously in tasks where eye movements were allowed (e.g. Glazek, 2012; Mitchell et al., 2005; Perdreau & Cavanagh, 2013b) were not critically dependent on differences in eye movement-related processes, but demonstrate general advantages in processing object structure no matter what the context. Our results here are only correlational, however, so there is no evidence of causality. We did not find any evidence for a link between drawing skill and a larger visual span (Rayner, 1998) or a more efficient use of peripheral information. We did find evidence suggesting better attentional resolution (less crowding) for skilled participants and although this advantage only becomes measurable in the periphery (there is no crowding in the fovea), this advantage did not increase over the range of eccentricities that we tested.

References

Bacon-Macé, N., Macé, M. J.-M., Fabre-Thorpe, M., & Thorpe, S. J. (2005). The time course of visual processing: backward masking and natural scene categorisation. *Vision Research, 45*(11), 1459–1469. doi:10.1016/j.visres.2005.01.004

Bates, D., Maechler, M., & Bolker, B. (2012). lme4: Linear mixed-effects models using S4 classes. ◀

Bouma, H. (1970). Interaction effects in parafoveal letter recognition. *Nature, 226*, 177–178. doi:10.1038/226177a0

Brainard, D. H. (1997). The psychophysics toolbox. *Spatial Vision, 10*(4), 433–436. doi:10.1163/156856897X00357

Cai, R. H., Pouget, A., Schlag-Rey, M., & Schlag, J. (1997). Perceived geometrical relationships affected by eye-movement signals. *Nature, 386*(6625), 601–604. doi:10.1038/386601a0

Carrasco, M., & Seamon, J. G. (1996). Priming impossible figures in the object decision test: The critical importance of perceived stimulus complexity. *Psychonomic Bulletin and Review, 3*(3), 344–351. doi:10.3758/BF03210758

Carson, L., Millard, M., Quehl, N., & Danckert, J. (2012). Drawing expertise predicts not just quality but also accuracy. *Perception*, *41* (ECVP Abstract Supplement), 231.

Chakravarthi, R., & VanRullen, R. (2011). Bullet trains and steam engines: Exogenous attention zips but endogenous attention chugs along. *Journal of Vision, 11*(4), 1–12. doi:10.1167/11.4.12

Chamberlain, R., & McManus, I. C. (2013). Subjective and objective measures of drawing accuracy and their relationship to perceptual abilities. *Perception*, *42* (ECVP Abstract Supplement), 106.

Chamberlain, R., McManus, I. C., Riley, H., Rankin, Q., & Brunswick, N. (2013). Local processing enhancements associated with superior observational drawing are due to enhanced perceptual functioning, not weak central coherence. *The Quarterly Journal of Experimental Psychology, 66*(November), 1448–1466. doi:10.1080/17470218.2012.750678

Coen-Cagli, R., Coraggio, P., Napoletano, P., Schwartz, O., Ferraro, M., & Boccignone, G. (2009). Visuomotor characterization of eye movements in a drawing task. *Vision Research, 49*(8), 810–818. doi:10.1016/j.visres.2009.02.016

Cohen, D. J. (2005). Look little, look often: The influence of gaze frequency on drawing accuracy. *Perception and Psychophysics, 67*(6), 997–1009. doi:10.3758/BF03193626

Cohen, D. J., & Bennett, S. (1997). Why can't most people draw what they see? *Journal of Experimental Psychology: Human Perception and Performance*, *23*(3), 609–621. doi:10.1037/0096-1523.23.3.609

Cohen, D. J., & Earls, H. (2010). Inverting an image does not improve drawing accuracy. *Psychology of Aesthetics, Creativity, and the Arts*, *4*(3), 168–172. doi:10.1037/a0017054

Cohen, D. J., & Jones, H. E. (2008). How shape constancy relates to drawing accuracy. *Psychology of Aesthetics, Creativity, and the Arts, 2*(1), 8–19. doi:10.1037/1931-3896.2.1.8

Cornelissen, F. W., Peters, E. M., & Palmer, J. (2002). The eyelink toolbox: Eye tracking with MATLAB and the psychophysics toolbox. *Behavior Research Methods, Instruments, and Computers, 34*(4), 613–617. doi:10.3758/BF03195489

Cowie, R., & Perrott, R. (1993). From line drawings to impressions of 3D objects: Developing a model to account for the shapes that people see. *Image and Vision Computing, 11*(6), 342–352. doi:10.1016/0262-8856(93)90013-7

Crawford, J. D., Medendorp, W. P., & Marotta, J. J. (2004). Spatial transformations for eye–hand coordination. *Journal of Neurophysiology, 92*(1), 10–19. doi:10.1152/jn.00117.2004

Donnelly, N., Found, A, & Müller, H. J. (1999). Searching for impossible objects: Processing form and attributes in early vision. *Perception and Psychophysics, 61*(4), 675–690. doi:10.3758/BF03205538

Drake, J. E., & Winner, E. (2011). Realistic drawing talent in typical adults is associated with the same kind of local processing bias found in individuals with ASD. *Journal of Autism and Developmental Disorders, 41*(9), 1192–1201. doi:10.1007/s10803-010-1143-3

Elo, A. E. (1978). *The rating of chessplayers, past and present*. London: Batsford.

Freud, E., Avidan, G., & Ganel, T. (2013). Holistic processing of impossible objects: Evidence from Garner's speeded-classification task. *Vision Research*. doi:10.1016/j.visres.2013.10.001

Freud, E., Ganel, T., & Avidan, G. (2013). Representation of possible and impossible objects in the human visual cortex: Evidence from fMRI adaptation. *NeuroImage, 64*, 685–692. doi:10.1016/j.neuroimage.2012.08.070

Germine, L., Nakayama, K., Duchaine, B. C., Chabris, C. F., Chatterjee, G., & Wilmer, J. B. (2012). Is the Web as good as the lab? Comparable performance from Web and lab in cognitive/perceptual experiments. *Psychonomic Bulletin and Review, 19*(5), 847–857. doi:10.3758/s13423-012-0296-9

Glazek, K. (2012). Visual and motor processing in visual artists: Implications for cognitive and neural mechanisms. *Psychology of Aesthetics, Creativity, and the Arts, 6*(2), 155–167. doi:10.1037/a0025184

Gobet, F., & Simon, H. A. (1996). Templates in chess memory: A mechanism for recalling several boards. *Cognitive Psychology, 31*(1), 1–40. doi:10.1006/cogp.1996.0011

Green, C. S., & Bavelier, D. (2007). Action-video-game experience alters the spatial resolution of vision. *Psychological Science, 18*(1), 88–94. doi:10.1111/j.1467-9280.2007.01853.x

Greene, M. R., & Oliva, A. (2009). Recognition of natural scenes from global properties: Seeing the forest without representing the trees. *Cognitive Psychology, 58*(2), 137–176. doi:10.1016/j.cogpsych.2008.06.001

Greenwood, J. A, Bex, P. J., & Dakin, S. C. (2009). Positional averaging explains crowding with letter-like stimuli. *Proceedings of the National Academy of Sciences of the United States of America, 106*(31), 13130–13135. doi:10.1073/pnas.0901352106

Hayes, S., & Milne, N. (2011). What's wrong with this picture? an experiment in quantifying accuracy in 2D portrait drawing. *Visual Communication, 10*(2), 149–174. doi:10.1177/1470357211398442

He, S., Cavanagh, P., & Intriligator, J. (1996). Attentional resolution and the locus of visual awareness. *Nature, 383*(3), 334–337. doi:10.1016/S1364-6613(97)89058-4

He, S., Cavanagh, P., & Intriligator, J. (1997). Attentional resolution. *Trends in Cognitive Sciences, 1*(3), 115–121. doi:10.1016/S1364-6613(97)89058-4

Hochstein, S., & Ahissar, M. (2002). View from the top: Hierarchies and reverse hierarchies in the visual system. *Neuron, 36*(5), 791–804. doi:10.1016/S0896-6273(02)01091-7

Kesten, H. (1958). Accelerated stochastic approximation. *The Annals of Mathematical Statistics, 29*(1), 41–59. doi:10.1214/aoms/1177706705

Kosslyn, S. M., Ball, T. M., & Reiser, B. J. (1978). Visual images preserve metric spatial information: evidence from studies of image scanning. *Journal of Experimental Psychology. Human Perception and Performance, 4*(1), 47–60. doi:10.1037/0096-1523.4.1.47

Kozbelt, A., Seidel, A., ElBassiouny, A., Mark, Y., & Owen, D. R. (2010). Visual selection contributes to artists' advantages in realistic drawing. *Psychology of Aesthetics, Creativity, and the Arts, 4*(2), 93–102. doi:10.1037/a0017657

Land, M. F. (2006). Eye movements and the control of actions in everyday life. *Progress in Retinal and Eye Research, 25*(3), 296–324. doi:10.1016/j.preteyeres.2006.01.002

Locher, P. (2010). How does a visual artist create an artwork? In J. C. Kaufman & R. J. Sternberg (Eds.), *The Cambridge handbook of creativity* (pp. 131–144). Cambridge: Cambridge University Press.

Martelli, M., Majaj, N. J., & Pelli, D. G. (2005). Are faces processed like words? A diagnostic test for recognition by parts. *Journal of Vision, 5*, 58–70. doi:10.1167/5.1.6

McManus, I. C., Loo, P., Chamberlain, R., Riley, H., & Brunswick, N. (2011). Does shape constancy relate to drawing ability? Two failures to replicate. *Empirical Studies of the Arts, 29*(2), 191–208. doi:10.2190/EM.29.2.d

Mitchell, P., Ropar, D., Ackroyd, K., & Rajendran, G. (2005). How perception impacts on drawings. *Journal of Experimental Psychology. Human Perception and Performance, 31*(5), 996–1003. doi:10.1037/0096-1523.31.5.996

New, B., Pallier, C., Brysbaert, M., & Ferrand, L. (2004). Lexique 2: A new French lexical database. *Behavior Research Methods, Instruments, and Computers, 36*(3), 516–524. doi:10.3758/BF03195598

Ostrofsky, J., Kozbelt, A., & Seidel, A. (2012). Perceptual constancies and visual selection as predictors of realistic drawing skill. *Psychology of Aesthetics, Creativity, and the Arts, 6*(2), 124–136. doi:10.1037/a0026384

Pelli, D. G. (1997). The videotoolbox software for visual psychophysics: Transforming numbers into movies. *Spatial Vision, 10*(4), 437–442. doi:10.1163/156856897X00366

Perdreau, F., & Cavanagh, P. (2011). Do artists see their retinas? *Frontiers in Human Neuroscience, 5*(171), 1–10. doi:10.3389/fnhum.2011.00171

Perdreau, F., & Cavanagh, P. (2013a). Is artists' perception more veridical? *Frontiers in Neuroscience, 7*(6), 1–11. doi:10.3389/fnins.2013.00006

Perdreau, F., & Cavanagh, P. (2013b). The artist's advantage: Better integration of object information across eye movements. *i-Perception, 4*(6), 380–395. doi:10.1068/i0574

Posner, M., Petersen, S., Fox, P., & Raichle, M. (1988). Localization of cognitive operations in the human brain. *Science, 240*(4859), 1627–1631.

Prins, N. (2012). The psychometric function: the lapse rate revisited. *Journal of Vision, 12*(6), 1–16. doi:10.1167/12.6.25

Rayner, K. (1998). Eye movements in reading and information processing: 20 years of research. *Psychological Bulletin, 124*(3), 372–422. doi:10.1037/0033-2909.124.3.372

Schacter, D. L., Cooper, L. A., & Delaney, S. M. (1990). Implicit memory for unfamiliar objects depends on access to structural descriptions. *Journal of Experimental Psychology General, 119*, 5–24. doi:10.1037/0096-3445.119.1.5

Schacter, D. L., Cooper, L. A, Delaney, S. M., Peterson, M. A, & Tharan, M. (1991). Implicit memory for possible and impossible objects: Constraints on the construction of structural descriptions. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 17*(1), 3–19. doi:10.1037/0278-7393.17.1.3

Seamon, J., & Carrasco, M. (1999). The effect of study time on priming possible and impossible figures in the object decision test. *Psicothema, 11*(4), 801–813.

Soldan, A., Hilton, H. J., & Stern, Y. (2009). Bias effects in the possible/impossible object decision test with matching objects. *Memory and Cognition, 37*(2), 685–692. doi:10.3758/MC.37.2.235

Tchalenko, J. (2007). Eye movements in drawing simple lines. *Perception, 36*(8), 1152–1167. doi:10.1068/p5544

Tchalenko, J. (2009). Segmentation and accuracy in copying and drawing: experts and beginners. *Vision Research, 49*(8), 791–800. doi:10.1016/j.visres.2009.02.012

Tchalenko, J., & Miall, R. C. (2009). Eye–hand strategies in copying complex lines. *Cortex, 45*(3), 368–376. doi:10.1016/j.cortex.2007.12.012

Thorpe, S., Fize, D., & Marlot, C. (1996). Speed of processing in the human visual system. *Nature, 381*, 520–522. doi:10.1038/381520a0

Toet, A., & Levi, D. (1992). The two-dimensional shape of spatial interaction zones in the parafovea. *Vision Research, 32*(7), 1349–1357. doi:10.1163/156856894X00350

Treisman, A. M., & Gelade, G. (1980). A feature-integration theory of attention. *Cognitive Psychology, 12*(1), 97–136. doi:10.1016/0010-0285(80)90005-5

Whitney, D., & Levi, D. M. (2011). Visual crowding: a fundamental limit on conscious perception and object recognition. *Trends in Cognitive Sciences, 15*(4), 160–168. doi:10.1016/j.tics.2011.02.005

Williams, P., & Tarr, M. J. (1997). Structural processing and implicit memory for possible and impossible figures. *Journal of Experimental Psychology. Learning, Memory, and Cognition, 23*(6), 1344–1361. doi:10.1037/0278-7393.23.6.1344

Florian Perdreau is a PhD fellow under the supervision of Patrick Cavanagh at the Laboratoire Psychologie de la Perception (Paris, France). He received a first Master's degree in philosophy at the University of Tours (2008, France. Science and Metaphysics in Henri Bergson), followed by another Master's degree in Cognitive sciences at Ecole Normale Supérieure (2011, France). He started his PhD in 2011 on the effects of expertise on visual cognition.

Patrick Cavanagh received a degree in Electrical Engineering from McGill University in 1968 and a PhD in cognitive psychology from Carnegie-Mellon in 1972. He taught first at the Université de Montréal in Psychology, and in 1989 he moved to Harvard as Professor of Psychology. In 2007, he accepted a Chaire d'Excellence at the Université Paris Descartes. Current projects study the roles of visual attention in selecting and locating targets and the contribution of various features such as shadow, color, motion, and texture to representations of visual form.